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Frontiers of Potassium

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ROME, ITALY

JANUARY 25-27, 2017

Frontiers of Potassium
an International Conference

Proceedings
for the
Frontiers of Potassium Science Conference

January 25-27, 2017

T.S. Murrell and R.L. Mikkelsen (Eds.). Frontiers of Potassium Science. Rome, Italy. 25-27 Jan. 2017. International Plant Nutrition Institute, Peachtree Corners, GA, USA.

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Organized and Published by:
International Plant Nutrition Institute
3500 Parkway Lane, Suite 550
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Potassium and Human Health

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Abstract
Potassium is an essential nutrient. It is the most abundant cation in intracellular fluid where it plays a key role in maintaining cell function. Approximately 90% of potassium consumed (60–100 mEq) is lost in the urine, with the other 10% excreted in the stool, and a very small amount lost in sweat. Little is known about the bioavailability of potassium, especially from dietary sources. Less is understood on how bioavailability may affect health outcomes. Potassium was identified as a shortfall nutrient by the Dietary Guidelines for Americans 2015 Advisory Committee. There is growing evidence for the association between potassium intake and blood pressure reduction in adults; hypertension (HTN) is the leading cause of cardiovascular disease (CVD) and a major financial burden ($50.6 billion) to the US public health system, and has a significant impact on all-cause morbidity and mortality worldwide. Evidence is also accumulating of the protective effect of adequate dietary potassium on age-related bone loss, and kidney health. These benefits depend on organic anions associated with potassium as occurs in foods such as fruits and vegetables, in contrast to blood pressure, which is potassium-dependent. Benefits to blood pressure and bone health may occur at levels below current recommendations for potassium intake, especially from diet, but dose-response trials are needed to confirm this. Regardless, intakes considerably above current levels are needed for optimal health. Western diets have led to a decrease in potassium with reduced consumption of fruits and vegetables and increased sodium through greater consumption of processed foods. Understanding the benefit of potassium intake and bioavailability from various sources may help to reveal how specific compounds and tissues influence potassium movement, and further the understanding of its role in health.

INTRODUCTION

Potassium is an essential nutrient. It is the most abundant cation in intracellular fluid where it plays a key role in maintaining cell function. Because potassium is a major intracellular ion, it is widely distributed in foods once derived from living tissues. Potassium concentration is higher in fruits and vegetables than in cereals and meat. Western dietary practices with higher consumption of cereal, low nutrient density processed foods and lower consumption of fruits and vegetables has led to a diet lower in potassium and higher in sodium in recent decades (Weaver, 2013).

Recommended adequate intakes for potassium were set by the Food and Nutrition Board of the Institute of Medicine at 4700 mg/d (Institute of Medicine, 2005). This was largely based on meta-analyses of randomized, controlled trials investigating the effect of potassium supplementation on reducing blood pressure. Few Americans meet the recommended intakes; the average intake is 2591+/- 19 mg/d (Fulgoni et al., 2011). This large gap between potassium intakes and recommended intakes led to potassium being identified as a shortfall nutrient in the Dietary Guidelines for Americans (US Department Of Health And Human Services And Us Department Of Agriculture, 2015; Desalvo et al. 2016).

Actual potassium requirements would vary with an individual's genetics, sodium intake, and status of various health related biomarkers. Blood pressure (BP) is currently the primary criterion for determining potassium requirements. Other benefits of increasing potassium consumption may include healthy kidney function, and possible benefit to bone (He and MacGregor, 2008, Weaver, 2013). These differences may support personalized nutrition approaches.

ASSESSING POTASSIUM INTAKE NEEDS

The reference values for the intake of any nutrient are referred to as the Dietary Reference Intakes (DRIs) and include: the Estimated Average Requirement (EAR), or intake level at which 50% of the population are met; the Recommended Dietary Allowance (RDA), sufficient to meet the requirements of nearly the entire population (98%); Adequate Intake (AI), established when there insufficient evidence for an RDA; and the Tolerable Upper Intake Level (UL), the maximum intake that poses no health risk (Fulgoni, 2007, Lupton et al., 2016, Millen et al., 2016, Institute of Medicine, 2005). DRIs are quantitative values established by United States Dietary Guidelines Committee after a review of the appropriate research surrounding any nutrient's role in eliminating nutritional deficiencies, and reducing risk of chronic disease. Basic concepts of establishing the proper level of intake for each nutrient are that the needs of healthy (non-diseased) individuals are met, nutrients are grouped by physiological functionality, and age groupings are revised to reflect changes of biological patterns (e.g., gender, growth, pregnancy, etc.)(Lupton et al., 2016, Millen et al., 2016, Institute of Medicine, 2005). Chronic disease endpoints are only considered when a sufficient body of knowledge has been established.

Worldwide Potassium Intakes

It is estimated that only 3% of adults and 10% of children under the age of 5 in the United States meet the adequate intake (AI) level for potassium (Cogswell et al., 2012, National Centre for Chronic Disease Prevention and Health Promotion, 2013). However it should be noted that the US AI, set at 4,700 mg/d for adults, is substantially higher than the World Health Organization's (WHO) guidelines which recommend 3,150 mg/d for adults (US Department of Health and Human Services Dietary Guideliens Advisory Committee, 2010, World Health Organisation (WHO), 2012). National Health and Nutrition Examination Survey (NHANES) data indicates that 99.2% of potassium in the US diet is naturally occurring, with the remaining 0.8% coming from fortified foods (Fulgoni et al., 2011). These naturally occurring sources include milk and other non-alcoholic beverages, as well as potatoes and fruit, which rank highest as sources of potassium intake among US adults (O'Neil et al., 2012).

Welch et al. (2009) examined potassium intakes from 10 European countries and found that for both men and women, Greece had the lowest average intakes at 3,536 and 2730 mg/day respectively, and Spain the highest at 4870 and 3723 mg/d, respectively (Welch et al., 2009). Meat/meat products and cereals/cereal products are the main contributors to potassium intake in Europe; however, there is substantial geographical variation in the contribution of other potassium rich foods (Welch et al., 2009). It is estimated that fruit and vegetables provide 17.5% of total potassium intake in Nordic countries compared to 39% in Greece, while in the United Kingdom (UK) vegetables and potatoes are the largest contributor, providing 24.5% (Public Health England and Food Standards Agency, 2014).

Despite an increase of 300 mg/day since 1991, potassium intakes in China remain poor at 1800 mg/day (Du et al., 2014). This does not meet the Chinese DRI for potassium, which is set at 2000 mg/day, and is less than half of the WHO recommendation of 3150 mg/day (Chinese Nutrition Society, 2013, WHO, 2012). Intakes are higher in Korea where the average potassium intake is 2900 mg/day yet still do not meet the WHO guidelines (Lee et al., 2013). The primary potassium sources in the Korean diet are white rice, fruits and vegetables (Lee et al., 2013).

INTERNAL BALANCE OF POTASSIUM

Total body potassium (K+) is estimated to be approximately 43mEq/kg in adults, with only 2% of this found in the extracellular fluid. Most of the body potassium content is found in the intracellular space of skeletal muscle. Potassium is the primary intercellular cation and plays a key role in maintaining cell function, having marked influence on transmembrane electro-chemical gradients (Palmer, 2015). The gradient of potassium across the cell membrane determines cellular membrane potential which, based on the normal ratio of intracellular to extracellular K+, is -90mV. This potential difference is maintained in large part by the ubiquitous ion channel the sodium-potassium (Na+-K+) ATPase pump. When activated,

the Na+-K+ ATPase pump exchanges two extracellular K+ ions for three intracellular sodium (Na+) ions, influencing membrane potential based on physiological excitation or inhibition. These channels are partially responsible, along with the Na+-K+ chloride (Cl) symporter, and sodium-calcium (Ca) exchanger, for maintaining the potential difference across the resting cell membrane as well. Both resting membrane potential and the electro-chemical difference across the cell membrane are crucial for normal cell biology, especially in muscle, cardiac, and nervous tissue (Palmer, 2015, Unwin et al., 2011).

Approximately 90% of potassium consumed (60-100 mEq) is lost in the urine, with the other 10% excreted in the stool, and a very small amount lost in sweat (Shils and Shike, 2006). Potassium has a higher ratio of dietary intake to extracellular pool size; only 2% of the total body K+ is distributed in ECF with the remaining distributed in the ICF of various tissues (Youn, 2013). To meet the challenge of a high potassium meal the K+ homeostatic system is very efficient at clearing plasma K+ via an increase in renal K+ excretion. When dietary K+ intake increases or decreases the kidneys modulate excretion accordingly, ensuring the maintenance of plasma [K+]. In addition, with the administration of acute K+ loads only approximately half of the dose appears in the urine after 4-6h, suggesting that extra-renal tissues (e.g. muscle) play an important role in K+ homeostasis as well (Bia and DeFronzo, 1981, Youn, 2013).

Potassium is freely filtered by the glomerulus of the kidney, with most of it being reabsorbed (70-80%) in the proximal tubule and loop of Henle (Shils and Shike, 2006). Under physiological homeostasis delivery of K+ to the nephron remains constant. Conversely, secretion of K+ by the distal nephron is variable and depends on intracellular K+ concentration, luminal K+ concentration, and cellular permeability (Palmer, 2015, Unwin et al., 2011). Reabsorption in the proximal tubule is primarily passive and proportional to reabsorption of solute and water, accounting for ~60% of filtered K+ (Penton et al., 2015, Ludlow, 1993). Within the descending limb of Henle's loop a small amount of K+ is secreted into the luminal fluid, while in the thick ascending limb reabsorption occurs together with Na+ and Cl, both trans- and paracellularly. This leads to the K+ concentration of the fluid entering the distal convoluted tubule to be lower than plasma levels (~2mEq/L) (Ludlow, 1993). Similar to reabsorption in the proximal tubule, paracellular diffusion in Henle's loop is mediated via solvent drag, while transcellular movement occurs primarily through the apical sodium-potassium-chloride (Na+-K-2Cl) co-transporter (Ludlow, 1993, Palmer, 2015). Major regulation of K+ excretion occurs in the late distal convoluted tubule (DCT) and the early connecting tubule (Meneton et al., 2004). Increased distal delivery of Na+ increases Na+ reabsorption, leading to a more negative luminal/plasma potential gradient and an increase in K+ secretion.

Dietary potassium may also slow the progression of kidney disease. High potassium intake in hypertensive rats reduces microscopic renal lesions, improving glomular function, tubular flow, and decreasing nephron loss (Tobian et al., 1984). In rat models of chronic kidney disease, compared with the basal diet, potassium supplementation decreased renal tubulointerstitial injury and suppressed renal inflammation via decreased macrophage infiltration, upregulation of renal Smad 7 and downregulation of transforming growth factor b, lower expression of inflammatory cytokines, and decreased NF-kappaB activation. (Wang et al., 2007, Pere et al., 2000). No controlled trials have been published that determine the role of dietary potassium and renal health in humans with hypertension or kidney disease.

POTASSIUM BIOAVAILABILITY

Potassium is intrinsically soluble and quickly dispersed in the luminal water of the upper digestive tract. The small intestine is the primary site of potassium absorption, with approximately 90% of dietary potassium being absorbed by passive diffusion (Demigne et al., 2004). Little is known about the bioavailability of potassium, with the majority of work being centered on the assessment of urinary potassium losses after potassium salt supplementation (Melikian et al., 1988, Bechgaard and Shephard, 1981, Betlach et al., 1987).

Many different models of potassium movement within the body have been proposed, each developed to fit various areas of biological interest. The complexity of each model varies, from early recommendations by the International Commission on Radiological Protection for evaluation of radiopotassium exposure limiting the body to one large mixed pool of potassium, to more complex anatomically related compartmentalization (2007, 1975, Valentin, 2002). In one of the earliest schemes, Ginsburg and Wilde constructed a five compartment model, mathematically derived from murine data looking at tissue groupings (muscle/testes, brain/RBC, bone, lung/kidney/intestine, liver/skin/spleen) and their potassium exchange between a common compartment of extracellular fluid (ECF) (Ginsburg, 1962, Ginsburg and Wilde, 1954). Utilizing $^{42}K+$ intravenous (IV) injections, a wide spectrum of tracer exchange rates between tissues, with kidneys being the fastest (equilibrium with plasma at 2 min) and muscle and brain being the slowest (≥600 min) were observed (Ginsburg, 1962, Ginsburg and Wilde, 1954). Later, Leggett and Williams proposed a more anatomically specific model based on the quantitative movement of potassium through mathematically derived compartments within a physiologically relevant framework (Leggett and Williams, 1986). Their model, similar to previous depictions, identified plasma/ECF as the primary feeding compartment, with equilibrium distribution of potassium, regional blood flow rates, and potassium tissue extraction fractions, all influencing potassium exchange. The model also depicted potassium exchange from plasma/ECF to tissues as a relatively rapid and uniform process; skeletal muscle being the only exception, with slower exchange due to its role as the main site of potassium storage (Leggett and Williams, 1986).

In our recent study (Macdonald et al., 2016), the bioavailability of potassium from potato sources (non-fried white potatoes, French fries) and a potassium supplement (potassium gluconate) was compared. Thirty-five healthy men and women (29.7 ± 11.2 years, 24.3 ± 4.4 kg/m^2) were randomized to nine, five-day interventions of additional K+ equaling: 0 mEq (control at phase 1 and repeated at phase 5), 20 mEq (1500 mg), 40 mEq (3000 mg), 60 mEq (4500 mg) K+/day consumed as K+ gluconate or potato, and 40 mEq K+/day from French fries. Bioavailability of potassium was determined from serum area under curve (AUC) (serial blood draws) and 24 h urinary excretion assessed after a test meal of varying potassium dose given on the 4th day. Increases in serum potassium AUC with increasing dose were reported, regardless of source, while potassium 24 h urine concentration also increased with dose but was greater with potato compared to supplement. These outcomes reveal the need for a full potassium balance study, looking at complete losses (urine and feces), to fully understand potassium bioavailability differences between dietary intake vs. supplements, and their subsequent health effects (Macdonald-Clarke et al., 2016).

POTASSIUM AND HYPERTENSION

Hypertension (HTN) is the leading cause of cardiovascular disease (CVD) and a major contributing risk factor for the development of stroke, coronary heart disease (CHD), myocardial infarction, heart failure, and end-stage renal disease, amounting to a US public health financial burden of $50.6 billion (Roger et al., 2012). Nearly 1 in 3 American adults (~72 million) are estimated to have HTN, while nearly 70 million are at risk for developing pre-hypertension (BP between 120/80 mmHg – 140/90 mmHg). Approximately 90% of US adults older than 50 are at risk for the development HTN, with systolic rises being the most prevalent (Svetkey et al., 2004). Hypertension is a leading cause of morbidity and mortality worldwide and second only to smoking as a preventable cause of death in the United States (Lopez and Mathers, 2006).

Numerous epidemiological studies show diet as a key component in blood pressure (BP) control, with some studies showing lower BP in populations consuming higher amounts of fruits and vegetables (Young et al., 1995, 1988, Elford et al., 1990). Dietary patterns known to lower BP include reduced sodium intake, increased potassium and magnesium intake, increases in fruit and vegetable consumption, as well as other foods rich in antioxidants (Appel et al., 1997, Svetkey et al., 1999). A population study conducted by Khaw et al. (1982) in St. Lucia, West Indies suggested an increase in potassium by 20-30

mmol/d (~700-1200 mg/d) resulted in a 2 to 3 mmHg reduction in systolic blood pressure (SBP) (Khaw and Rose, 1982). In adults a 2-mmHg reduction in BP can reduce CHD and stroke mortality rates by 4 and 6%, respectively (Stamler, 1991). The American Heart Association has estimated that increasing potassium intake may decrease HTN incidence in Americans by 17% and lengthen life span by 5.1 years (Roger et al., 2012). Attaining adequate potassium intake may be the most influential dietary component in lowering BP, with a diet containing >3500 mg/d recommended for primary prevention of HTN (Chobanian et al., 2003).

Observational studies have evaluated the effects of potassium from foods, while clinical intervention trials have primarily used potassium supplements. Several meta-analyses show a significant reduction in BP with increasing potassium supplementation (Beyer et al., 2006, Whelton et al., 1997, Cappuccio and MacGregor, 1991, Geleijnse et al., 2003). In an early meta-analysis Cappuccio and MacGregor reviewed 19 clinical trials looking at the effect of potassium supplementation on BP in primarily hypertensive individuals (412 of 586 participants). With the average amount of potassium given at 86 mmol/day (~3300mg/d; as primarily KCl) for an average duration of 39 days, researchers found that potassium supplementation significantly reduced SBP by 5.9 mmHg and diastolic blood pressure (DBP) by 3.4 mmHg. Greater reductions were found in individuals who were on supplementation for longer periods of time (Cappuccio and MacGregor, 1991). As is evident, the effect of potassium supplementation on BP reduction is generally positive, but not consistent. According to a more recent meta-analysis conducted by Dickinson et al. (2006), potassium supplementation did not significantly reduce BP in those with hypertension, although this analysis was only based on five trials, and findings, while not statistically significant, did reveal reductions in both SBP and DBP (Beyer et al., 2006, Dickinson et al., 2006). In general, these outcomes show that the BP lowering effects of potassium supplementation are greater in those with HTN and more pronounced in blacks compared to whites. Other noted factors that may influence the effects of potassium supplementation on BP include pre-treatment BP, age, gender, intake of sodium and other ions (magnesium, calcium), weight, physical activity level, and concomitant medications.

Overall findings from clinical trials on the effect of increased potassium intake have been conflicting (Appel et al., 1997, Svetkey et al., 2004, Gu et al., 2007, Kawano et al., 1998). Evidence from dietary interventions is extremely limited, with the majority of findings being extrapolated from The Dietary Approaches to Stop Hypertension (DASH) study (Appel et al., 1997). The DASH intervention revealed that a diet rich in fruit and vegetables, fiber, and low fat dairy products, with reductions in saturated and total fat and sodium could positively influence BP compared to the average American diet (Sacks and Campos, 2010). Although the DASH diet does lead to a dramatic increase in potassium consumption (+1447 to 2776 mg/d) and reduction in BP, due to its other dietary modifications these beneficial effects cannot be attributed to potassium alone (Svetkey et al., 1999). In an earlier study conducted by Chalmers et al. (1986), the effects of both the reduction of dietary sodium and increase of dietary potassium on BP were assessed (Chalmers et al., 1986). Two-hundred-and-twelve subjects (age 52.3±0.8 years; 181 males and 31 females) with a DBP between 90 and 100 mmHg were recruited and placed in one of the 4 following diet groups: a normal diet group (control), a high potassium diet (>100mmol K/d; >3900mg/day), a reduced sodium diet (50-75mmol Na+/d; 1150-1725mg/day), or a high potassium/low sodium diet. Subjects completed the diet phase for 12 weeks in which they were regularly counseled on how to adequately modify their food choices based on their group (e.g. avoiding salt and high sodium foods or increasing fruit and vegetable intake). Significant reductions in both SBP and DBP in each dietary intervention group compared to controls were observed, but no significant differences were observed between groups. Reductions in the high potassium group were 7.7±1.1 and 4.7±0.7 mmHg for SBP and DBP, respectively. Although high potassium intake did appear to reduce BP the lack of differences between groups points to the possibility of an overall diet effect. In addition, for both the high potassium and low sodium groups there was a significant reduction in weight during the study, which may have further confounded the results. In a more recent study, Berry and colleagues (2010) assessed the

effects of increased potassium intake from both dietary sources and supplements on BP in untreated pre-hypertensive individuals (DBP: 80-100 mmHg) (Berry et al., 2010). In a cross-over design, subjects (n=48, 22-65 years) completed four, 6 week dietary interventions including a control diet, an additional 20 or 40 mmol K/d (780 or 1560mg/day) from fruit and vegetables and 40 mmol potassium citrate/d capsules. Similar to the Chamlers study, nutrition coaching was used to regulate participant food choice during each dietary intervention, primarily focused on increasing fruit and vegetable intake. No significant changes in ambulatory BP between the control group and any of the dietary or supplement interventions were observed. The sample size was small and the cohort heterogeneous, but the lack of control used to conduct the potassium dietary intervention was the primary limiting factor in the Berry study. Given these results it seems that to adequately assess the true effect of increased dietary potassium intake on BP and other health outcomes a controlled feeding study is necessary.

POTASSIUM AND BONE

Adequate potassium intake may benefit overall bone health, and has been proposed to do so primarily through its effect on acid-base balance (Barzel, 1995, Brandao-Burch et al., 2005). Support for the acid-base bone theory stems from the idea that the Western diet is high in meats and cereal grains and low in fruits and vegetables, creating an environment of low-grade metabolic acidosis (75 to 100 mEq acid/d) (Barzel, 1995). Buffering of this increased acid load via bone tissue derived calcium salts, would lead to bone loss. Alkaline potassium salts produced from metabolizing fruits and vegetables or potassium supplements (potassium bicarbonate or citrate) are thought to protect against bone resorption, and maintain pH homeostasis (~7.35-7.45). The impact of excess systemic acid on bone is proposed to be mediated by two mechanisms: pH buffered through skeleton acting as an ion-exchange column, and cell based mechanisms (e.g. upregulation of osteoclast activity) (Barzel, 1995, Brandao-Burch et al., 2005).

Potassium intake has also been associated with reduced urinary calcium excretion. Clinical trials show persistent hypocalciuria in both men and women given potassium supplements (bicarbonate or citrate) vs. similar sodium supplements, suggesting potassium may have a role in bone benefit beyond acid balance (Lemann et al., 1989, Frassetto et al., 2005). In a recent randomized, double-blind, placebo-controlled study, 52 men and women randomly assigned to six months of 0, 60 mmol/d, or 90 mmol/d of potassium citrate supplementation showed decreased urinary calcium and decreased acid excretion resulting in more positive calcium balance on the highest dose (Moseley et al., 2013).

Beyond potassium's effect on calcium balance, several studies have accessed the influence of potassium on biochemical markers of bone turnover. Studies have shown decreases in the bone resorption markers C- and N-telopeptide and procollagen type I N-terminal propeptide, with potassium supplementation (Dawson-Hughes et al., 2009, Marangella et al., 2004). In postmenopausal women potassium bicarbonate at 60 to 120 mmol/d decreased urinary hydroxyproline excretion by 10%, while increasing serum osteocalcin, a marker of bone formation (Sebastian et al., 1994).

The relationship between increased potassium intake and bone mineral density shows conflicting results. Only three clinical trials have been reported all done in populations of postmenopausal women or the elderly (>60y). One trial showed protection from BMD loss in the spine, hip, and femoral neck, with a potassium citrate supplement compared to potassium chloride (30 mEq/d), but lacked a placebo control. (Jehle et al., 2006). A second trial revealed no BMD benefit with increased intake from potassium citrate (55 or 18.5 mEq/d), fruits and vegetables (18.5 alkali mEq/d), or a placebo (Macdonald et al., 2008). And the third, and strongest, reported a 1.7% increase in spine BMD with potassium citrate supplementation (60 mEq/d) compared to placebo (Jehle et al., 2006, Jehle et al., 2013, Macdonald et al., 2008). While generally inconclusive, findings may reveal the significance of potassium form and dose in any potential benefit for BMD.

CONCLUSION

Increasing dietary potassium has potential benefit to lowering risk of hypertension, and may provide benefit to both kidney function and bone. We need to understand more about bioavailability of potassium from foods. Only the potato has been studied for potassium bioavailability and this food is constituted mostly of easily digested starch. Are there as of yet unidentified inhibitors to potassium absorption or food matrix effects? Do some anions that accompany potassium in foods have differential functional advantages? Organic salts of potassium appear to have more benefit to bone, perhaps through effects on acid-base balance. The form seems less important for controlling blood pressure. Research on potassium is likely to increase because it is an identified shortfall nutrient and increasing dietary potassium is a well-established modifiable factor for hypertension, the largest risk of some of our most common chronic diseases.

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What can Long-Term Experiments Teach Us about Potassium Management?

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Abstract
Long-Term Experiments (LTEs) can be defined as experiments that have been carefully and consistently managed for a long time, with those of 50 years or more being defined as 'Classical'. However, their age is not the only critical aspect but also the number of cropping cycles or rotations completed. Several web-based lists or directories exist. A review of the literature shows that LTEs can teach us much about the management of potassium in soils and crop plants. They: (i) provide benchmark soils for calibrating methods of soil analysis and the basis for K fertiliser recommendations; (ii) show that the effective recycling of organic manures is essential for maintaining and improving K supply and overall soil fertility; (iii) reveal the details of K exchange processes in the soil and show the importance of soil reserves and which soils can release these reserves; (iv) alone enable a K balance to be calculated and whether applications of K in fertilisers and manures are sufficient to avoid soil degradation; (v) show the importance of balanced nutrition and key nutrient interactions such as N:K; (vi) show how tillage interacts with K supply and distribution in the soil; and (vii) are invaluable for the development and calibration of K cycle models. No comprehensive study of potassium management would be complete without a review of the role of LTEs.

INTRODUCTION

Wikipedia describes a long-term experiment (LTE) as: "… an experimental procedure that runs through a long period of time, in order to test a hypothesis or observe a phenomenon that takes place at an extremely slow rate" (https://en.wikipedia.org/wiki/Long-term_experiment). Stewart et al. (2005) list many of the LTEs relevant to potassium (K) research in their review of the importance of fertilisers for crop production. Other lists can be found on the International Soil Carbon Network, which includes >250 LTEs (http://iscn.fluxdata.org/partner-networks/long-term-soil-experiments/) and the Long-Term Ecological Research Network (https://lternet.edu/).

In reviewing what we can learn about K management from LTEs, this chapter will refer to the various components and dynamic process involved in K cycling as drafted at the workshop: 'Frontiers in Potassium Science: Developing a Roadmap to Advance the Science of Potassium Soil Fertility Evaluation', Kona, Hawaii, 2015: (i) the soil solution K (Ksl), (ii) the exchangeable K (Kex), (iii) the interlayer K (Ki), and (iv) K in the lattice of primary minerals (Kl) (Fig. 1).

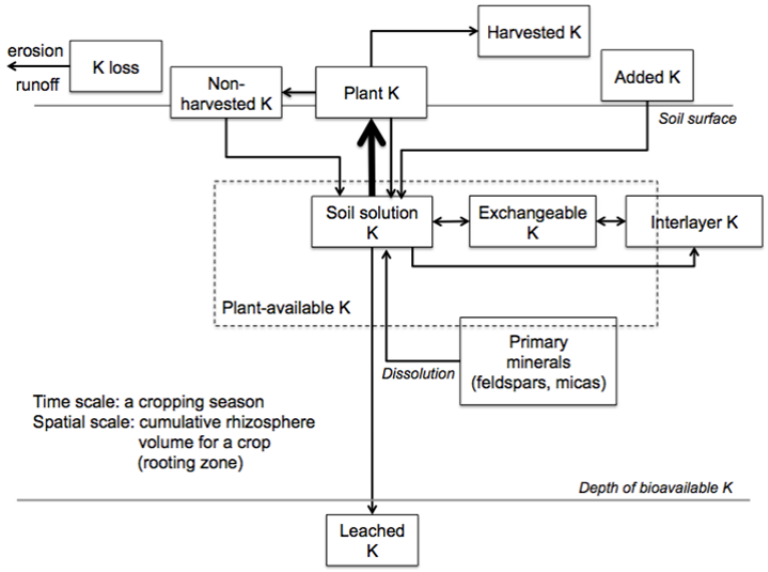

Figure 1: The Potassium cycle in the soil-plant system as drafted at the workshop: 'Frontiers in Potassium Science: Developing a Roadmap to Advance the Science of Potassium Soil Fertility Evaluation', Kona, Hawaii, 2015.

What Can Long-Term Experiments Teach Us About Potassium Management?

Soil Testing and Fertilizer Recommendations

In IPI Research Topics No 1, Kemmler and Malicornet (1989) state: "It is generally agreed that fertilizer recommendations for perennial crops should be based upon long-term experiments. It is not so widely appreciated that long-term investigation is just as important for annual crops. In recent years, however, the importance of long-term fertilizer experiments has been increasingly recognized in the case of food grains and other annual crops." This repeated what had been emphasised by Cooke (1985), LTEs:

> "…will provide the basic information needed to guide extension work which is aimed at improving the productivity, efficiency, and profitability of agricultural systems. They will provide information on the following topics:

1. Basic data required for the calculation of nutrient cycles.
2. Information on responses to fertilizers and the interactions between nutrients and between nutrients and other inputs (such as irrigation and/or pesticides) to the system.
3. A basis for the associated work involving soil analysis and crop composition.

All this information is required to derive the correct recommendations for the amounts of fertilizers to be used and the times when they should be applied ... At present, there are too few of these experiments … and I would insist that they should have the highest priority as they are essential for the correct and efficient management of fertilizers."

LTEs are indispensable for testing and calibrating methods of soil K analysis. Mallarino et al. (1991a and 1991b) showed the importance of soil testing for K recommendations in 11- and 14-year experiments on corn and soybeans: annual applications of K boosted yields of corn and soybeans at 'medium', but not 'high' soil test levels and so soil testing is critical for determining whether or not to withhold K fertiliser. Recent research by that group (Mallarino et al. 1991b; unpublished data) on a 35-year old experiment has shown that K fertiliser can be withheld from 'high-testing soils' for at least 7 years and no consistent responses to K were seen for 18 years; they have also seen a positive interaction between K and phosphorus.

Goulding (1984) used soils from the Rothamsted and other LTEs to compare a resin extraction method for an improved assessment of K availability to crops against the 'standard' ammonium acetate extraction. The availability of multiple years of data is essential for overcoming variations in climate and pest and disease infestations. Mutscher (1995) noted the special value of LTEs as benchmark soils for improving the efficiency of soil testing for fertiliser recommendations. Based on the analysis of soil K status in 11 long-term fertility experiments in Asia, Dobermann et al. (1996b) evaluated two approaches for assessing the K-supplying power of lowland paddy soils to predict total K uptake by irrigated rice: (i) a regression model combining commonly used static soil test parameters, and (ii) mixed-bed ion exchange resin capsules to measure K release during a two-week anaerobic incubation. The resin method provided an integrative measure of soil K status and the factors controlling K transformation and diffusion rates. It was sensitive to past fertilizer history and the resulting build-up or depletion of soil K reserves, and was a better predictor of total K uptake than static soil tests.

Effectiveness of Different Sources of Applied K

The LTEs at Rothamsted (UK), Bad Lauchstaedt (Germany) and Skierniewice (Poland) were used by Blake et al. (1999) to quantitatively assesses the fate of K derived from mineral fertilizers and organic manures. Plant availability and utilization of applied K was partly related to clay content, but more closely to the cation exchange surfaces on mineral and organic constituents and also, at Rothamsted, to the K fixation capacity of clays. The recovery of K from fertilisers was least in the most strongly K fixing soil (at Rothamsted; 44% maximum utilisation) and most in the soil with the highest cation exchange capacity at Bad Lauchstaedt (62% maximum utilisation). Recoveries of K from farmyard manure (FYM) varied from 22–117%, recoveries of >100% indicating subsoil uptake or the release of reserves. The effectiveness of mineral K fertilizer decreased when applied in combination with FYM because FYM was the preferred source of K.

Miao et al. (2011) reviewed results from LTEs around the world, which indicated that well-managed combinations of chemical and organic fertilizers can sustainably achieve higher crop yields, improve soil fertility, alleviate soil acidification and increase nutrient-use efficiency compared with only using chemical fertilizers. Morari et al. (2008) analysed two LTEs established in the early 1960s in north-eastern Italy for Olsen phosphorus, exchangeable cations including Kex, and salinity. The use of organic fertilizer resulted in higher Kex, and a soil quality index including Kex explained up to 74% of yield variability and highlighted the positive role of organic and mixed organic/chemical fertilisers in increasing and maintaining the soil quality.

Fate of K Applied in Fertilisers and Manures and the K Balance

As indicated in Figure 1 and shown in many long-term experiments, Ksl, Kex and Ki are related to each other through reversible exchange processes (Syers 1998; Kraus & Johnston 2002). K removed in crops and/or leached into the subsoil is replenished by K released from both the Kex and Ki pools, unless replaced in fertilisers or biosolids. K can be released from Kex and Ki simultaneously or from Ki to Kex to Ksl. Which of these occurs is not of practical importance provided it meets the needs of the growing crop, but it is important to our theoretical understanding and modelling of the process. Surplus applied K is transferred to Kex and Ki through exchange and fixation. The amount and rate of K released from Ki and Kl will differ with the type and amount of clay minerals, their degree of weathering, the climate and management. The net result of these processes is the K balance, which can only be effectively calculated using LTEs.

Dobermann et al. (1996a) measured K uptake, K use efficiency, and K balance in six different fertilizer treatments of long-term fertility experiments with rice at 11 sites in five Asian countries, noting significant depletion of soil K reserves at many sites. They found that, at that time, recommendations for K addition in most intensive irrigated rice systems were insufficient to replace K removals and that

efficient K management for rice should be based on the K balance, the achievable yield target, and the effective K-supplying power of the soil.

Madaras and Lipavsky (2009) studied the dynamics of plant-available K in an 8-year crop rotation in a LTE started in 1980. The fertilization scheme included 10 combinations of potassium chloride and FYM. An approximate K balance was achieved with an annual application of 153 kg K/ha, but proportionally larger applications were needed by the most demanding crops - silage maize and sugar beet. Changes in Kex mirrored the K balance, with statistically significant fluctuations from 88 to 149 mg K/kg within one crop rotation. Kex was affected primarily by the crop and some unexplained factors; interannual weather fluctuations and field differences had little effect.

Mercik et al. (2000) reported K balances from the LTEs at Warsaw Agricultural University, Skierniewice, started in 1923. In the treatment not fertilized with K, the plants took up 49 kg K/ha/yr from slow release forms; Kex remained constant. The comparison of organic and mineral fertilisers showed a higher K-efficiency from FYM than from inorganic fertilizer. Kraus and Johnston (2002) reported research by Merbach et al. (1999) showing that, where no K was applied, the content of Kex decreased over the first ten years from 90 mg/kg to approximately 50 mg/kg, but then remained constant for the following 30 years. Further, a LTE with grassland cut for hay and given no K at Rothamsted showed that the content of Kex after 7 years even increased slightly despite considerable amounts of K being removed in harvested grass (Fig. 2). Substantial quantities of K had come from K reserves not measured in routine soils tests, and the rates of exchange between the different soil K fractions were obviously fast enough to replenish any short-term reductions in Kex.

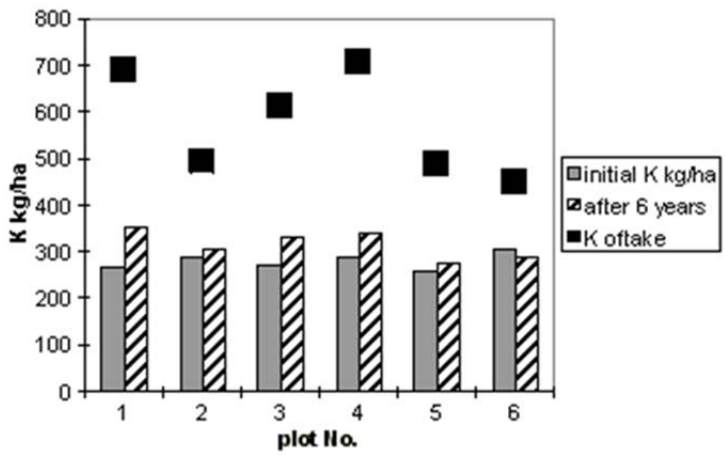

Figure 2. Relationship between the change in soil Kex and K removal by crops (after Kraus and Johnston 2002)

On the Garden Clover Experiment at Rothamsted, a total positive balance of 1667 kg K/ha over a period of 10 years increased the content of Kex by only 690 kg/ha (41% of the K balance), so 59% of the K balance had gone into Ki, assuming that no K was leached. In contrast, the subsequent long-term omission of K, and a negative K balance of 1494 kg K/ha due to crop removal, resulted in a reduction in Kex of only 563 kg K/ha (38% of the K balance). The other 62% of the K removed would have been supplied by Ki and Kl.

Mineral Reserves of K and the Risk of Depletion

LTEs can reveal the importance of mineral reserves of soil K, i.e. Ki and Kl. Madaras et al. (2014) investigated changes in Kex, Ki (as acid-extractable) and Kl in a 40-year old field trial with a range of K application rates, established at 8 sites of different climate and soils. K-feldspars were a dominant source

of K when the balance was negative, and differences in Kex in treatments with negative K balances of < 30 kg K/ha/year were small compared to those of fixed K. In control treatments, the calculated average depletion of Kex was 18 kg/ha/year and the average depletion of Ki was 12 kg/ha/year; Ki accounted for 6–31% of the K budget. They concluded that, where K balances are negative, monitoring of Ki is advisable to avoid depletion of soil fertility.

The ability of some soils to supply K from Ki and Kl to crops can make the prediction of K fertiliser requirement difficult. Kaminsky et al. (2010) used a 16-year old experiment in Brazil to assess the contribution of non-exchangeable forms of K; they estimated the recommended K fertiliser rate as the amount exported in the crop. In other words, they sought to use fertiliser to balance crop removals and maintain soil K. They were able to calculate the average change in Ki (1.3 mg/kg soil) per 1 kg/ha/yr K balance, noting again that applying insufficient K fertiliser results in a significant depletion of Ki, greater than that of 'available K' (Ksl+Kex), and so resulting in fertility depletion.

Potassium in crops

LTEs have been used to examine whether there is a critical concentration of K in plant dry matter at any growth stage below which yield will be lost. On the basis that much of the K in crops is in tissue water, Leigh and Johnston (1983a, 1983b) expressed the K concentrations in spring barley grown in the Hoos Barley LTE at Rothamsted on a tissue water basis and found that they were essentially constant throughout the growing season until the onset of ripening, when they increased significantly as the crop lost water. Concentrations of K were little affected by the availability of N and P and water throughout the season but they were affected by plant-available K in the soil. With a Kex of 325 mg/kg, tissue water K was approximately 200 mM but only 50 mM with 55 mg/kg Kex and yields of grain and straw were less suggesting that tissue water K could be used to identify soils with and without adequate levels of plant-available K.

The concentration of K within cereal straw can vary greatly with cultivar, yield and soil type, making reliable estimates of K offtake difficult to obtain unless the straw is analysed. This information is an essential requirement for replacing the K removed in harvested crops especially when the aim is to maintain an appropriate level of plant-available K in soil. Data on yields of grain and straw of winter wheat grown on Broadbalk at various times between 1852 and 2014, plus grain-straw ratios and K offtakes in grain and per tonne grain harvested were used to calculate K removals. The removal per tonne of grain was remarkably constant for yields that range from 2.2 to 12.4 t/ha over a period of some 170 years. In contrast, %K in straw has tended to decrease and total K offtake in grain plus straw per tonne of grain has thus declined, especially since the 1990s.

Importance of Balanced Nutrition

LTEs were used by Stewart et al. (2005) to show the general importance of K (and other) fertilisers in crop production and global food supply. A total of 362 seasons of the production of maize, wheat, soybean, rice and cowpea showed that the average percentage of yield attributable to fertilizer was between 40 and 60% in the USA and England and much higher in the tropics. Magen (2008) commented that "Results from long-term experiments … play an important role in demonstrating the benefits of balanced fertilization". He noted that, globally, the ratio of $N:P_2O_5:K_2O$ had changed from 2.5:1.3:1 in the 1980s to 3.6:1.4:1 in 2002 as N consumption outstripped that of K, despite many crops needing as much if not more K than N. He discussed outcomes for India, China, Egypt, and Bulgaria and explained how balanced fertilization reduces pest and disease infestation, resulting in higher returns through larger yields and better quality.

Johnston and Milford (2012) noted the strong interaction between K and N, using evidence from LTEs to show that inputs of nutrients, especially N, are used less efficiently when soils contain less than adequate amounts of K. They used the examples of Hoos Spring Barley and a potato experiment at Rothamsted,

and a 20-year old experiment on wheat and sugar beet at Woburn Farm, to show that adequate Kex optimised the use of N, and less N was needed for maximum yields. However, the application of organic manure that improved structure and so root growth and development allowed the barley to grow at a lower Kex.

A positive interaction between K and P has been observed in recent research on corn and soybeans in the US (Mallarino; unpublished data). The yield response to P was much greater when K was applied.

Tillage and Nutrient Distribution

Lopez-Garrido et al. (2011) studied the impacts of tillage and cropping sequences on soil organic matter and nutrients in short-term and long-term (16 years) experiments. Kex increased under conservation tillage and No-till, and the authors suggested that K availability is a good indicator of the changes caused by tillage.

Model Development and Testing

Finally, LTEs are ideal if not essential for developing and validating mathematical models of soil processes. The best examples of this are probably the many carbon cycling models (e.g. Smith et al. 1997). There has been only very limited modelling of K cycling. Etchevers et al. (2005) reported data on the distribution of K in different soil types after many years of frequent K fertilizer applications to two Mollisols and an Entisol from LTEs in Hungary. They thought that the data would be useful for modelling purposes. Fodor et al. (2012) reported the development of a nutrient cycling module to include in the Hungarian ecological systems '4M model', which was calibrated and validated for P and K using Hungarian LTEs.

CONCLUSIONS

- LTEs provide benchmark soils for calibrating methods of soil analysis; K fertilizer recommendations should be based on the results of LTEs.
- LTEs show that the effective recycling of organic manures is essential for maintaining and improving K supply and overall soil fertility.
- LTEs reveal the details of K exchange processes in the soil and show the importance of soil reserves and which soils release sufficient of these to supply crop needs.
- Only LTEs can reveal the K balance and show whether applications of K in fertilisers and manures are sufficient to avoid soil degradation.
- LTEs show the importance of balanced nutrition and key nutrient interactions such as those between N and K.
- LTEs show how tillage interacts with K supply and distribution in the soil.
- LTEs are invaluable for the development and calibration of K cycle models.

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How Do Potassium Inputs and Outputs Compare for Different Cropping Systems and Geopolitical Boundaries?

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Abstract
Estimating nutrient balances using information on nutrient additions and removals generates useful, practical information on nutrient status of a soil or area. A *negative* input-output balance of nutrients in the soil results when the crop nutrient removal and nutrient losses to other sinks become higher than the nutrient inputs into the sytem. Potassium input-output balance varies among regions that have different climates, soil types, cropping systems and cropping intensity. The present article illustrates the farm-gate K balances in major production areas of the world, and its impact on native K fertility and crop yields. On-farm and on-station research examples showed significant negative K balances in South Asia and Sub-Saharan Africa, while China, the USA, Brazil, and countries of the Latin America Southern Cone highlighted continued requirement of location-specific K application to maintain crop yields and soil K fertility status at optimum levels.

CONCEPTS OF POTASSIUM MASS BALANCE

Nutrient balance is the principal of mass balance applied to crop nutrients. Mass balance accounts for the material entering, present in, and leaving a system. Öborn et al. (2003) separated nutrient balances into three categories, with the first being "farm-gate balance." This type of balance compares nutrient imports to nutrient exports. Farm-gate balances are not limited to farms but can be calculated at a variety of scales, depending on the data available (Sacco, Bassanino & Grignani 2003). In this paper, we focus on potassium (K) farm-gate balances at the state/province and country levels across major production areas of the world.

CHINA

Potassium deficiency was initially reported in Southern China in the 1970s (Lin, 1989). However, for a long time, K did not receive as much attention as nitrogen (N) and phosphorus (P), and became a widespread limiting factor in agricultural production. Recent research has demonstrated that deficiencies of K in intensified agricultural production areas in China continue (He et al., 2009). Sheldrick et al. (2003) calculated potassium balances for the 30 provinces in China from 1961 to 1997, illustrating annual K depletion which increased from 2.9 million Mg in 1961 to 8.3 million Mg in 1997. Zhang et al. (2010), reported negative apparent K balances (from -17 to -245 kg ha^{-1} yr^{-1}) under long-term fertilization in rice-based systems at four experimental sites, irrespective of mineral K application and site. A winter wheat study in the North China plain during 2005-2007 (Niu et al., 2013) showed negative K balance in all the treatments under different production practices, especially at high-yield levels. Tan et al. (2012) found that negative K balances persisted on wheat-maize rotations under various K application rates of 112.5-300 kg ha^{-1}. In recent years, with the increase of fertilizer K application rates along with straw returns, the potassium deficiency has reduced in soils of China (Bai et al. 2014). He at al (2015) showed that between 1990 and 2012, soil available K increased slightly in soils planted with grain crops, but increased significantly in soils planted with cash crops. The higher K levels in soils under cash crops increased the average soil K estimations in China, leading to assumptions of surplus K in all soils. Even though available K in soils under grain crops increased in the Northcentral, Southeast and Southwest China in the 2000s as compared with that in 1990s, the relative yield demonstrated no differences in these regions between the two periods. The results indicated that the soil available K continue to show a declining trend

with large crop removal associated with higher yields. The partial K balance (PKB), calculated by taking the ratio of K nutrient removal in aboveground plant parts to fertilizer K application in the same study, was over 1.0 for both cash and grain crops (Fig. 1), showing that K removal by crop uptake was more than K input from K fertilizer application. The PKB was higher with 2.1 (ranging from 1.1 to 4.2) for cash crop than that of 1.3 (ranging from 1.0 to 1.5) for grain crops, indicating higher K removal in cash crops.

SOUTH ASIA

Nutrient balance in most soils of India showed that crop nutrient removal far exceeded the nutrient additions through manures and fertilizers. Tandon (2004) reported an annual gap of 9.7 million Mg of NPK in 1999-2000, of which 19% was N, 12% was P, and 69% was K. The negative K balance is a concern for long-term sustainability of crop production. Long-term cropping with negative K balances has been associated with yield declines in the rice-wheat system in South Asia and China (Regmi et al. 2002). The K balances were negative even with recommended rates of K, and were least negative when farmyard manure was a nutrient source or wheat residues were returned. Although the K-supplying capacity of illite-dominated alluvial soils of the Indo-Gangetic Plains (IGP) is relatively high (Dobermann et al., 1996), long-term intensive cropping with inadequate application of K can result in large negative balances and depletion of native K reserves (Gami et al., 2001).

Satyanarayana and Tewatia (2009) estimated K balances in major agriculturally important states of India (Table 1). Overall negative K balance was estimated at 9.7 Mt, and the western region (3.8 Mt) had the highest share, followed by northern, southern and eastern regions, respectively. On-farm results from the All India Coordinated Research project on Integrated Farming Systems (Table 2) showed negative K balances in cultivators' field across locations and cropping systems. Dutta et al. (2013) estimated K input-output balances in different states of India using the IPNI NuGIS approach (IPNI 2012) and reported large negative balances in northern, western and eastern regions (Figure 2). Buresh et al. (2010) showed that maintaining near neutral K balance in rice-wheat cropping systems would require 100% and 15% retention of rice and wheat residues respectively, with an irrigation water contribution of 125 kg K/ha. Nutrient depletion-replenishment studies in the rice-wheat systems in Bangladesh have also shown negative balances for K (Timsina et al., 2013).

UNITED STATES

Potassium budgets for the U.S. were calculated using the NuGIS model (IPNI 2012). Potassium budgets were calculated for each county in each state for 1987, 1992, 1997, 2002, 2007, 2010, 2011, and 2012. Briefly, the NuGIS model considers nutrient removal by 21 major crops. The same K removal constant for a given crop was applied across all U.S. counties and states.

Figure 3 shows K balances for the contiguous 48 states of the U.S. The balance metric is the removal to use ratio. Removal to use greater than 1.0 (orange colors in Figure 3) indicates that removal of K by crop harvest exceeds the application rates of K, both fertilizer and manure. Removal to use less than 1.0 indicates that more K is applied as fertilizer and recoverable manure than is removed by crop harvest (green colors in Figure 3). Removal to use approximately equal to 1.0 (the yellow color for category 0.91 – 1.09 in Figure 3) indicates K application rates are approximately equivalent to K removal rates.

Based on a visual assessment of removal to use ratios, the U.S. was divided into four groups, and trends in removal to use over time were assessed (Figure 4). Temporal trends were evaluated through linear regression of the log of the removal to use ratios calculated for each group as well as for the U.S. For the 48 contiguous states considered as a group, K removal to use ratios have been increasing at a rate of 1.3% yr^{-1}. Similar increases (1.1% yr^{-1}) were also observed in the northeastern states in group A and the corn-soybean growing states in group B. States in group D had the greatest increase in K removal to use (1.8% yr^{-1}). Much of this area is where cotton has traditionally been grown, although cotton production has

declined in recent years and is being replaced by other crops, such as soybean. In the more arid western states in group C, soil K levels have historically been high; consequently, farmers have not applied much K, resulting in higher K removal to use rates averaging 3.63.

Figures 3 and 4 demonstrate varied K balance patterns across the U.S due to interactions of climate, cropping patterns, market conditions, governmental policies, and many other factors. In general, the combination of rather steady K consumption but increased yields and therefore increased nutrient removal has led to negative K balances that are becoming more negative (greater removal to use ratios) in much of the U.S.

SUB-SAHARAN AFRICA

Potassium balances in sub-Saharan Africa (SSA) show consistent negative trends due to continuous cultivation of crops for many decades with low K inputs in the region. Annual potassium balances at the regional level average less than -15 kg K/ha and range between -5 and -45 kg K/ha for various countries (Stoorvogel et al., 1993). The losses of K translate to about 3 million Mg of K per year. The average rate of fertilizer use in the SSA is about 18 kg of NPK, of which contribution of K is less than 3 kg/ha. Fertilizers that are recommended and used in crop production in SSA exclude K, and application of K through organic resources is also limited and negligible due to low amounts of manures and crop residues that are available for recycling. The removal of K in grain and crop residues, and K losses through erosion and leaching result in severe nutrient depletion. Average yield of cereal crops which cover 80% of croplands are about 1.5 t/ha, accounting for removal of 20-30 kg/ha of K.

Despite the overall large negative K balances in SSA, nutrient balances vary greatly in different cropping systems and agro-ecological zones. The largest losses of 20-50 kg/ha/year occur in the Sub-Humid savannahs of West Africa and the highlands and sub-humid areas of East Africa and southern Africa, a region with high potential for crop production and high population densities. Moderate K losses for 10-20 kg/ha/year occur in the Humid forests and wetlands of Southern Central Africa and Sudan. The soils of the regions in the arid zones in southern and west Africa have the lowest K losses (5-15 kg/ha/year), mainly due to low nutrient removals from low yields.

Potassium balances for regions within countries are highly variable, similar to the patterns of K balances at the continental level. For example, partial K balances in Kenya are consistently negative (Table 3). However, the K balances range from -5 to -34 kg/ha/yr (Henao and Baanante, 2006). The rift valley region with the lowest balances is characterized by high potential crop production and intensive cultivation, while the highest nutrient balances in north-eastern Kenya is associated with arid conditions that result in low crop yields and nutrient removals. In addition, K balances are influenced by resource management at farm level between farms in different wealth categories and between plots at different distances from homesteads (Shepherd and Soule, 1998; Giller et al., 2006).

BRAZIL

Soil K fertility of Brazilian soils is generally low and adequate amounts of nutrients are necessary to make agriculture effective and profitable. Brazil consumed 5.4 million tons of K_2O in 2015, ranking second in the world. Potassium budgets have been calculated for the whole country, states and main crops in the country based on fertilizer consumed (Statistics from the Brazilian National Association for Fertilizers; ANDA 2010-2015), crop production for the eighteen major crops in Brazil (Brazilian Institute of Geographics and Statistics; IBGE, 2010-2015), and nutrient concentration in harvested products of the respective crops, (Cunha et al., 2011, 2014).

Table 4 summarizes the data for the most recent survey (Francisco et al., 2015) for the average of four years (2009-2012). The Midwest region of Brazil, the core of soybean and maize production in the

country with low soil available K, utilized 34% of the total K consumption in the country, with a removal to use ratio of 0.82. The removal-to-use ratio of K for the whole country was 0.80.

Nutrient budgets for nine crops grown between the years of 2009-2012 are presented in Table 5. Soybean, maize and sugarcane utilized about 80% of the potassium consumed in Brazil. Potassium use is higher than crop removal in most crops, except beans. Soybean received the most balanced K application with a removal-to-use ratio of 0.99, followed by rice (0.86) and sugarcane (0.85). Coffee has the lowest removal-to-use values for K_2O (0.20) among the crops. The removal-to-use ratio for crops in Brazil highlights judicious use of potassium.

SOUTHERN CONE OF LATIN AMERICA

Soil K availability is high in most of the cropping areas of the Southern Cone of Latin America (Argentina, Bolivia, Chile, Paraguay, and Uruguay) (Barbazan et al., 2012; Sainz Rozas et al., 2013). Thus, fertilizer consumption in the region is low, about 335 to 425 thousand Mg of K_2O in the last years, and the soil K balances have historically been negative. However, expansion of agriculture into new areas and replacement of pastures by annual crops in the last 20 years (Wingeyer et al., 2015) have increased K removal by grains and induced K deficiencies in several regions of Uruguay (Barbazan et al., 2012), and some areas of Paraguay and Argentina.

In Argentina, the K application and its removal through four major grain crops (soybean, corn, wheat, and sunflower) indicates a partial nutrient balance of 1962 for the 2012-14 triennium (Garcia and Gonzalez Sanjuan, 2016). The negative K balance have reduced soil K availability (0 to 20 cm depth) by 32-62% in the central Pampas, from pristine soil test K (STK) values of 990-1140 mg/kg to current STK of 370-750 mg/kg in agricultural fields (Correndo et al., 2013). Areas in northwestern Argentina under continuous sugarcane production for more than 50 years without K fertilization have decreased STK with responses to K fertilization (Pérez Zamora, 2015).

Potassium balances in Uruguay have historically been negative due to the low K fertilization (Mancassola and Casanova, 2015). Furthermore, as soybean area increased in the last two decades, the K balance in the soil has become more negative due to high K requirements of soybean (Figure 5). Considering an average grain K content, 3.6 Mt of soybean exports in 2014 implied approximately 63,000 t of K_2O removal from the soil. In addition, agriculture has also expanded to marginal soils in the northcentral and eastern regions of the country, where low STK soils are common. As a result, K deficiencies in crops were evident since early 2000´s (Barbazan et al., 2012).

Most of Paraguay's agricultural production takes place in the eastern half of the country on lateritic soils (mainly oxisolls and ultisolls), and includes soybean as main field crop along with maize, wheat, sunflower, canola, and others. The PNBs for K have varied between 1.44-1.73 in the last 10 years.

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Table 1. Regional potassium additions, removal by crops and apparent balances in India

Region	Nutrient	Addition	Removal	Balance
	---------- (1000 Mg) ----------			
Eastern Region	K_2O	517.6	2428.2	-1910.6
Western Region	K_2O	756.7	4579.0	-3822.3
Northern Region	K_2O	918.1	3534.0	-2615.9
Southern Region	K_2O	1118.1	2447.7	-1329.6
India	K_2O	3310.5	12988.9	-9678.4

Table 2. Potassium use and removal (kg/ha) at cultivators' field in India

Cropping system/Location	Treatment	Potassium addition	Potassium removal	Apparent balance
Rice-wheat/ Kaushambi,	FFP	0.0	150.0	-150.0
UP	SR	74.7	160.0	-85.3
(24)	SR + M	74.7	174.0	-99.3
Rice-rice /Warangal, AP	FFP	70.6	172.0	-101.5
(24)	SR	66.4	189.0	-135.6
	SR + M	66.4	202.0	-135.6
Pearl millet-	FFP	0.0	104.0	-104.0
mustard/Deesa, Gujarat	SR	54.0	116.0	-62.1
(18)	SR + M	54.0	122.0	-65.1
Pearl millet-	FFP	0.0	65.0	-65.0
wheat/Thesra, Gujarat	SR	83.0	95.0	-12.0
(18)	SR + M	83.0	101.0	-18.0
Maize-bengal gram/	FFP	0.0	133.0	-133.0
Gadak, Karnataka (24)	SR	20.8	169.0	-148.3
	SR + M	20.8	181.0	-160.3
Rice-green	FFP	34.0	129.0	-95.0
gram/Kakdwip, WB	SR	66.4	161.0	-94.6
(18)	SR + M	66.4	176.0	-109.6
Maize-wheat/Kangra,	FFP	21.6	53.0	-31.4
HP (18)	SR	58.1	89.0	-30.9
	SR + M	58.1	97.0	-38.9
Cotton-pearl millet/	FFP	0.0	85.0	-85.0
Deesa, Gujarat (18)	SR	83.0	91.0	-8.0
	SR + M	83.0	102.0	-19.0

† Source: AICRP-IFS Reports (2011-12);
‡ FFP: Farmers' Fertilizer Practice; SR: State Recommendation (NPK); SR + M: State Recommendation + Micro & Secondary Nutrients

Table 3. Regional partial K balances in Kenya (kg/ha/year)

	K removal	K added		
Region	Crop removal	K fertilizer	Manure	K balance
Central	20	8	3	-9
Coast	21	-	1	-20
Eastern	22	1	1	-20
Nairobi	11	2	1	-8
North Eastern	6	-	1	-5
Nyanza	27	2	1	-24
Rift Valley	40	5	1	-34
Western	25	3	2	-20

Table 4. Annual nutrient budgets for regions in Brazil (average of 2009-2012)

Region	Crop removal (Mt)	Applied (Mt)	Balance (Mt)	Removal to use ratio
South	0.91	0.96	0.05	0.95
Midwest	1.06	1.29	0.23	0.82
Souteast	0.66	1.02	0.35	0.65
Northeast	0.30	0.43	0.13	0.70
North	0.09	0.09	0.00	1.04
Brazil	3.03	3.79	0.76	0.80

† Source: ANDA (2010-2013)

Table 5. Annual nutrient budgets for main crops in Brazil (average of 2009-2012)

Crop	Removal	Applied	Balance	Removal to use ratio
Soybean	1.64	1.66	0.02	0.99
Maize	0.34	0.52	0.18	0.65
Sugarcane	0.66	0.78	0.12	0.85
Coffee	0.05	0.25	0.20	0.20
Cotton	0.08	0.14	0.06	0.57
Rice	0.06	0.07	0.01	0.86
Beans	0.06	0.05	-0.01	1.20
Orange	0.03	0.05	0.02	0.60
Wheat	0.02	0.06	0.04	0.33

† Source: Cunha et al. (2014);
‡ For sugarcane, a 20% reduction was considered for K removal considering the regular disposal of vinasse

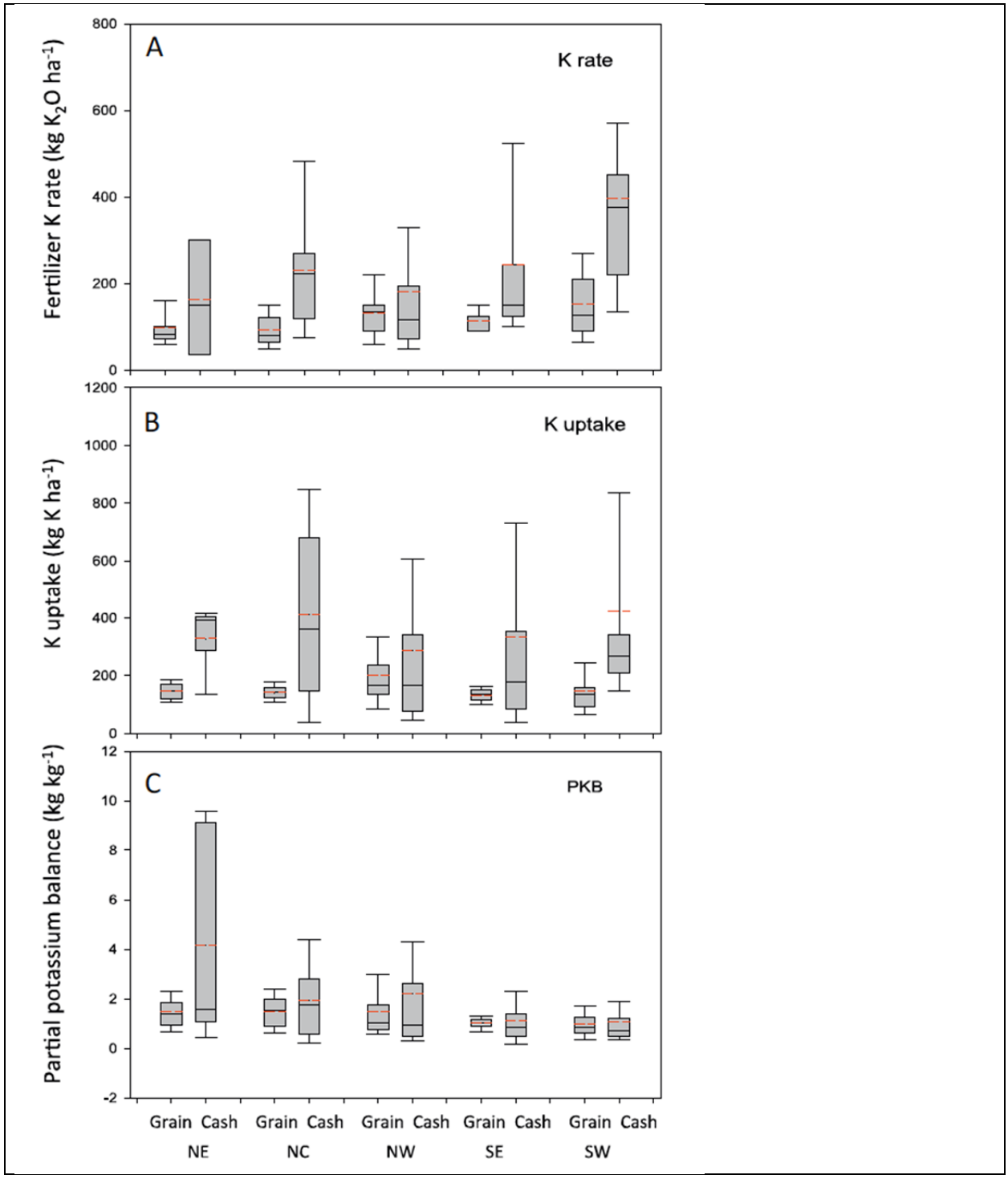

Figure 1. Potassium application rate (A), K uptake (B) and partial K balance (C) across northeast (NE), north central (NC), northwest (NW), southeast (SE) and southwest (SW) of China for grain (left box) and cash crops (right box).

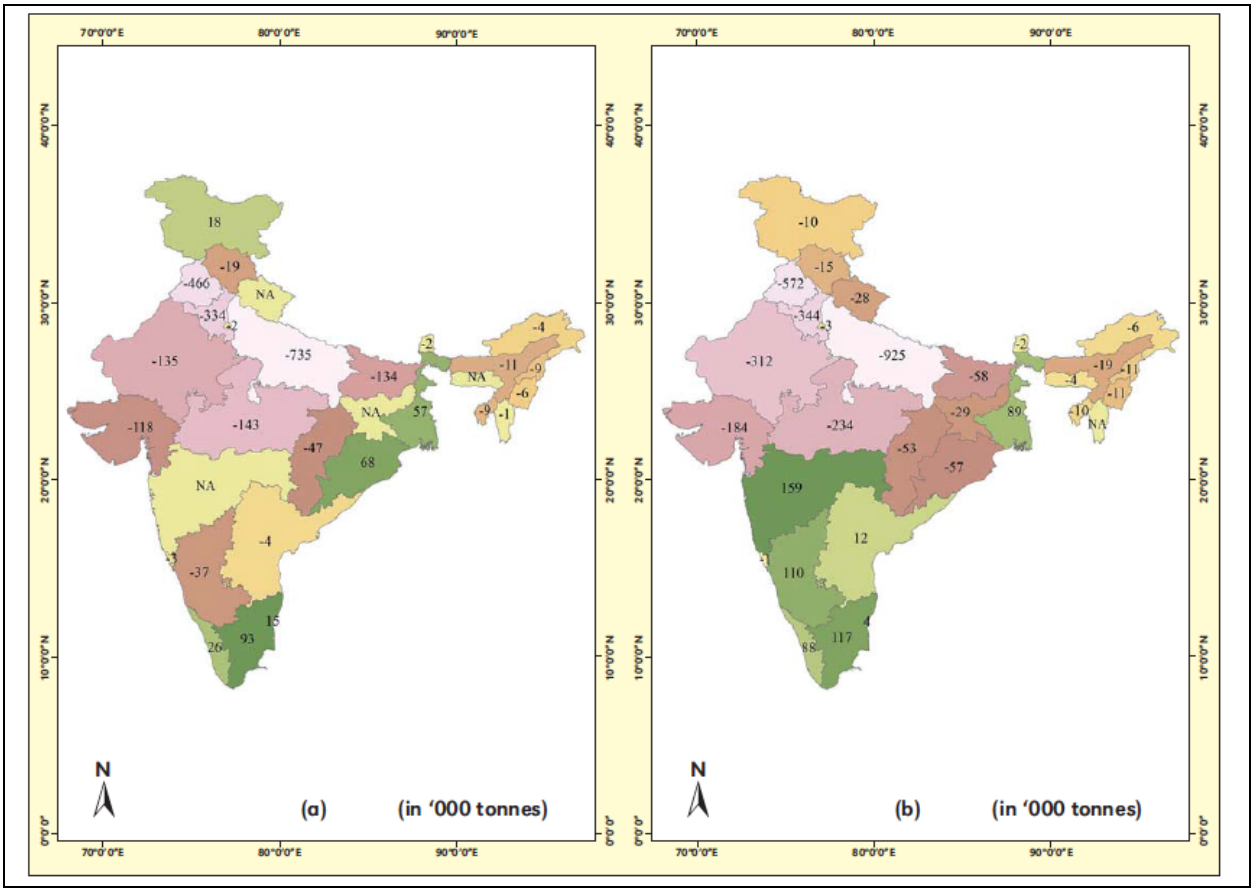

Figure 2. The K_2O balance (applied fertilizer + manure – crop removal in Mg ('000 t) for (a) 2007 and (b) 2011 across different states of India (Dutta et al. 2013).

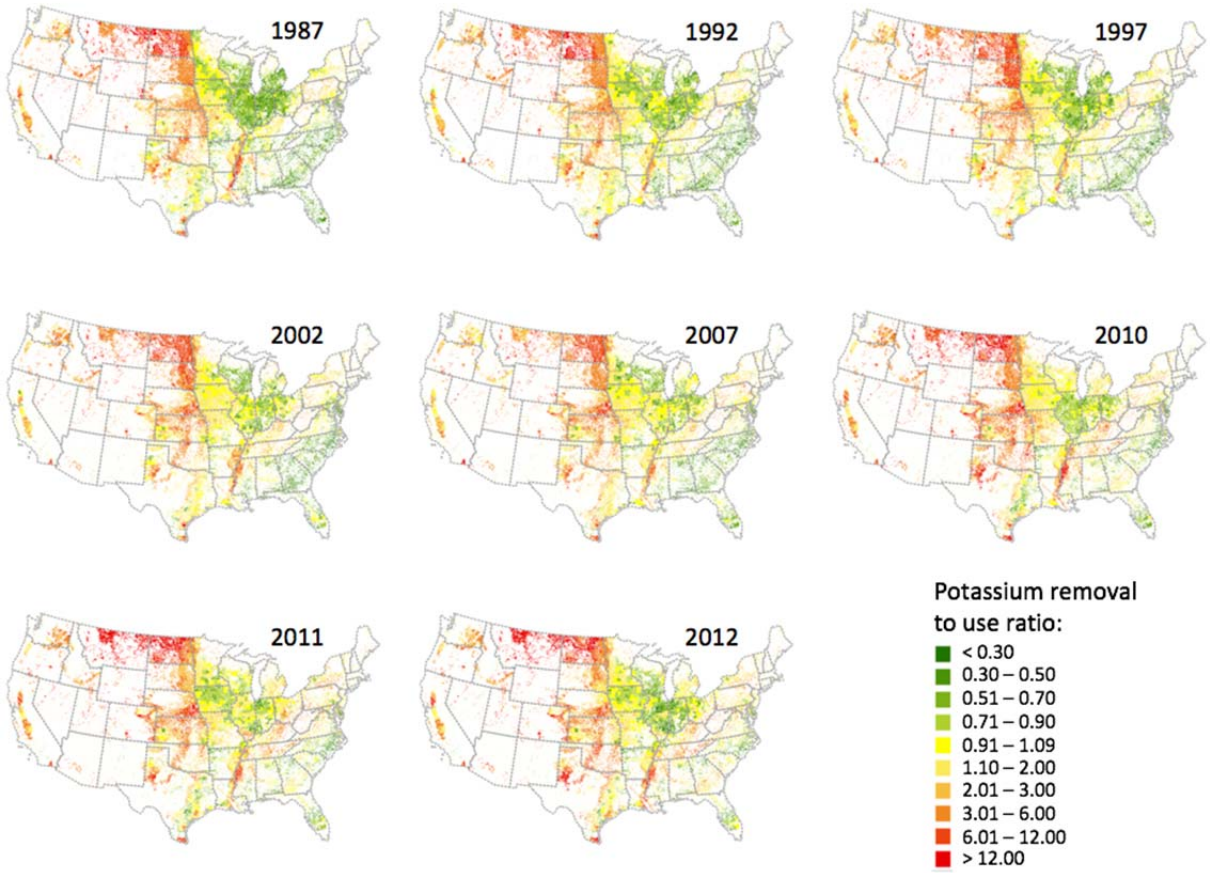

Figure 3. Potassium nutrient balance for the contiguous 48 states of the U.S. for years 1987, 1992, 1997, 2002, 2007, 2010, 2011, and 2012.

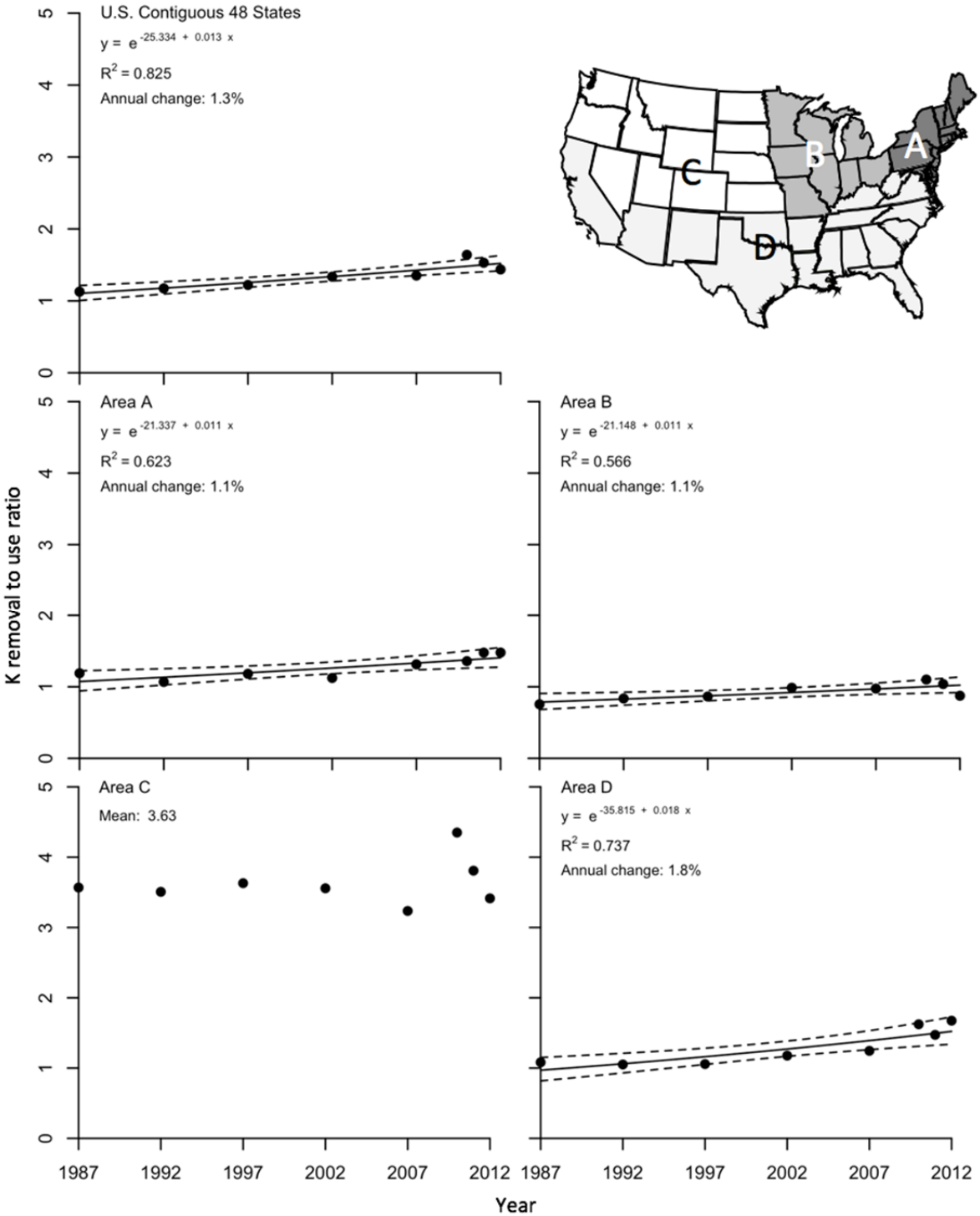

Figure 4. Temporal trends in K removal to use ratios for the contiguous 48 states of the U.S. and for four groupings of U.S. states, denoted as areas A, B, C, and D. Dotted lines are the 95% confidence intervals for the regression curves.

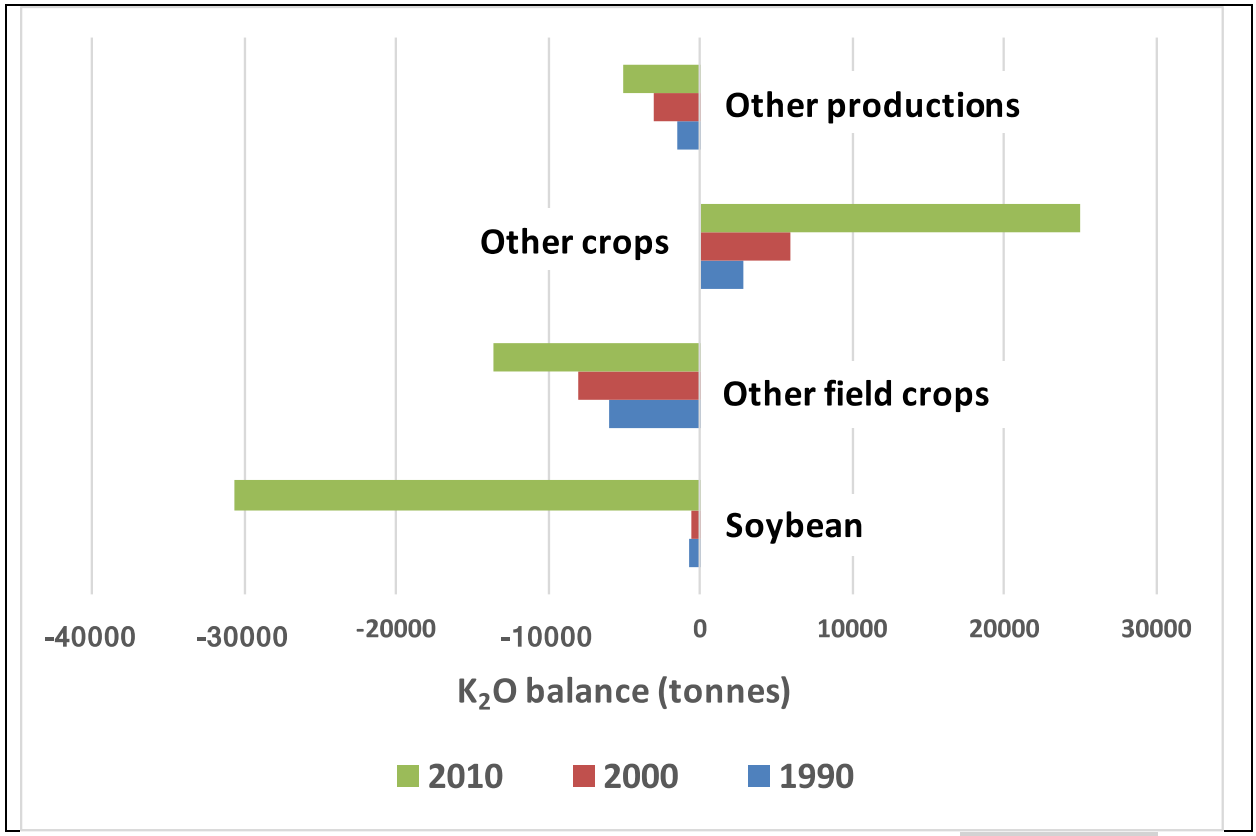

Figure 5. Potassium balance by production in 1990, 2000, and 2010 at Uruguay (Mancassola and Casanova, 2015). Other field crops include wheat, corn, barley, sunflower, sorghum, and rice; Other crops include fruits, citrus, and vegetables; and Other productions includes forestry, beef, dairy, and sheep production

Potassium Removal and Use in Australia

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Abstract

Since 2002, K use in Australia has remained essentially static at around 180 kt/y with a range between 130 kt (2008/09) to 215 kt (2015/16). Over the past two decades, the use of P has declined by around 10% while N use has increased by 50%, so that Australian growers are using relatively more N and relatively less K. The industries that use the most K are the grains and cotton industries (37%) and the dairy industry (30%), with horticulture ((17%) and sugar (14%) comprising the other major segments. The grains industry produces around 40 Mt annually with the main crops being wheat, barley and canola.

Much of Australian agriculture is extensive and yields are relatively modest as most production is rainfed. Based on agricultural production figures and fertilizer use data, but excluding recycled materials and manures, Australia has a negative K balance of around nearly 400 kt per year, which is a removal to use ratio (Partial Nutrient Balance, PNB) of 3.2 across all agricultural areas. All states, except Tasmania, shown K removals more than K application, and there is significant variation from year to year in these values due to changing production in response to seasonal conditions. There are large differences among industries, with cotton showing positive balances (+9 kg K/ha/y) but most of the extensive cropping industries with negative balances (– 4 kg K/ha/y), and this pattern of removal> use has been consistent over the past 20 years. The sugar industry shows the largest apparent deficit, but the values estimated do not include recycled mill wastes.

To investigate the distribution of nutrient performance indicators among growers, a survey of 514 grain production fields over 3-5 years in south-eastern Australia was undertaken. Annual K balances were estimated from the input of fertilizer K and the removal of products. This region in particular is undergoing increased cropping intensity and the high rainfall zones in particular have high yield potentials and has promise for future expansion of the grains industry. K nutrient performance indicators were estimated for the period 2010-2014 from these survey data. Even though 15% of soil test K levels are less that the critical value, only 9% of crops received a mean K application rate of 75 kg K/ha while K removal ranged up to 250 kg K/ha/y. In only 6 fields survey there was a K-PNB<1. but 6 fields K balance was negative. Where K was applied, partial factor productivity values were in the range of 150-300 kg grain/kg K applied. Given these factors of increased production, low K application, high removals, and marginal soil K levels, growers will need to pay increasing attention to K management in particular.

Keywords: Partial nutrient balance, partial factor productivity, nutrient balance intensity, cropping systems.

INTRODUCTION TO AUSTRALIAN AGRICULTURE

Agriculture is a vital part of the Australian economy, with some 310,000 people employed directly in agriculture (2.6% of workforce) on 130,000 commercial farms over 417 Mha of agricultural land. Grazing land accounts for 87% of agricultural land use, although only 16% of land carries improved pastures. Around 50 Mha is used for cropping, and 2.5 Mha of crops and pastures are irrigated. Total factor productivity has been rising at 2.5% annually over the past 20 years and the gross value of agriculture at the farm gate in Australia has been steadily rising and in 2016 will exceed $60 billion (AUD) (ABARES 2016).

For 2016-17 the gross value of livestock and crop production is forecast to be $28.5 billion and $31.7 billion respectively. Winter crops (~40 Mt) are grown in all states, but summer crops (~5 Mt) are mainly produced in Queensland and northern New South Wales, which has a summer dominant or equi-seasonal rainfall pattern. The top three crops are wheat, barley and canola, and these are grown in the southern and western states, most often in rotation with each other and with pulse crops and pastures for sheep grazing. Over the past 20 years, the area of crops produced in the high rainfall zones (>600 mm average annual rainfall) has dramatically increased, while sheep numbers have declined. Poor livestock profitability and the development of better cultivars and agronomic support has driven this change.

Beef and sheep are grazed on annual or perennial pastures, with fertilizers and pasture improvement common in the higher rainfall zones. Half the beef cattle herd is in northern Australia, while Victoria is the principal dairy farming state. Sugar cane is produced on 3,500 cane farms along the sub-tropical and tropical regions of the north-east coastline, and is highly productive and relatively stable industry, but is very exposed to international sugar prices.

Australia stretches from the tropics of Cape York at 12°S to the temperate maritime climate of southern Tasmania at 42°S, so that there is a great diversity in horticultural crops. The main industries in northern Australia are avocados, macadamia nuts, mangoes, bananas and pineapples. In the south, citrus, pome and stone fruits and nuts are produced. Major ground crops are potatoes and tomatoes, along with a wide range of other crops from asparagus to zucchini.

POTASSIUM FERTILIZER USE IN AUSTRALIA

The first used of mineral fertilizers in Australia was in the early 1900's when "English Superphosphate" was introduced. In the 1950's phosphorus expanded from crop production and became widely used on pastures used for sheep and dairy production. Potassium use was minimal as yields were generally low and the major limitation was phosphorus. Over the past 40 years in particular, the development of improved varieties, better plant protection strategies and improved soil management has resulted in higher yield potentials particularly in the grains industry, but also in the sugar and dairy industries.

All the K used in Australia is imported, and the peak quantity of muriate of potash importation was ~480 kt in 2004/2007, while the peak of sulfate of potash imports of 60 kt in 2012. Long term K used has been around 170 kt of K, but during the "Millennium Drought", total K fertilizer use declined to a low of 134 kt K in 2009 (Figure 1), but has since recovered to 211 kt K in the 2016 report from Fertilizer Australia (N Drew, pers. comm.). This amount makes up less than 1% of global K used.

The regional use patterns shown in Figure 1 largely reflect the balance of enterprises within each region, as well as the inherent K fertility of the soils. Western Australia is the largest K user, and the soils there are generally inherently low in K and most of the K is applied to annual grain crops. In Queensland, the sugar industry is the major user of K, although there are declining K levels in central and southwestern cropping systems (Bell et al. 2012). In Victoria, K use is principally on intensively managed pastures for cattle and sheep, although cropping systems are showing signs of increasing demand for supplementary K particularly in the high rainfall zones (Christy et al. 2014). The use in the other states is mainly in horticulture and pastures. The cotton industry is based mainly in New South Wales and southern Queensland, varies greatly in response to seasonal water storage levels, can be a significant K user.

Over the previous 15 years while K use has fluctuated, there has been a 50% increase in the use of N fertilizers and a 10% decline in the use of P. The attention growers pay to N management is recognised but such an imbalance in nutrient supply suggests that growers and advisors should reconsider the importance of balanced nutrition.

NATIONAL AND REGIONAL REMOVAL AND USE OF POTASSIUM

The Australian National Land and Water Audit (NLWA) (2001) reported data on a series of a series of farm-gate nutrient balances for data collected during the 1990's. While the apparent balances for nitrogen, phosphorus, sulfur, and calcium are mainly neutral (inputs ≈exports) or moderately positive (inputs ≥ exports) across much of the southern agricultural zone. However, potassium and magnesium balances are usually negative (inputs < exports) indicating that soil reserves were being progressively depleted. For all cropping regions, K balances were negative. A summary of the findings from that time is shown in Table 1.

Later estimates were reported by Edis et al. (2012) using essentially the same protocols in the NLWA, and this also showed that across Australia there were few areas that were in K excess. Figure 2 shows these regional patterns for two periods (2009-10 and 2011-12). In essence, the areas where K was in the largest deficit were in the sugar growing areas in Queensland and the lower rainfall grain growing regions of Western Australia, South Australia and Central Queensland. These data have been loaded onto an interactive map at http://www.ozdsm.com.au/ozdsm_map.php. It should be noted that the data used to generate these maps did not include any recycled materials such as mill wastes from sugar processing or manures used as inputs into crop production. In aggregate, the national removal to use ratio for K was 2.9 for the audited period, and the nutrient balance intensity was -0.6 kg K/ha, with the denominator used as the areas of land used for agricultural production. These values are consistent with the earlier NLWA assessment that K use was around one third of the amount of K supplied.

Nutrient performance indicators for K (and other nutrients) can be estimated at national scales and the date in Table 2 reports K indicators for cereals using production area and mean cereal yield, mean potassium application rate to calculate K-PNB and K-PFB. The PNB is based on a weighted cereal grain K content of 0.54% (*as is basis*). The data for cereal production is derived for two periods (2006 and 2010) from FAO crop statistics database (FAOSTAT), and fertilizer use is derived from IFA surveys (Heffer, 2013) for the same two years.

Edis et al. (2012) used farm survey data that included fertilizer inputs estimated for each industry and also by region, and a national summary of these data is provided in Table 3. Both partial nutrient balance (removal to use) and nutrient balance intensity values are presented, along with the apparent application rates for each industry. The farmer reported use data is re-aggregated into total K use of about 102 kt K, compared to the industry supplied use of 160 kt K. This under-reporting by growers is a consequence of somewhat imprecise questions asked in these surveys, such as specifying the mass of K fertilizer used rather than particular K fertilizers used.

This inconsistency also flows through the industry use patterns, with the data in Table 3 suggesting that the grains industries used 27% of the K fertilizer, cotton 7%, sugar 7%, vegetable and fruits 11%, and the grazing industries 41%. This is somewhat at odds with the industry based figures which suggested that the amounts used were grains (22%), cotton (1%), sugar (20%), vegetable and fruits (24%) and grazing industries (34%) (Heffer 2013).

Despite the data inconsistencies, it is clear that there is much less K applied than is removed and the largest apparent deficits are in the sugar industry. However, these data do not consider K-rich recycled materials from sugar mills, which are reapplied to grower's fields. Similarly, the K balance figures for the dairy industry do not include K supplied to pastures that is ultimately derived from feeds purchased from outside the farm gate. Gourley et al. (2012) reported that K from cattle feed averaged 25 kg K/ha compared to a fertilizer input of 32 kg K/ha from data collected on 44 dairy farms across Australia.

Another significant deficiency in these data is that means estimated provide little or no intelligence to growers on their farm level balances. The data collected by Gourley et al. (2012) does give error terms

around the inputs as well as the derived metrics concerning nutrient use efficiency. As such, these metrics can be used by farmers to assess their position relative to others in similar industries and regions.

K USE AND REMOVAL ON SOUTHERN AUSTRALIAN GRAIN FARMS

Information on nutrient removal and use at farm or field level is important to inform growers about build up or depletion of nutrients over time, and to assist them make decisions about appropriate interventions to address any imbalances. To understand the value and distribution of nutrient performance indicators at farm level, a survey of 118 grain growers used data from 474 fields covering 34,900 ha over 4 or 5 years between 2010 and 2014 in south-eastern Australia. The data came from farms in four different agro-ecological zones with different rainfall distributions and land use patterns. The zones were the High Rainfall Zone of Victoria and South Australia (HRZ), southern New South Wales (SNSW), the Victorian and South Australian Mallee, and the Victorian and South Australian Wimmera. A summary of the data collected is shown in Table 3. Nutrient balances (N, P, K and S) for each field over the audit period (3-5 years) was estimated from fertilizer use, stubble management (burned, removed, grazed) and crop yield. Grain and hay yields were recorded in the farm records, and regional wheat grain nutrient concentrations for wheat (Norton 2012) and canola (Norton 2014) were used to estimate removal in grains. Other values were derived from the values used in the NLWA (2001). The summary presented here is for the K balances alone.

The use of K on fields in this survey was largely restricted to the HRZ, where about 9% of the crops received K. Rates where K was used were about 90 kg K/ha on canola and 66 kg K/ha on cereals. Because K was only applied to 92 fields, K partial nutrient balance (PNB) and K partial factor productivity (PFP) can be calculated only for those survey fields, as the denominator - fertiliser applied - is zero. For those fields, the median PNB was 3.0 and seven of the fields surveyed showed more K use than removal over the audit period. Even where K was used, 12 fields had PNB>5 (Figure 3a). The PFP values where K was used had a median of 350 kg grain/kg K (Figure 3b).

The nutrient balance data collected is displayed in Figure 4, graphed as applied and removed K. On the 91% of fields that did not receive K, removals ranged from nil to over 250 kg K/ha. In all except seven fields the K balance was negative – that is more K was added than removed. This includes fields where K was applied at rates that were mostly sufficient to replace removals.

K REMOVAL AND USE ON NORTHERN GRAIN FARMS

Bell and Moody (2005) reported on the K balance for grain production farms in the northern cropping region of Australia, and they reported consistently negative K budgets, which led to a significant decline in native fertility. The extent of the deficit was linked to region crop productivity and the low use of K fertiliser. K removal was highest in chickpea crops because of the higher average grain K concentrations in chickpeas being consistently higher than higher yielding crops like sorghum. Typically, K removals were between 8 and 20 kg K/ha/y over a five crop sequence.

They expressed concern about this trend as earlier research showed soils in the region have variable reserves of exchangeable and slow release K reserves. Indeed, the consistently low grain K concentrations in some areas coupled with some very low K suggested that soil K status may be approaching dangerously low levels – whether due to stratification, presence of high Na or the lack of substantial slow release K reserves.

SOIL TEST K LEVELS

The low use of K in eastern Australia in particular could be explained if there were sufficient soil reserves to supply crops and pastures so that supplementary K was not required. There is little public data on K status of soils as most of the laboratory derived soil test data are held corporately and in some cases treated as commercial-in-confidence. Christy et al. (2014) re-analysed soil test data collected in the

NLWA to assess the proportion of areas where a response to K was likely based on the soil test critical values (Brennan and Bell 2013). Figure 5 shows this distribution of southern Australia showing that large areas of Western Australia have low soil K levels, so are likely to respond to applied K. In the south-eastern grain producing areas, soil K values are generally higher in the lower rainfall areas but in the higher rainfall zones nearer the coast, there are regions where responses are likely.

It should be noted that these soil test values were derived in the mid-1990's so may not necessarily reflect the current status. A more recent analysis of soil test data was compiled from a commercial soil test database from 2010, and this found that for the HRZ of Victoria and South Australia about half the sandy and loam soil types seem to have low K, whereas on the heavier soils deficiency was not such a problem (Christy et al. 2014).

Bell and Moody (2005) also reported low, and decline soil K test levels in many of the summer cropping regions in Queensland. Soil test K values showed stratification with around 1.6-3.2 more exchangeable-K in the topsoil than the subsoil. This depletion in the subsoil has led to research projects investigating deep placement of K (and P) as a means of alleviating this deficiency.

CONCLUSIONS

Potassium fertilizer use in Australia is relatively modest on a world scale, and there is approximately 3 times more K removed in agricultural products than is supplied. While K removal is highest on sugar farms, there is a modest deficit for most farms due to low productivity. Regional differences in K use and PNB reflect the intensity of production and the inherent K fertility of the regions, although there are inconsistencies in the data available to estimate K balances and nutrient performance indicators. Western Australia uses most K on grain production, Victoria uses K mainly on intensive pastures while in Queensland K is mainly focused on the dairy industry. The data presented here indicates that grain producing fields in the higher rainfall regions of southern Australia are in significant K deficits, despite the low inherent K fertility, and IPNI in association with state and federal agencies addressing and communicating 4R nutrient management strategies to growers to overcome these deficits and improve productivity (Norton 2014, 2016).

ACKNOWLEDGEMENTS

The Grains Research and Development Corporation supported the research into farm level nutrient performance indicators reported here and the involvement of Ms Elaina vanderMark and Southern Farming Systems is acknowledged. The estimation of national and regional nutrient performance indicators was done in collaboration with Dr Robert Edis.

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Figure 1. Potassium (K) use in Australia by state from 2002-2003 until 2015-16. Data from Fertilizer Australia.

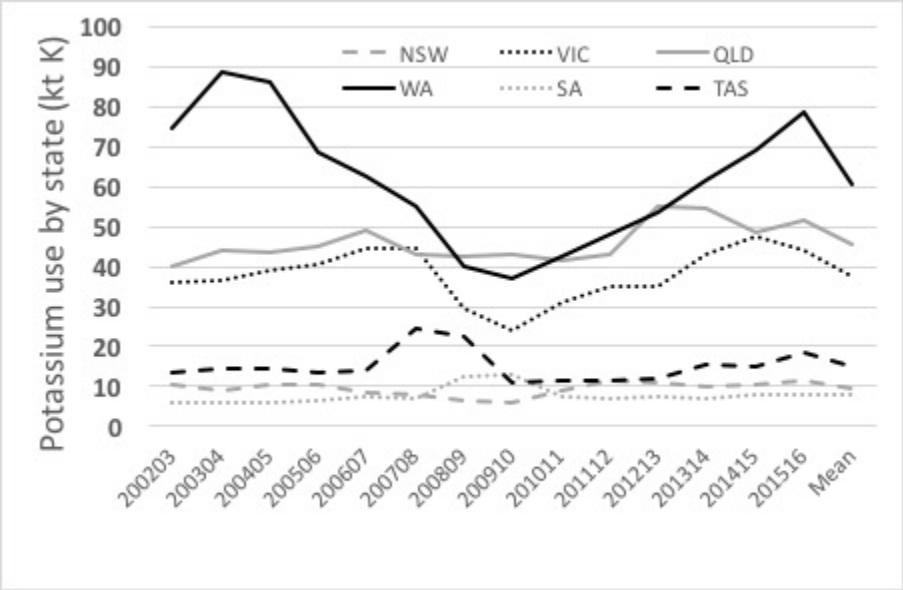
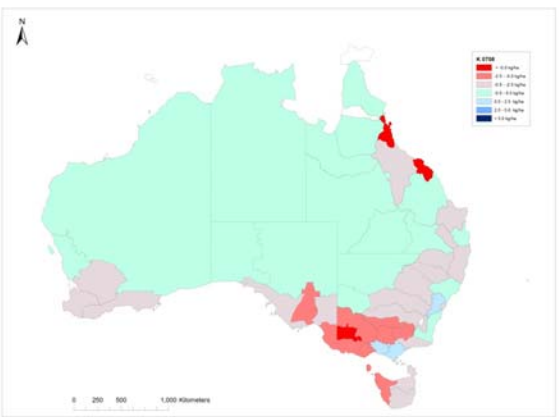
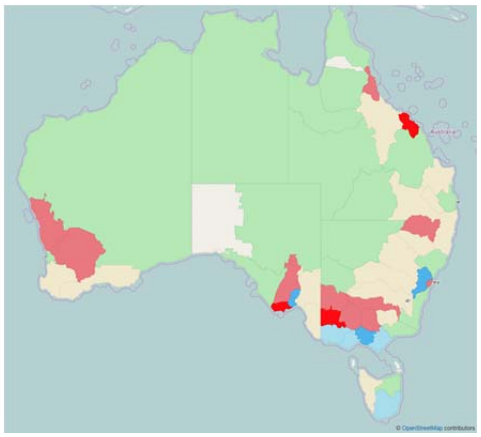


Figure 2. Nutrient balance intensity K (kg K/ha) across different natural resource management regions across Australia for a) 2007-08 and b) 2010-11. Values reported are the means for each two year period. In general, the red regions indicate where nutrient removal is more than nutrient supply, and the scales are provided on the individual graphics.





2007-08 b) 2010-11

Figure 3. Nutrient performance metrics for K as derived from a survey of farmers' fields. a) is the K partial nutrient balance, b) the K partial factor productivity.

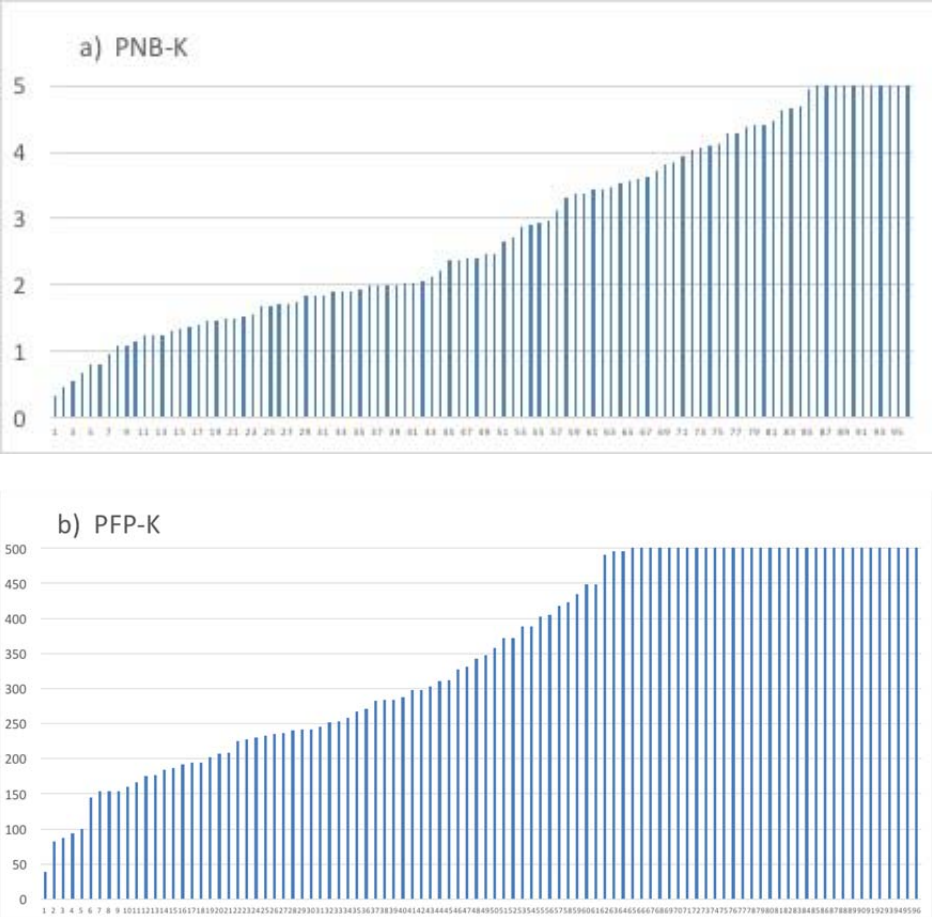


Figure 4. Potassium removal and application in surveyed fields in south-eastern Australia over the period 2010-2014. A 1:1 line is shown for reference.

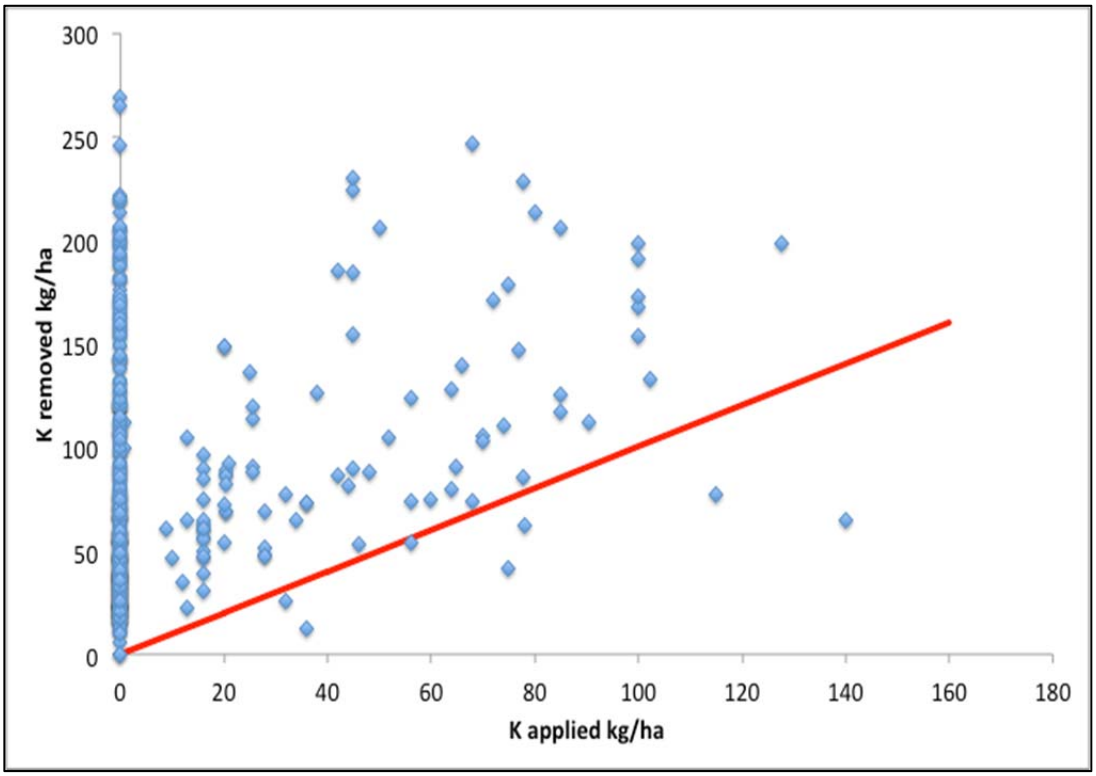


Figure 5. Percentage of soil tests indicating a response to potassium. Soil test data were derived from the NLWA (2001) and interpreted based in critical soil test values published in that report. Graphic is taken from Christy et al. (2014).

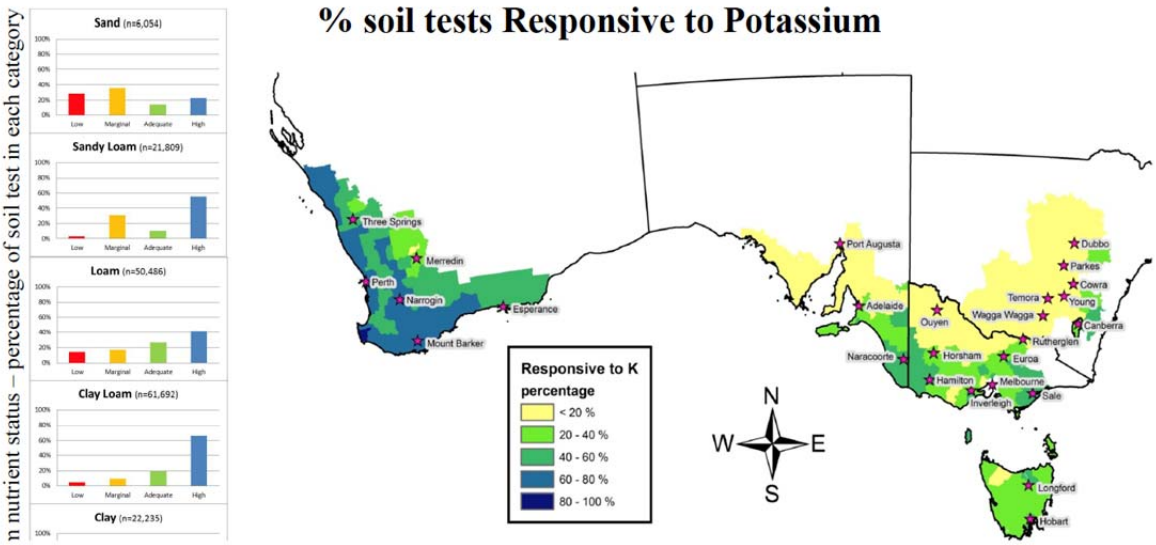


Table 1. Generalized state assessments of farm gate nutrient balance for two broad land uses within Australian agricultural zones from the Australian National Land and Water Resources Audit (2001) reporting data from 1994-1996.

Nutrient	Western Australia	South Australia	Victoria	Tasmania	New South Wales	Queensland*
Grazing						
Nitrogen	positive	positive	variable	neutral/positive	positive/neutral	negative
Phosphorus	positive/neutral	neutral/negative	neutral/positive	positive	positive/neutral	negative
Potassium	negative/positive	negative	positive/negative	neutral/positive	neutral/negative	negative
Sulfur	positive	positive/neutral	positive/neutral	positive	positive/neutral	negative
Calcium	positive	positive	positive	positive	positive	negative
Magnesium	neutral	negative	neutral/negative	neutral	neutral	negative
Cropping						
Nitrogen	positive/neutral	neutral/negative	negative	positive	neutral/positive	negative/neutral
Phosphorus	neutral/positive	neutral	negative/neutral	positive	neutral/negative	negative
Potassium	negative	negative	negative	neutral	negative	negative
Sulfur	positive/neutral	neutral/positive	neutral/positive	positive	neutral/positive	negative/neutral
Calcium	positive	neutral/positive	positive/neutral	positive	positive/neutral	negative/neutral
Magnesium	negative/neutral	negative	negative	neutral	negative/neutral	negative/neutral

* Atherton Tableland in Queensland had positive nitrogen, phosphorus, potassium and calcium balances.

Table 2. Cereal area and mean cereal yield, mean potassium application rate, and the performance indicators of Partial Nutrient Balance (kg nutrient removed/kg nutrient applied) and Partial Factor Productivity (kg yield/kg nutrient applied). The Partial Nutrient Balance is based on a weighted cereal grain K content of 0.54% (*as is basis*). The data for cereal production is derived for two periods (2006 and 2010) from FAO crop statistics database (FAOSTAT), and fertilizer use is derived from IFA surveys (Heffer, 2013) for the same two years.

	Cereal area (Mha)	**Mean cereal yield (t/ha)**	**Mean K rate (kg/ha)**	**K PFP (kg grain/kg fertilizer K)**	**K PNB (kg K_{grain}/kg fertilizer K)**
Argentina	9.24	4.37	0.4	**14619**	**78.94**
Australia	18.37	1.39	1.8	**724**	**3.91**
Brazil	18.42	3.63	36.2	**101**	**0.55**
Canada	15.95	3.26	6.8	**386**	**2.08**
China	83.14	5.48	20.3	**286**	**1.54**
Indonesia	15.13	4.62	10.4	**422**	**2.28**
Mexico	10.01	3.36	2.0	**1394**	**7.53**
Morocco	5.59	1.60	1.9	**706**	**3.81**
Russia	40.54	1.87	3.0	**565**	**3.05**
South Africa	2.99	3.65	8.0	**750**	**4.05**
Turkey	13.04	2.68	1.5	**1527**	**8.25**
USA	52.86	6.69	40.9	**178**	**0.96**
Vietnam	8.36	4.96	29.0	**182**	**0.98**
World	**679.08**	**3.43**	12.2	**278**	**1.50**

** Disaggregated data for EU-27 member countries for fertilizer use by crop is not publicly available.*

Table 3. The partial nutrient balance (PNB-K) and the nutrient balance intensity (NBI-K) for potassium taken from the ABS Agricultural Commodities, Australia (7121.0) releases averaged for 2008 and 2010. Mean rates are derived from the reported fertilizer use and the areas fertilized. The proportion of potassium of fertilizer used by each industry was derived from the survey data, which estimated a total use of 102 kt K for the audited periods.

Industry	**PNB-K kg K/kg K**	**NBI-K kg K/ha**	**Rate kg K/ha**	**% Use**
Grain & Livestock	3.1	-3.7	2	7
Other Grain Growing	5.5	-4.1	1	20
Rice Growing	6.9	-7.7	1	0
Cotton Growing	0.5	9.1	20	8
Sugar Cane Growing	7.6	-78.2	12	6
Vegetable Growing (outdoors)	1.2	-4.1	18	7
Tree Fruits & Vines	1.3	10.5	8	4
Sheep Farming Specialised	2.9	-3.6	2	4
Beef Cattle Farming (specialised)	0.9	-3.3	6	17
Sheep-Beef Cattle Farming	3.2	-3.6	2	2
Dairy Cattle Farming	1.5	-5.2	10	18

Table 4. Summary of survey data collected from south-eastern Australia, including approximate annual rainfall for each region, the number of field records surveyed and relative areas of cereals, oilseeds and legumes (pulse and pasture). Also shown are the number of fields where K was applied and the application rates on canola and cereals where applied.

Region	High Rainfall Zone	Southern New South Wales	Wimmera	Mallee
Annual Rainfall (mm)	>600	450-600	450-350	<350
Growers	45	33	17	23
Fields & Years	829	316	411	1030
Area	7,600	5,300	4,200	17,800
% Cereal	57	56	46	70
% Oilseed	34	34	14	11
% Legume	9	9	34	16
No of fields where K used	85	0	7	0
Rate on canola (kg/ha)	90	-	25	-
Rate on cereal (kg/ha)	66	-	81	-

The Global Potassium Market: Reserves, Supply, Demand, and Trade

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Abstract

Global potassium demand totaled 38.8 million tonnes K_2O in 2015, according to the most recent estimates by the International Fertilizer Association (IFA). Demand has increased at a compound annual growth rate of 2.6% since 2000, and IFA projects that demand will grow 2.1% per year to reach 43.1 million tonnes K_2O by the end of this decade. Agricultural and industrial uses account for roughly 90% and 10% of total demand, respectively.

The six largest potassium consuming countries – namely China, Brazil, United States, India, Indonesia and Malaysia -- account for more than 70% of current use and were responsible for more than 90% of the demand increase since 2000. The Big Six are expected to account for about two-thirds of the projected growth from 2015 to 2020.

On the supply side of the ledger, material quantities of potassium were mined in just 14 countries in 2015. The top three countries – Canada, Belarus and Russia – accounted for more than 60% of the total, and the six largest countries accounted for nearly 90%. Only eight countries produced more than 1.0 million tonnes K_2O, or the equivalent of one world scale mine in 2015.

Potassium ***resources*** are abundant and found in many regions spanning the entire globe. These mineral ores were formed millions of years ago during the Paleozoic Era when sea and lake waters evaporated and potassium chloride (KCl) and sodium chloride (NaCl) crystallized to form deposits in sedimentary rock basins. Even today's mineral rich surface brines are remnants of larger ancient lakes from this era.

However, economically recoverable ***reserves*** are concentrated in just a few countries today due to their quality and location, capital costs of mine development, historical price levels, and current mining and milling technologies. Where deposits have been developed, reserves typically are plentiful and provide for many years of operation. For example, the most recent estimates by the U.S. Geological Survey (USGS) show that current global reserves total 3.7 billion tonnes K_2O equivalent, or more than 90 years of production at current rates. The three largest producing countries have roughly 80 to 120 years of reserves at current output levels and account for nearly two-thirds of estimated global reserves.

The Genetics of Potassium Uptake and Utilization in Plants

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Abstract
Potassium (K) is an essential plant nutrient. Many agricultural soils lack sufficient phytoavailable K for maximal crop production and K fertilizers are, therefore, applied in both intensive and extensive agricultural systems. However, in the interests of profitability and agro-environmental security it is sensible to minimise the use of K fertilizers. This can be achieved by developing crops that are better able to acquire K from the soil or that require less K in their tissues to obtain maximal yields. Substantial, heritable variation exists among the genotypes of many crops in their ability to acquire K from the soil, the relationship between plant K accumulation and yield, and the response of their yield to K supply. This genetic variation can allow plant breeders to produce genotypes that require less K fertilizer. This article describes how plant roots acquire K from the soil solution and how K is redistributed within the plant. It identifies traits that enable plants to acquire K more effectively and achieve maximum yields with a smaller K content, thereby producing greater yields with less K fertilizer input. Finally, it highlights recent insights to genetic factors underpinning these traits that might be exploited in breeding programmes.

INTRODUCTION

Potassium (K) is an essential plant nutrient (Hawkesford et al. 2012). Tissue K concentrations greater than about 5-40 mg g^{-1} dry matter (DM) are required for optimal growth and development, depending upon the plant species, environmental conditions and tissue sampled (Fageria 2009; Römheld 2012). Unfortunately, many agricultural soils lack sufficient phytoavailable K for the nutrition of rapidly growing crops and K fertilizers are applied to maximise production in both intensive and extensive agricultural systems (Baligar, Fageria & He 2001; Rengel & Damon 2008; Fageria 2009; Römheld & Kirkby, 2010; Mueller et al. 2012; Zörb, Senbayram & Peiter 2014). There are sufficient economically viable K reserves (3.7 billion tonnes K_2O) and global K resources (205 billion tonnes K_2O) to support agricultural demand for inorganic K fertilizers, which approached 26.6 million tonnes of K (32 million tonnes K_2O) in 2015 and is predicted to reach 30.7 million tons of K by 2020, for several centuries (US Geological Survey 2016; Heffer & Prud'homme 2016). Nevertheless, it is sensible to optimise the use of K fertilizer in the interests of future agricultural sustainability. One strategy to effect this is to develop crop genotypes that achieve maximal yields with less K fertilizer or with less K offtake from the field (Baligar, Fageria & He 2001; Rengel & Damon 2008; Fageria 2009, 2015a; White 2013). This can be achieved by developing crops that are better able to acquire K from the soil or that require less K in their tissues to obtain maximal yields. Substantial, heritable variation exists among the genotypes of many crops in their ability to acquire K, the relationship between plant K accumulation and yield, and the response of their yield to K supply (Baligar, Fageria & He 2001; Rengel & Damon 2008; Fageria 2009, 2015a; White 2013). This genetic variation could allow breeders to produce genotypes that require less K fertilizer. Knowledge of the molecular basis of genetic variation facilitates its use in breeding programmes by enabling molecular-marker assisted approaches or target-gene manipulation. This article describes how plant roots acquire K from the soil and how K is redistributed within the plant. It identifies traits that enable plants to acquire K more effectively and achieve maximum yields with a smaller K content, thereby producing greater yields with less K fertilizer input. Finally, it highlights recent insights to genetic factors underpinning these traits that might be exploited in developing improved crop genotypes.

THE ACQUISITION AND REDISTRIBUTION OF POTASSIUM IN PLANTS

Potassium in the Soil, its Phytoavailability and Movement to Roots

Most soils contain between 0.3 and 25 g K kg^{-1} soil and K^+ concentrations in soil solutions generally range from 0.1 to 1.0 mM (Fageria 2009, 2015a; White & Greenwood 2013; Zörb, Senbayram & Peiter 2014). Soil K is divided into several fractions. Most of the K available to crops resides in the topsoil and is present as K^+ in the soil solution, as exchangeable K associated with cation exchange sites on the surface of clay minerals and humic substances, and as non-exchangeable K associated with clay lattices that can be solubilised by root or microbial exudates (Fageria 2009, 2015a; Römheld & Kirkby 2010; White & Greenwood 2013; Zörb, Senbayram & Peiter 2014; Bar-Yosef et al. 2015). These fractions generally constitute less than 2-10% of the total K in soil. The remainder of the soil K is held in structural forms that are largely unavailable to annual crops (White & Greenwood 2013; Zörb, Senbayram & Peiter 2014; Bar-Yosef et al. 2015). The interchange of K^+ in the soil solution with exchangeable K is rapid, but the interchange of K^+ in the soil solution with the non-exchangeable K is slow (White & Greenwood 2013; Zörb, Senbayram & Peiter 2014). The total amount and distribution of K between soil fractions, and the rates of interchange between these fractions, determine the temporal availability of K to crops (Römheld & Kirkby 2010). Potassium reaches the root surface by transpiration-driven mass flow of the soil solution and local diffusion through the rhizosphere (Jungk & Claassen 1997; Fageria, Baligar & Jones 2011; Matimati, Verboom & Cramer 2014). It is taken up from the rhizosphere solution by transport proteins in the plasma membrane of root epidermal cells. Factors affecting K acquisition by plants include the amount of K that is readily available in the soil solution and exchangeable fractions, the ability to accelerate the release of non-exchangeable K from clay lattices, the speed of replenishment of K^+ in the rhizosphere solution, the proliferation of roots through the soil volume, the K^+ concentration at the root surface, and the K^+ uptake capacity of root cells (Jungk & Claassen 1997; Rengel & Damon 2008; White 2013; Zörb, Senbayram & Peiter 2014).

Potassium Uptake by Roots and Redistribution within the Plant

The uptake and distribution of K between plant tissues, cell types and subcellular compartments are determined by proteins that transport K^+ across cell membranes (White & Karley 2010). These can be divided into transporters that facilitate K^+ transport in the direction of its electrochemical gradient (channels and carriers) and transporters that couple K^+ transport to the movement of a driving ion, generally the proton (H^+), either in the same (symport) or opposite (antiport) direction to harness the electrochemical gradient of the driving ion (White 2017). The proton electrochemical gradient is generally generated by membrane-bound H^+-ATPases or H^+-pyrophosphatases (White 2017).

Most K is taken up from the rhizosphere solution by K^+ transporters in the plasma membranes of root epidermal cells, including root hairs (White & Karley 2010). Early studies of the relationship between K^+ uptake and rhizosphere K^+ concentration, its pharmacology and dependence upon plant K-nutritional status indicated the presence of both inducible 'high-affinity' H^+-coupled K^+-transporters and constitutive 'low-affinity' K^+ channels (Epstein & Bloom 2005; Britto & Kronzucker 2008; Hawkesford et al. 2012). The former were proposed to dominate K^+ influx at rhizosphere K^+ concentrations <1 mM and in K-deficient plants, whilst the latter were proposed to contribute to K^+ influx at rhizosphere K^+ concentrations >1 mM irrespective of plant K-nutritional status. Subseqently, the gene *AtHAK5* was found to encode the inducible H^+/K^+-symporter and *AtAKT1* the constitutive K^+ channel mediating most K^+ influx to arabidopsis (*Arabidopsis thaliana* [L.] Heynh.) roots (Table 1; White & Karley 2010; Sharma, Dreyer & Riedelsberger 2013; Nieves-Cordones et al. 2016). In addition to these transporters, the AtKUP7 H^+/K^+-symporter might also contribute significantly to K^+ uptake by arabidopsis root cells at low rhizosphere K^+ concentrations (Han et al. 2016). Although homologs of these transporters have been found in all plant species studied (Véry et al. 2014; Nieves-Cordones et al. 2016), species differ in (a) the relationship between K^+ uptake and rhizosphere K^+ concentration (e.g. Asher & Ozanne 1967; Wild et al. 1974; Spear, Asher & Edwards 1978a; Steingrobe & Claassen 2000; El Dessougi, Claassen & Steingrobe

2002; Brennan & Bolland 2004; Wang et al. 2011; White 2013) and (b) the selectivity of monovalent cation accumulation (Broadley et al. 2004; Watanabe et al. 2007; Broadley & White 2012; White et al. 2012) even when grown under the same environmental conditions. These observations suggest that the complement of proteins catalysing K^+ influx to root cells differs between plant species (White 2013; Nieves-Cordones et al. 2016). In particular, members of HKT subfamily II are thought contribute to K^+ influx to root cells of monocotyledonous plant species, but not dicotyledonous species (Chérel et al. 2014; Véry et al. 2014). The relationships between K^+ uptake and rhizosphere K^+ concentration can also vary between genotypes of a plant species (e.g. Spear, Asher & Edwards 1978ab; Siddiqi & Glass 1983ab; Chen & Gabelman 1995, 2000; Zhang et al. 2007; Sanes et al. 2013; White et al. 2016).

Following uptake by root cells, K^+ is transported symplastically to the stele where it is loaded into the xylem through outward-rectifying K^+ channels (White & Karley 2010). In arabidopsis, this function is provided primarily by AtSKOR, which is present in pericycle and stelar parenchyma cells (Table 1; Gaymard et al. 1998; Dreschler et al. 2015). Increasing transpiration generally results in greater xylem K flux to the shoot, but reduces the K concentration in the xylem sap (Goodger et al. 2005; White & Karley 2010). Whilst traversing the root, K can be stored in the vacuoles of root cells. The K concentration in the vacuoles of root cells increases with K supply (White & Karley 2010). In arabidopsis, members of the CPA1 cation-proton antiporter family, including AtNHX1, AtNHX2 and AtNHX4, and other transporters, such as AtCCX3 (Morris et al. 2008) and AtZIFL1.1 (Remy et al. 2013), catalyse K^+ influx to vacuoles of root cells, whilst members of the TPK/KCO K^+ channel family mediate K^+ efflux from the vacuoles of root cells (Table 1; White & Karley 2010).

Transpirational water flows determine the delivery of K within the shoot and, since the apoplastic K^+ concentration at the point of xylem unloading is 5-20 mM, plasma membrane K^+ channels can facilitate K^+ influx to shoot cells (Keunecke et al. 2001; Wigoda, Moshelion & Moran 2014). In arabidopsis, these are encoded by Shaker-type K^+ channels whose activity is complemented by members of the KUP/HAK/KT family of K^+/H^+-symporters (Table 1; White & Karley 2010). The vacuolar K concentration of shoot cells increases with increasing K supply (White & Karley 2010). In a similar manner to root cells, members of the CPA1 cation-proton antiporter family catalyse K^+ influx to vacuoles of leaf cells and members of the TPK/KCO K^+ channel family mediate K^+ efflux from their vacuoles (Table 1; White & Karley 2010). Potassium can be redistributed rapidly from leaves to phloem-fed tissues (White & Karley 2010). In arabidopsis the K^+ channel AtAKT2/AKT3 is primarily responsible for loading K^+ into the phloem (Table 1; Deeken et al. 2002). The K concentration in phloem sap ranges from about 10 to 150 mM, depending upon a variety of factors including plant K-nutritional status (Marschner, Kirkby & Engels 1997; White & Karley 2010). Since the loading of K^+ into the phloem enables the loading of other solutes, such as sucrose, plant K-nutritional status determines both the composition of phloem sap and rate of phloem transport (Hermans et al. 2006; Hawkesford et al. 2012). It is been estimated that up to 90% of the K delivered to the shoot via the xylem is returned to the root via the phloem (White & Karley 2010). The recirculation of K within the plant serves a number of functions, including (1) redistributing K from senescing to developing tissues, especially during periods of restricted rhizosphere K availability, (2) maintaining high K/Na quotients in sensitive meristematic tissues, (3) maintaining cation-anion balance within the plant, especially when nitrate assimilation occurs in the shoot, and (4) enabling the movement of sugars, organic compounds and developmental signals (Marschner, Kirkby & Engels 1997; Hawkesford et al. 2012).

DIFFERENCES IN POTASSIUM UPTAKE AND UTILIZATION BETWEEN PLANT SPECIES

Many definitions exist to describe aspects of K uptake and utilization by plants (Table 2; White 2013). The definitions used most frequently in an agricultural context are (1) agronomic K use efficiency (KUE), which is defined as crop yield per unit K available (g Y [g Ka]$^{-1}$) and is numerically equal to the product of (2) the K uptake efficiency (KUpE) of a crop, which is defined as crop K content per unit K available (g K_{crop} [g Ka]$^{-1}$) and (3) its K utilization efficiency (KUtE), which is defined as yield per unit crop K

content (g Y [g K_{crop}]$^{-1}$). These are often complemented by measurements of (4) the response of crop yield to K availability, (5) the response of crop K content (K_{crop}), or tissue K concentration, to K availability, and (6) the relationship between crop yield and crop K content or tissue K concentration (Table 2). Relationships (4) and (6) are often described using Michaelis–Menten equations with two parameters. For equation (4) these are Y_{max}, the maximum yield that can be obtained and Km_{Ka}, the Ka at which Y equals $Y_{max}/2$, and for equation (6) Y_{max}, and Km_{Kcrop}, the K_{crop} at which Y equals $Y_{max}/2$ (White et al. 2016). In addition, (7) the apparent recovery (acquisition) of applied K-fertilizer and (8) the increased crop yield resulting from the application of K-fertilizers relative to the amount of K fertilizer applied are also frequently assessed (Fageria 2009).

Plant species differ in their growth response to K supply, their ability to acquire K from the soil and their ability to utilize K physiologically for vegetative and reproductive growth (Fageria 2009; Römheld & Kirkby 2010; White 2013). Plant roots can acquire sufficient K for maximal growth from solutions containing micromolar K concentrations, provided the K supply to the roots matches the minimal K demand of the plant and that ammonium, which competes with K^+ for transport and inhibits the expression of genes homologous to *AtHAK5* (Qi et al. 2008), is absent from the rhizosphere (e.g. Asher & Ozanne 1967; Wild et al. 1974; Spear, Asher & Edwards 1978a; Siddiqi & Glass, 1983a; White 1993). Species from the Poales and Brassicales generally achieve their growth potential at a lower K supply than other angiosperms and compete best in K-limited environments (Asher & Ozanne 1967; Hoveland, Buchanan & Harris 1976; Grant et al. 2007; Hafsi et al. 2011). Similarly, cereal and brassica crops often require less K fertilizer than most vegetable, solanaceous or beet crops to achieve maximum yields (Greenwood et al. 1980; Pretty & Stangel 1985; Steingrobe & Claasen 2000; Brennan & Bolland 2004; Trehan 2005; Fageria 2009; Kuchenbuch & Buczo 2011; White 2013; Schilling et al. 2016). Crops also differ in their temporal demand for K, which is related to their individual phenology, and K supply must be synchronized with their K demand to achieve maximal yields (White 2013). For example, both maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) accumulate K during early growth, whilst grain sorghum (*Sorghum bicolor* [L.] Moench) accumulates K roughly in proportion to its biomass accumulation (Figure 1). One explanation for the temporal difference in K accumulation between these species might be tillering: The main stems of wheat and sorghum show an almost identical pattern of relative accumulation of K and DM as the uniculm maize, but the subsequent production of tillers requires continued K accumulation in new vegetative structures. Whilst tillering in wheat occurs at a similar time to the development of the main stem, tillering in sorghum continues until much later in crop development.

Achieving maximal growth or yield at a lower K supply can be a consequence of better KUpE or KUtE (White 2013). Plant species differ in their ability to acquire K from the soil, which has been attributed to differences in (1) the capacity of their root cells to take up K^+ swiftly at low rhizosphere K^+ concentrations, (2) the ability of their root systems to exploit the soil volume effectively, (3) their ability to release non-exchangeable K from the soil and (4) their longevity (Greenwood et al. 1980; Steingrobe & Claassen 2000; Wang et al. 2000, 2011; Jungk 2001; Rengel & Damon 2008; Römheld & Kirkby 2010; Samal et al. 2010; White 2013). The roots of cereals and grasses often have a greater K uptake capacity than other plants, which not only accelerates K diffusion to the root surface but also promotes the release of non-exchangeable K from the soil (Pettersson & Jensén 1983; Jungk & Claasen 1997; Steingrobe & Claasen 2000; Samal et al. 2010; Wang et al. 2011). The roots of grasses and cereals exploit the soil volume more effectively than those of other crops because of a greater investment in root biomass, rapid development of their root system, greater root density and rooting depth, and the abundance of long root hairs (Steingrobe & Claasen 2000; Høgh-Jensen & Pedersen 2003; Samal et al. 2010; White 2013). This not only allows access to a greater K supply but also reduces K concentrations in the rhizosphere solution, which accelerates K diffusion to the root and promotes the release of non-exchangeable K (Zörb, Senbayram & Peiter 2014). In particular, Jungk (2001) reported a linear relationship between the specific rate of K^+ uptake (mg K cm^{-1} root) and the length of root hairs among onion (*Allium cepa* L.), maize, ryegrass (*Lolium perenne* L.), tomato (*Solanum lycopersicum* L.) and canola (oilseed rape; *Brassica*

napus L.) and Høgh-Jensen & Pedersen (2003) reported a linear relationship between K accumulation and root hair length among red clover (*Trifolium pratense* L.), pea (*Pisum sativum* L.), barley (*Hordeum vulgare* L.), alfalfa (lucerne; *Medicago sativa* L.), canola, ryegrass and rye (*Secale cereale* L.). Roots of Caryophyllales, including grain amaranths (*Amaranthus* spp.) and beets (*Beta vulgaris* L.), access non-exchangeable K by exuding copious amounts of organic acids (Wang et al. 2011). By contrast, legumes and solanaceous crop are relatively ineffective in acquiring non-exchangeable K from the soil and generally have low KUpE (Wang et al. 2000; Høgh-Jensen & Pedersen 2003; Brennan & Bolland 2004). It is, perhaps, noteworthy that interspecies or intercultivar grafting of rootstock and scion can influence KUpE in the resulting union (Nawaz et al. 2016).

Plant species also differ in their ability to utilize the K they have acquired for growth and yield formation (White 2013). Most plants have a high K demand, which is ultimately set by their growth rate and, most often, by nitrogen (N) supply (Fageria 2009, 2015a; White & Greenwood 2013). The physiological K requirement of a plant is determined by its critical tissue K concentration, defined as the concentration at which the plant achieves 90% of its maximum growth, and its growth rate (White 2013). The tissue K concentration at which K deficiency symptoms appear in leaves is generally lower in cereals and grasses than in legumes and other eudicots, which reflects their lower physiological K requirements (Johnson, 1973; Greenwood et al. 1980; Brennan & Bolland 2004, 2007; Römheld 2012; White 2013). In general, physiological K utilization can be improved by (1) reducing vacuolar K concentrations to maintain appropriate cytoplasmic K concentrations, either by anatomical adaptations or by greater substitution of K for other solutes in the vacuole, and (2) redistributing K from older to younger tissues to maintain growth and photosynthesis (Rengel & Damon 2008; Wakeel et al. 2011; White 2013; Maillard et al. 2015). The ability to substitute K for sodium (Na) in the vacuole is important for efficient K utilization in many, but not all, plant species and is particularly evident in natrophilic species, such as sugar beet (Wakeel et al. 2011; Zörb, Senbayram & Peiter 2014; White et al. 2017). About 60% of the K in the cells of sugar beet can be replaced by Na, whereas less than 15% of the K in cells of wheat can be replaced (Zörb, Senbayram & Peiter 2014). The ability to retranslocate K from senescing tissues also differs between plant species (Hocking & Pate 1977; Milla et al. 2005; Maillard et al. 2015). In general, plant species with greater KUtE are able to maintain their water relations, photosynthetic activity and harvest index when grown in environments with a low K supply (Rengel & Damon 2008; White 2013).

DIFFERENCES IN POTASSIUM UPTAKE AND UTILIZATION WITHIN CROP SPECIES

Genetic Variation in Potassium Use Efficiency within Crop Species

Differences in growth and yield responses to K supply, KUE, KUpE, and KUtE, have been reported among genotypes of many crop species (Baligar, Fageria & He 2001; Rengel & Damon 2008; Fageria 2009, 2015ab; Römheld & Kirkby 2010; White 2013; Zörb, Senbayram & Peiter 2014). Although variation in KUE has been correlated with variation in both KUpE and KUtE, depending upon plant species and growth conditions, it is most often correlated with KUpE in crop species.

Variation in KUpE has been observed among genotypes of barley (Pettersson & Jensén 1983; Siddiqi & Glass 1983a; Wu et al. 2011; White et al. 2016), wheat (Zhang, Chen & Tirore 1999; Damon & Rengel 2007), wild oats (*Avena fatua* L.; Siddiqi et al. 1987), rice (*Oryza sativa* L.; Yang et al. 2004; Fageria 2009; Liu, Li & Porterfield 2009; Fageria, dos Santos & de Moraes 2010; Fageria et al. 2013; Sanes et al. 2013; Fageria & dos Santos 2015), maize (Feil et al. 1992; Nawaz et al. 2006; Ning et al. 2013), common bean (*Phaseolus vulgaris* L.; Fageria, Barbosa Filho & da Costa 2001; Fageria & Melo 2014; Fageria, Melo & Knupp 2015), faba bean (*Vicia faba* L.; Stelling, Wang & Römer 1996), soybean (Moreira, Moraes & Fageria 2015), lupin (*Lupinus angustifolius* L.; Brennan & Bolland 2004), canola (Damon, Osborne & Rengel 2007; Lu et al. 2016), *Brassica oleracea* L. (White et al. 2010), Indian mustard (*Brassica juncea* [L.] Czern.; Shi, Wang & Yan 2004), cassava (*Manihot esculenta* Crantz; Spear, Asher & Edwards 1978b), sweet potato (*Ipomoea batatas* L.; George, Lu & Zhou 2002; Wang et al. 2015),

tomato (Chen & Gabelman 1995, 2000; Sánchez-Rodríguez et al. 2010), potato (*Solanum tuberosum* L.; Trehan 2005), cotton (*Gossypium hirsutum* L.; Ali et al. 2006; Zhang et al. 2007; Yang et al. 2011; Zia-ul-hassan et al. 2014; Rochester & Constable 2015) and watermelon (*Citrullus lanatus* [Thunb.] Matsum. & Nakai; Fan et al. 2013). The same traits that contribute to differences in KUpE between plant species also contribute to differences in KUpE among genotypes within plant species. For example, when compared at low K supply, genotypes of potato with greater KUpE have a more extensive root system, greater K uptake capacities and mobilise more non-exchangeable K than other genotypes (Trehan 2005), genotypes of tomato with greater KUpE often exhibit swifter root growth and greater K uptake capacity than other genotypes (Chen & Gabelman 1995, 2000), genotypes of barley with greater KUpE have greater K uptake capacities than other genotypes (Siddiqi & Glass 1983b), and genotypes of rice (Jia et al. 2008; Sanes et al. 2013) and cotton (Yang et al. 2011; Zia-ul-hassan & Arshad 2011) with greater KUpE all have greater root length than other genotypes.

Variation in KUtE has been observed among genotypes of barley (Pettersson & Jensén 1983; Wu et al. 2011; White et al. 2016), wheat (Woodend & Glass 1993; Zhang, Chen & Tirore 1999; Baligar, Fageria & He 2001; Damon & Rengel 2007; Moricioni et al. 2012), wild oats (Siddiqi et al. 1987), rice (Yang et al. 2003, 2004; Fageria 2009; Liu, Li & Porterfield 2009; Fageria, dos Santos & de Moraes 2010; Fageria et al. 2013; Zhang et al. 2013; Fageria & dos Santos 2015), maize (Feil et al. 1992; Baligar, Fageria & He 2001; Nawaz et al. 2006), sorghum (*Sorghum bicolor* [L.] Moench; Baligar, Fageria & He 2001), common bean (Fageria, Barbosa Filho & da Costa 2001; Fageria & Melo 2014; Fageria, Melo & Knupp 2015), faba bean (Stelling, Wang & Römer 1996), soybean (Moreira, Moraes & Fageria 2015), alfalfa (*Medicago sativ*a L.; Baligar, Fageria & He 2001), lupin (Brennan & Bolland 2004), canola (Damon, Osborne & Rengel 2007; Lu et al. 2016), *Brassica oleracea* (White et al. 2010), Chinese cabbage (*Brassica rapa* L.; Wu et al. 2008), Indian mustard (Shi, Wang, & Yan 2004), spinach (*Spinacia oleracea* L.; Grusak & Cakmak 2005), cassava (Spear, Asher & Edwards 1978ab), sweet potato (George, Lu & Zhou 2002; Wang et al. 2015), tomato (Chen & Gabelman 1995), potato (Trehan 2005), cotton (Ali et al. 2006; Zhang et al. 2007; Yang et al. 2011; Zia-ul-hassan et al. 2014; Rochester & Constable 2015) and watermelon (Fan et al. 2013). However, it is noteworthy that KUtE for vegetative growth does not always correlate with KUtE for crop yield. The same traits that contribute to differences in KUtE between plant species also contribute to differences in KUtE among genotypes of a particular species. For example, barley cultivars that are less susceptible to K deficiency symptoms partition K more effectively from the vacuole to the cytoplasm of root cells at low K supply (Memon, Saccomani & Glass 1985), the ability of tomato (Figdore, Gabelman & Gerloff 1989) and maize (Moriconi et al. 2012) genotypes to grow in Na-rich, K-limiting conditions correlates with their ability to substitute Na for K as a vacuolar osmoticum, and genotypes of cassava (Spear, Asher & Edwards 1978b) and rice (Yang et al. 2004) with greater KUtE redistribute K from older to younger leaves better than other genotypes. Differences in harvest index, which is a component trait of KUtE, contribute to variation in yield among rice (Yang et al. 2003, 2004; Fageria, dos Santos & de Moraes 2010; Zhang et al. 2013), wheat (Woodend & Glass 1993; Zhang, Chen & Tirore 1999; Damon & Rengel 2007), common bean (Fageria, Barbosa Filho & da Costa 2001), faba bean (Stelling, Wang & Römer 1996), canola (Rose et al. 2007), sweet potato (George, Lu & Zhou 2002) and cotton (Rochester & Constable 2015) genotypes, especially when grown with a low K supply.

Chromosomal Loci Affecting Potassium Use Efficiency

There appears to be sufficient, heritable genetic variation within crop species to breed for genotypes with greater KUE, KUpE, and KUtE (White 2013). However, these traits are controlled by multiple chromosomal loci (QTL) and strong interactions between genotype and environment can occur (e.g. White et al. 2010; Guo et al. 2012; Genc et al. 2013; White 2013; Gong et al. 2015). This implies that breeding programmes should incorporate beneficial alleles of several genes to improve these traits and consider carefully the conditions under which genotypes are screened and cultivated.

Chromosomal loci influencing KUpE, KUtE, shoot K concentration, or biomass production at low K supply have been identified in a few model species, such as arabidopsis (e.g. Harada & Leigh 2006; Ghandilyan et al. 2009; Kanter et al. 2010; Prinzenberg et al. 2010), and in several crops, including rice (Wu, Ni & Luo 1998; Koyama et al. 2001; Lin et al. 2004; Cheng et al. 2012; Wang et al. 2012; Miyamoto et al. 2012; Fang et al. 2015), wheat (Genc et al. 2010, 2013; Guo et al. 2012; Kong et al. 2013; Zhao et al. 2014; Gong et al. 2015), barley (Nguyen et al. 2013ab), maize (Zdunić et al. 2014), miscanthus (*Miscanthus sinensis* Andersson; Atienza et al. 2003), tomato (Villalta et al. 2008; Asins et al. 2013), barrel medic (*Medicago truncatula* Gaertn.; Arrauadi et al. 2012), *Brassica oleracea* (White et al. 2010) and cotton (Liu et al. 2015). However, few genes underpinning these QTL have been identified. Nevertheless, it has been reported that genes encoding K^+ transporters, such as AtAKT1, AtHAK5, AtKUP9, AtTPK1, AtCNGC1 and AtSKOR, are located within QTL affecting shoot K concentration in arabidopsis (Harada & Leigh 2006; Kanter et al. 2010) and genes encoding homologs of the arabidopsis K^+ transporters AtKUP9, AtAKT2, AtKAT2, and AtTPK3 occur within a QTL affecting shoot K concentration in *Brassica oleracea* (White et al. 2010). Similarly genes affecting shoot K concentration located within a QTL on chromosome 14 of cotton include numerous cation transporters including AKT2/3 and a Na^+/H^+-antiporter (Liu et al. 2015). In rice, the gene *OsHKT1;5* (*OsHKT8*), which encodes a Na transporter expressed predominantly in the parenchyma cells surrounding the xylem, underpins the locus SKC1, which affects shoot K concentration under saline conditions (Ren et al. 2005). Similarly, HvHKT1;5, TmHKT1;5-A and TaHKT1:5-D have been implicated in the control of shoot Na and K concentrations in barley and wheat (Munns et al. 2012; Nguyen et al. 2013a) and SlHKT1;1 and SlHKT1;2 have been implicated in the control of shoot Na and K concentrations in tomato (Asins et al. 2013). A candidate gene associated with the K1 locus affecting K concentration in sugar beet encodes a putative K channel (Schneider et al. 2002).

BREEDING CROPS FOR GREATER AGRONOMIC POTASSIUM USE EFFICIENCY

In a cropping system, the factor that determines K-fertilizer applications is ultimately K offtake from the field in crop material. Reducing the K content of produce, and returning crop residues to the field, can reduce K-fertilizer requirements. However, care must be taken that reducing K content of harvested produce does not impair its quality.

To breed genotypes for greater KUE, breeding programmes require the ability to screen many genotypes for variation in KUE, KUpE or KUtE or to identify genetic variation linked to these traits (Rengel & Damon 2008). In addition, a successful breeding programme also requires the ability to characterize the relationships between K supply, plant K content and yield formation in a variety of environments to reveal interactions between genotype, management and environmental conditions. In principle, the required data can be obtained from simple measurements of the response of yield and K content to varying K-fertilizer application at a number of well-chosen sites across several years. Breeding programmes have generally focussed on increasing yield under current management practice, which although resulting in greater KUE under current management practice, does not address the needs of reduced-input agriculture.

Although there appears to be sufficient, heritable genetic variation within crop species to breed for genotypes with greater KUE, KUpE, and KUtE, and QTL affecting these traits have been identified in some crops, these traits are rarely screened in breeding programmes. The principal reasons for this are that: (1) plants must be grown to commercial maturity to determine true KUE, KUpE and KUpE, which requires an entire cropping season, (2) large numbers of genotypes must be screened to identify QTL influencing traits or to assess variation within a breeding programme, which can be costly and laborious, and (3) plants must be screened in several environments, and with contrasting management practices, to determine whether the trait is sufficiently robust for the development of a new cultivar, which also increases costs and labour. Nevertheless, such screening can be undertaken in field trials at different locations over a number of years and attempts are being made (1) to reduce the number of treatments

required for estimating the responses of KUE, KUpE and KUtE to management and fertilizer practices, using crop modelling approaches or theoretical considerations (Moriconi & Santa-Maria 2013; Santa-María, Moriconi & Oliferuk 2015; White et al. 2016) and (2) to develop techniques to estimate crop K content that are less costly and labour intensive than conventional mineral analyses (Liu et al. 2011; Pimstein et al. 2011).

It might be suggested that screening traits associated with greater KUpE and KUtE, rather than screening for these traits directly, could provide a more practical and cost effective strategy to breeding crops for greater KUE. Plant traits that improve KUpE include (1) the exudation of organic compounds releasing nonexchangeable soil K, (2) a large root K uptake capacity, (3) rapid transpiration, (4) early root vigour, (5) large root/shoot biomass quotients, (6) high root length densities in the soil and (7) long root hairs (Rengel & Damon 2008; White 2013). With the exception of transpiration, these traits are difficult to assess in the field but, provided a trait is correlated with field performance it might be assayed in young plants using high throughput laboratory or glasshouse systems (Downie et al. 2015; Kuijken et al. 2015). Considerable genetic variation in these traits has been observed among seedlings of numerous crops and QTL affecting root traits have been identified (Lynch 2007; White et al. 2013; Kuijken et al. 2015). Plant traits that increase KUtE include (1) effective K redistribution from older to younger tissues and (2) the maintenance of optimal K concentrations in metabolically active cellular compartments, either by anatomical adaptation or replacement of K in non-essential roles, and, consequently, (3) the maintenance of water relations, (4) photosynthesis, (5) canopy cover and (6) harvest index at lower K supply (Rengel & Damon 2008; White 2013; Zörb, Senbayram & Peiter 2014). These traits can all be assayed either directly or indirectly in the field. The redistribution of K from older to younger leaves and tolerance of low tissue K concentrations can be determined from measurements of biomass and K apportionment between leaves in response to K-fertilizer applications but can be costly and requires significant labour. Water relations, photosynthesis and canopy cover can all be assayed in a cost-effective manner using modern imaging technologies (Mahajan et al. 2014, Rodriguez-Moreno et al. 2014; Zhao et al. 2016). Harvest index is often a breeding target and is routinely measured in crop trials.

In summary, there is potential to breed for KUE, KUpE and KUtE, and their component traits. Screening for KUE, KUpE and KUtE requires large field trials, on multiple sites, over several years, and can incur large analytical costs. Nevertheless, it is feasible. Screening for plant traits associated with KUpE would probably require screening young plants grown in laboratory or glasshouse environments. Traits observed in young plants must be correlated with crop performance in the field, but screening young plants has the advantage of accelerated throughput. Screening for traits associated with KUtE could be incorporated into field trials assessing KUE, KUpE and KUtE, but would require more labour and instrumentation.

If traits associated with greater KUE were introduced into elite germplasm they could help reduce K-fertilizer applications in agriculture. Thus, breeding crop genotypes with greater KUE appears achievable and a worthy pursuit that would ultimately reduce fertilizer costs, protect the environment, and slow the exhaustion of non-renewable resources.

ACKNOWLEDGEMENTS
This work was supported by the Rural and Environment Science and Analytical Services Division (RESAS) of the Scottish Government. We thank Dr Paula Pongrac for her comments on an early draft of the manuscript.

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TABLES AND FIGURES

Table 1. Principal transport proteins catalysing the uptake and movement of potassium (K) in plants. Proteins are divided into their families and the membrane location, transport mechanism and putative function of individual proteins is indicated. Abbreviations: PM = plasma membrane, TP = tonoplast, ER = endoplasmic reticulum, EN = endomembrane, CP = chloroplast, Mit = mitochondrion, nd = not determined, KIRC = inward-rectifying K^+ channel, KORC = outward-rectifying K^+ channel. For further information see White & Karley (2010), Chanroj et al. (2012), Bassil & Blumwald (2014) and Véry et al. 2014).

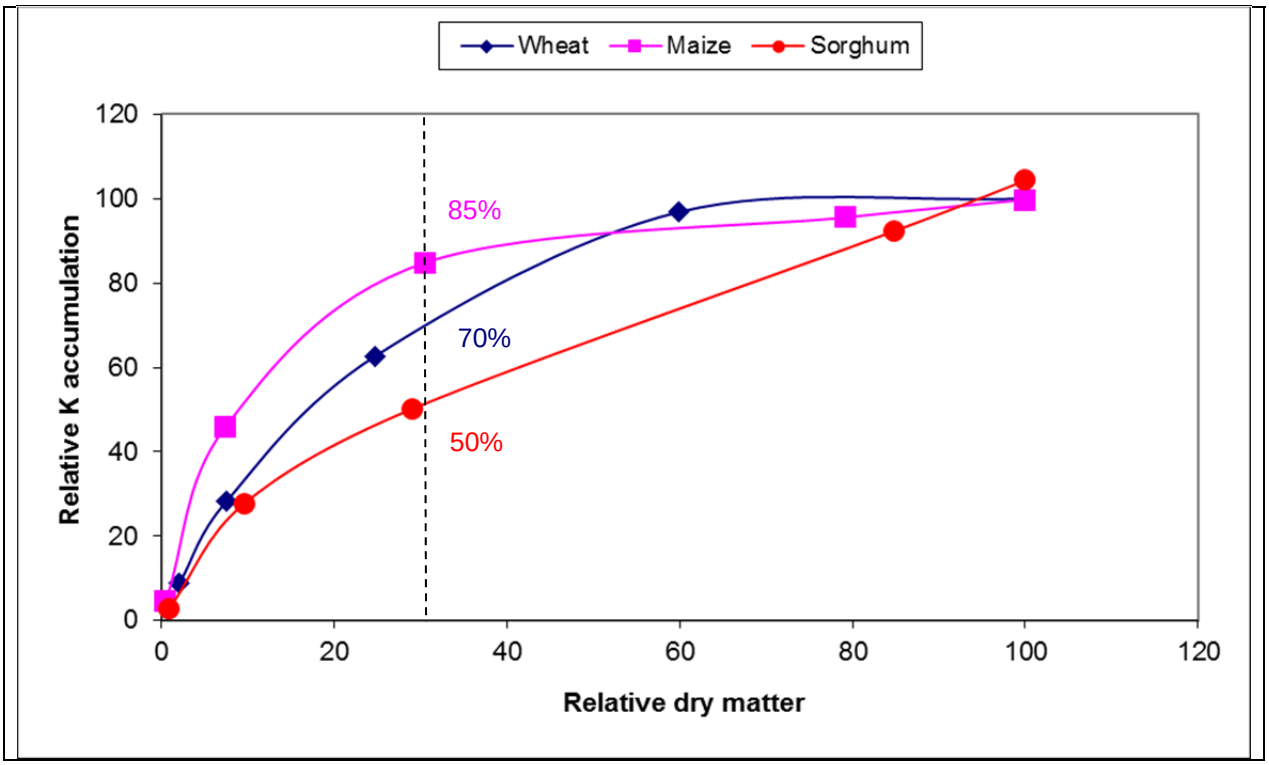
Family	Location	Transport Protein	Proposed Mechanism	Putative Function(s)
Shaker	PM	AtAKT1, AtAKT5, AtAKT6, AtKAT1, AtKAT2	K^+ channel (KIRC)	K^+ influx
	PM	AtKC1 (=AtKAT3)	K^+ channel subunit	regulation of AtAKT1
	PM	AtAKT2/3	K^+ channel (KIRC)	phloem K^+ loading
	PM	AtSKOR	K^+ channel (KORC)	xylem K^+ loading
	PM	AtGORK	K^+ channel (KORC)	K^+ efflux
TPK/KCO	PM	AtTPK4	K^+ channel	charge compensation
	TP	AtTPK1, AtTPK2, AtTPK3, AtTPK5, AtKCO3	K^+ channel	vacuolar K^+ release, cellular K^+ homeostasis
	CP	AtTPK3	K^+ channel	photosynthesis
CNGC	PM	AtCNGC1, AtCNGC10	Cation channel (K^+-permeable)	K^+ influx
	PM	AtCNGC2, AtCNGC4, AtCNGC11, AtCNGC12, AtCNGC18	Cation channel (K^+-permeable)	Ca^{2+} signalling
	PM	AtCNGC3, AtCNGC7, AtCNGC8	Cation channel	cation uptake
	PM	AtCNGC5, AtCNGC20		
	TP	AtCNGC19, AtCNGC20		
	nd	AtCNGC6, AtCNGC9, AtCNGC13, AtCNGC14, AtCNCG15, AtCNGC16, AtCNGC17		
GLR	PM	AtGLR3.3, AtGLR3.4	Cation channel (?)	
	Mit, CP	AtGLR3.5		
	nd	AtGLR1.1, AtGLR3.2, AtGLR3.7	Cation channel (K^+-permeable)	Ca^{2+} signalling
	nd	AtGLR1.4	Cation channel (K^+-permeable)	
	nd	AtGLR1.2, AtGLR1.3, AtGLR2.1, AtGLR2.2, AtGLR2.3, AtGLR2.4, AtGLR2.5, AtGLR2.6, AtGLR2.7, AtGLR2.8, AtGLR2.9, AtGLR3.1, AtGLR3.6		
KUP/HAK/KT	PM	AtHAK5, AtKUP1, AtKUP2, AtKUP7, AtKUP11	K^+/H^+ symport	K^+ influx
	TP	AtKUP4, AtKUP5, AtKUP7	K^+/H^+ symport	
	ER	AtHAK5	K^+/H^+ symport	
	CP	AtKUP12		
	nd	AtKUP3, AtKUP6, AtKUP8, AtKUP9, AtKUP10	K^+/H^+ symport	
CPA1 (NHX)	PM	AtSOS1 (AtNHX7), AtNHX8	Na^+/H^+ exchange	Na^+ efflux (salt tolerance)
	TP	AtNHX1, AtNHX2, AtNHX3, AtNHX4	Cation/H^+ exchange	vacuolar K^+ and Na^+ sequestration
	EN	AtNHX5, AtNHX6	K^+/H^+ exchange	endosomal pH regulation, membrane trafficking
CPA2 (CHX)	PM	AtCHX13	K^+/H^+ symport	K^+ influx
	PM	AtCHX17	K^+/H^+ exchange	cytosolic pH regulation
	PM	AtCHX21	Na^+/H^+ exchange	xylem Na^+ loading
	ER	AtCHX23	K^+/H^+ exchange	K^+ homeostasis, cytosolic pH regulation
	EN	AtCHX17, AtCHX20	K^+/H^+ exchange	K^+ homeostasis, pH regulation, membrane trafficking
	EN?	AtCHX16, AtCHX18, AtCHX19		K^+ homeostasis, pH regulation (EN), membrane trafficking
	nd	AtCHX1, AtCHX2, AtCHX3, AtCHX4, AtCHX5, AtCHX6A, AtCHX7, AtCHX8, AtCHX9, AtCHX10, AtCHX11, AtCHX12, AtCHX14, AtCHX15, AtCHX22, AtCHX24, AtCHX25, AtCHX26, AtCHX27, AtCHX28		
CPA2 (KEA)	CP	AtKEA1, AtKEA2, AtKEA3	K^+/H^+ antiport	chloroplast pH & osmoregulation
	nd	AtKEA4, AtKEA5, AtKEA6		
CaCA (CCX)	(PM)	AtCCX5	K^+ transport	K^+ influx
	TP	AtCCX1, AtCCX3	K^+/H^+ exchange	vacuolar K^+ sequestration
	nd	AtCCX4	K^+ transport	
	nd	AtCCX2		
MFS	PM	AtZIFL1.3	H^+/K^+ transporter	auxin redistribution
	TP	AtZIFL1.1	H^+/K^+ transporter	auxin redistribution

Table 2. Mathematical definitions of aspects of potassium (K) use efficiency in crops. For further information see Fageria (2009), White (2013), Maillard et al. (2015) and White et al. (2016).

	Name	Abbreviation	Calculation	Units
1	Agronomic K Use Efficiency	KUE	Y/Ka	g DM g^{-1} K
2	K Uptake Efficiency	KUpE	K_{crop}/Ka	g K g^{-1} K
3	K Utilization Efficiency	KUtE	Y/K_{crop}	g DM g^{-1} K
4	Yield Response to K Supply		$Y = Y_{max} \times (Ka / (Km_{Ka}+Ka))$	
5	Response of Plant K content to K supply		derived from equations (4) and (6)	
6	Yield Response to Plant K Content		$Y = Y_{max} \times (K_{crop} / (Km_{Kcrop}+K_{crop}))$	
7	Apparent Fertilizer Recovery Efficiency	ARE	$((K_{crop(Kf)}) - K_{crop(Ks)}) / Kf) \times 100$	%
8	Agronomic Efficiency of K fertilizer	AE	$(Y_{Kf} - Y_{Ks}) / Kf$	g DM g^{-1} K
9	Root Uptake Capacity		K_{crop} / R	g K g^{-1} DM
10	Apparent Remobilization Efficiency	AKR	$((K_{tissue(o)}-K_{tissue(t)})/K_{tissue(0)}) \times 100$	%

Abbreviations: DM = dry matter, Ka = phytoavailable K, K_{crop} = crop K content, $K_{crop(Kf)}$ = crop K content when fertilizer is applied, $K_{crop(Ks)}$ = crop K content without fertilizer, $K_{crop(max)}$ = maximum crop K content, $K_{tissue(o)}$ = original tissue K content, $K_{tissue(t)}$ = tissue K content after remobilization, Km_{Ka} = Ka at which Y equals $Y_{max}/2$, Km_{Kcrop}, K_{crop} at which Y equals $Y_{max}/2$, Kf = K supplied as fertilizer, Ks = phytoavailable K in soil with no fertilizer applied, R = root DM, Y = yield, Y_{Kf} = yield with fertilizer applied, Y_{Ks} = yield without fertilizer applied, Y_{max} = maximum yield.

Figure 1. Relative accumulation of dry matter and potassium (K) in wheat, maize and sorghum grown to maturity in an Oxisol soil under controlled conditions in the glasshouse (Bell et al, unpublished). Maize shows the classic K accumulation curve that is well in advance of biomass in relative terms, with >80% of total K uptake occurring in the first third of the growing season (when relative biomass accumulation is only ~30%). Wheat shows a similar tendency, although relative K accumulation occurs less rapidly than in maize, while grain sorghum shows accumulation that more closely reflects the pattern of dry matter accumulation.



Differential Potassium-use Efficiency in Crops and Genotypes

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Abstract
Genotypic differences in efficiency of K use have been reported in all major crops, including wheat, barley, rice, maize, lucerne, beans, soybean, tomato, potato, sweet potato, canola, cotton, etc. The K-use efficient genotypes can have higher acquisition of K from soil (uptake efficiency) and/or higher dry matter production per unit of K taken up (utilisation efficiency).

Potassium uptake efficiency is governed by mechanisms relying on root architecture (eg. thin roots, long and abundant root hairs), the high uptake capacity at the root surface (eg. efficient high-affinity K influx) as well as the capacity to mobilise non-exchangeable K by root exudates (eg. carboxylates, amino acids). However, when a capacity of root cells to take up K exceeds the rate of K replenishment at the root surface, the uptake rate is governed by the K supply rather than by the capacity of plants to take K up, putting an emphasis on a large surface area of contact between roots and soil.

Genotypic differences in capacity to utilise potassium can be attributed to differences in the (i) partitioning and redistribution of K at a cellular or whole-plant level (eg. maintenance of cytosolic K concentration, allocation of K to the photosynthesising organs), (ii) substitution of K with other ions (eg. Na^+), and/or (iii) the partitioning of resources into the economic product (high K harvest index).

Breeding for increased K-use efficiency is dependent on (i) identification of suitable markers and (ii) compounding of various efficiency mechanisms into locally adapted germplasm. Using K-use efficient genotypes in combination with soil K fertilization is the optimal management strategy for effective K cycling in the soil-crop-stubble continuum to underpin resilient and sustainable farming systems.

INTRODUCTION

With a projected increase in human population to at least 9 billion by 2050, there is a pressing need to increase food production by up to 100% (Ray et al., 2013) by 2050. Given that most land suitable for food production has been used already for that purpose, this increase in food production will have to come from increasing yield on the land already in production. For such sustainable intensification of food production, efficient use of native soil nutrients as well as applied fertilizers is an important component.

Recently, there has been a strong emphasis on increasing nutrient-use efficiency in food production across the crops and countries/regions (eg. Jiao et al., 2016, Ma et al., 2015, Kerbiriou et al., 2014). Even though most attention was devoted to N and P, there was a substantial amount of research activity regarding K efficiency as well (eg. Shin, 2014, Trehan and Singh, 2013, White, 2013, Rengel and Damon, 2008).

The present review will focus on the mechanisms governing increased K-use efficiency in species and genotypes within species, concentrating on physiology and genetics of K uptake and utilisation.

POTASSIUM DEFICIENCY

Potassium deficiency significantly affects root growth and root architecture, including inhibiting primary root growth and stimulating root hair elongation (Zörb et al., 2014). Development of root hairs increases root surface area and, consequently, the radius of the K depletion zone.

Potassium deficiency influences a range of morphological, physiological, biochemical and molecular responses (Alka et al., 2013). It also results in alteration of the key signalling sequences such as reactive oxygen species (Hernandez et al., 2012), intracellular Ca^{2+} dynamics, phosphatidic acid and phytohomones (ethylene, auxin and jasmonic acid) (Takehisa et al., 2013). In rice, the leaf accumulation of K-deficiency-induced reactive oxygen species was mediated by an increase in ABA concentration (Liu et al., 2012).

Plants have a large range of potassium transporters differing in structure, K affinity and regulation (eg. Shaker-type, two-pore channels, potassium-permeable non-selective cation channels, etc.) (Cuin et al., 2008). Genes associated with ion transporters were markedly upregulated by K deficiency in Arabidopsis and rice (Ma et al., 2012), indicating importance of uptake responses to K deficiency. Cytokinin concentration decreased in Arabidopsis under K deficiency, resulting in increased accumulation of reactive oxygen species, enhanced root hair growth, and upregulation of HAK5 expression (high-affinity K uptake transporter gene) (Nam et al., 2012).

There were numerous differences in the transcriptome of K-deficient Arabidopsis (Ma et al., 2012), wheat (cf. Wang et al., 2012a) and rice (Alka et al., 2013) as well as between the K-efficient and K-inefficient wheat genotype grown under K deficiency (Ruan et al., 2015), indicating how powerful a signal K nutrition may be in regulating gene expression.

DIFFERENTIAL POTASSIUM-USE EFFICIENCY

Some plant species (eg. Trehan and Singh, 2013, Debasmita et al., 2010, White et al., 2012) and genotypes within species (eg. Damon and Rengel, 2007, Chen et al., 2014, Moreira et al., 2015, Fageria et al., 2015) have a capacity to grow and yield well on soils low in available K; these species and genotypes are considered K-efficient (Rengel and Damon, 2008).

K-efficient genotypes can have higher acquisition of K from soil (uptake efficiency) and/or higher dry matter production per unit of K taken up (utilisation efficiency). In Chinese cabbage, K uptake efficiency appear to be more important that K utilisation efficiency (Li et al., 2015), whereas both types of efficiency are important in the cotton (Chen et al., 2014) and sweet potato genotypes (Wang et al., 2015a). It is likely that the relative importance of K uptake and utilisation efficiencies would differ in various plant species grown under variety of experimental conditions.

MECHANISMS GOVERNING DIFFERENTIAL K-USE EFFICIENCY

Potassium Uptake Efficiency

Increased K uptake can be achieved either by increasing the root surface area to augment the soil-root contact or by increasing K uptake per unit of root surface area (Chen et al., 2015). In different crops, genotypic differences in either root morphology (eg. Zia ul and Muhammad, 2011) or root functional (uptake) efficiency (Li et al., 2015) can govern differential K-use efficiency.

Root Morphology

A larger root system is associated with the K-efficient compared with K-inefficient genotypes grown under K deficiency, eg. in cotton (Zia ul and Muhammad, 2011), Chinese cabbage (Li et al., 2015), etc. In rice, enlarging the root system by overexpression of a WUSCHEL-related homeobox gene WOX11 resulted in a 72% increase in K uptake and a 24-42% increase in grain yield under K deficiency (Chen et al., 2015).

Root Hairs

Root hairs contribute to K absorption by increasing the surface area, enhancing K depletion in the rhizosphere, and creating a steeper diffusion gradient with the bulk soil (see Rengel and Marschner, 2005) and therefore may have an important role in K-use efficiency (Debasmita et al., 2010). The capacity to

take up K from a low-K soil was positively correlated with root hair length for a range of legume and cereal crops as well as oilseed rape (*Brassica napus*) (Hogh-Jensen and Pedersen, 2003). In addition, genotypic differences in K-use efficiency were found to be related to root hair differences. For example, the K-use efficient cotton genotype had greater frequency and length of root hairs in comparison with the K-inefficient genotype (Tao et al., 2012).

Root Exudates

Crop species and genotypes differ in their capacity to acquire soil K due to differential quality and quantity of root exudates. The most important components in root exudates of the forage species crested wheatgrass (*Agropyron cristatum*) grown under K deficiency were organic acid anions, particularly malate (Henry et al., 2007). Root exudates from *Cucurbita pepo* subsp. *pepo* were more effective in increasing availability of soil K than those from *Cucurbita pepo* subsp. *ovifera*, mainly because of greater citrate content in the former (Gent et al., 2005).

Strawberry plants increased root exudation of phenolics (particularly ferulic acid, p-coumaric acid and cinnamic acid) under K deficiency (Cao et al., 2016), but it remained unclear whether these compounds could be involved in enhancing K uptake.

Kinetics of K Influx

Genotypic differences in the maximal rate of K influx were confirmed among crops (eg. sugar beet had greater K influx than wheat or maize, Debasmita et al., 2010) as well as among genotypes within a crop, eg. in rice (Sanes et al., 2013), cotton (Liaqat et al., 2010), etc. In *Brassica oleracea*, a QTL associated with increased K-use efficiency corresponded to an Arabidopsis chromosomal segment harbouring a range of K transporter genes (White et al., 2010), suggesting that differential K uptake may underpin differential K-use efficiency.

Perennial ryegrass (*Lolium perenne*) had between 2-fold (when phlogopite was a substrate) and up to 13-fold (in case of vermiculite) greater capacity to accumulate K than grain amaranth (*Amaranthus* sp.) (Wang et al., 2011). The main reasons were greater maximum rate of K uptake and lower minimal K concentration at which K uptake commenced in ryegrass than grain amaranth.

Potassium Utilisation Efficiency

Genotypic differences in capacity to utilise potassium can be attributed to differences in the (i) partitioning and redistribution of K at a cellular or whole-plant level, (ii) substitution of K with other ions, and/or (iii) the partitioning of resources into the economic product (see Rengel and Damon, 2008). The resource partitioning mechanism appears to be particularly important in differential K-use efficiency in rice (Yang et al., 2004), cotton (Xia et al., 2013), wheat (eg. Damon and Rengel, 2007) and sweet potato (*Ipomoea batatas*) (George et al., 2002). Efficient internal utilisation of K (promotion of photosynthesis, biosynthesis of proteins, phloem loading, etc.) can also underpin genotypic differences in K-use efficiency, eg. in cotton (Hua et al., 2009) and sweet potato (Wang et al., 2015a).

Potassium deficiency influences the efficiency of light absorption in the photosynthetic process in species as diverse as soybean grown hydroponically (Wang et al., 2015b) and the *Eucalyptus grandis* plantation forests (Christina et al., 2015). The K-efficient soybean genotype avoided damage to PSII and continued to grow under K deficiency, whereas the K-inefficient genotype had severely decreased growth as a consequence of impaired photosynthesis (Wang et al., 2015b).

BREEDING FOR ENHANCED K-USE EFFICIENCY

Breeding crops that acquire and/or utilise K more effectively is one strategy that could reduce the usage of K fertilizers (eg. Rengel and Damon, 2008). Using K-efficient genotypes in combination with

optimised soil fertilization is the optimal nutrient management strategy for stable and sustainable farming systems (Rengel and Damon, 2008).

Quantitative Trait loci (QTL) have been reported for a range of traits associated with K uptake, translocation and utilisation, including K concentration in bean grains (Blair et al., 2016), K uptake in rice (Khan et al., 2015), K concentration in rice roots and shoots (Wang et al., 2012b) or grain (Cho et al., 2010), accumulation of K in maize grain (Gu et al., 2015) or ear-leaf (Zdunic et al., 2014), K content in sugar beet pulp (Schwegler et al., 2014), seedling K content in wheat (Kong et al., 2013), etc. Importantly, specific QTL for K utilisation efficiency were reported in wheat (Gong et al., 2015, Guo et al., 2012).

Despite a plethora of QTL identified for various phenotypic traits and in various crops, major work of advancing that knowledge to practical breeding remains to be done because of instability of many QTL across the year x environment combinations as well as QTL scattering across the genome (eg. seven QTL associated with K concentration in rice grain were distributed over five chromosomes, Cho et al., 2010). Another difficulty is posed by the population dependence of QTL and molecular markers (eg. Cianzio, 1999). Nevertheless, it is expected that important practical steps toward producing crop genotypes and commercial cultivars with increased K-use efficiency will be made in the near future.

It is noteworthy that favourable alleles that contributed to increased K concentration in rice grains came from common wild rice *Oryza rufipogon* (Garcia-Oliveira et al., 2009), suggesting that wild relatives of crops might by an important source of genes to be used in increasing K-use efficiency of future cultivars.

CONCLUSIONS

Sustainable intensification of crop production in the future will increasingly rely on nutrient-efficient cultivars. New crop cultivars with increased K-use efficiency will underpin improved acquisition and utilisation of K in the soil-crop-stubble continuum. The QTL and molecular markers associated with enhanced K-use efficiency are expected to play an important part in breeding new K-efficient cultivars. However, complementary agricultural management practices will be required for genotypes with increased K efficiency to allow for the full economic benefit of improved germplasm.

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Stress Mitigating Effects of Potassium in Crop Plants

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Abstract
Potassium (K) deficiency is one of the commonly occurring mineral nutrient deficiencies in crop plants, especially on sandy, saline and acidic soils with high leaching capacity and Al toxicity risk. Potassium depletion in soils is also a growing issue in agricultural soils and represents a potential threat to crop production.

When plants are exposed to stressful conditions, K nutritional status of plants is becoming more important. Among the mineral nutrients, K is known for having particular roles in stress mitigation, and enabling crop plants to grow and survive better under stressful conditions by affecting diverse of physiological processes. Potassium has been also recognized as an important signaling factor contributing to adaptive response of crop plants to environmental stress conditions (Anschütz et al., 2014). In a previous study it has been shown that wheat plants supplied with increasing K had more or less similar photosynthesis rate under non-stressed conditions; but, when the plants under same growth conditions are exposed to drought stress, then the photosynthesis rate was significantly enhanced by increasing K supply (Sen Gupta et al., 1989). It was very obvious that an over-optimal supply of K was needed for the plants subjected to drought stress. Indeed, upon exposure to stress conditions, such as drought stress, cellular demand for K is increasing in crop plants (Cakmak, 2005). However, at the same time, root uptake of K might be seriously restricted in soils with low water supply due to impaired K diffusion. Therefore, a particular attention should be paid to K nutritional status of plants under growth conditions with limited water supply (Cakmak, 2005; Römheld and Kirkby, 2010).

Drought stress is, probably, the most common and serious abiotic stress factor limiting crop production, globally. With the rise in global temperature, drought together with heat stress will be more common and intense, resulting in further impairments in crop production. Estimated losses in yield capacity of crop plants through abiotic stress factors are huge, being over 80 % in case of wheat (Bray et al., 2000). Drought stress may occur during all growth stages of plants; but more commonly and severely during the grain filling stage and often in combination with heat stress. During post-anthesis stage, soils are most commonly low in moisture due to erratic or very little rainfall and extensive water evaporation from soil. When plants suffer from drought or heat stress during the grain filling period, leaf chlorosis (earlier senescence) starts, photosynthetic capacity of plants diminishes and transportation of carbohydrates in the grains is declined. Normally, the grain filling and final grain yield depend on the current photosynthesis and remobilization of reserve carbohydrates from the vegetative organs. Under drought stress conditions, the contribution of the current photosynthesis to grain filling is known to be very minimal, and grain filling is, therefore, more dependent on the pool and remobilization of reserves. Reserve carbohydrates in plant tissues are considered as an important factor in buffering grain yield against stress conditions such as drought and heat. Number of published evidence show that reserve carbohydrates may contribute up to 60 % of final grain yield under drought stress. An adequate K nutrition may play a critical role in accumulation of carbohydrate reserves in vegetative tissue and remobilization of those reserves into grain under stress conditions. This paper will introduce a new concept contributing to better understanding of the stress mitigating effects of K in crop plants, and highlight that a good K nutrition of crop plants is needed during the post-anthesis period for better grain filling and grain yield under drought and heat stress.

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Restricted CO_2 Diffusion through the Leaf Mesophyll and not Stomatal Regulation Limits Photosynthesis in K Deficient Crop Plants

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Abstract

Potassium (K) is the major inorganic solute in plants and is crucially involved in osmoregulation, cell growth and stomatal movement. A major physiological effect of low K availability is the impairment of net CO_2 assimilation (A_N) during photosynthesis, which results in a reduction of crop growth and can lead to substantial yield losses. The fact that K is required for the opening of stomata has strongly contributed to the general opinion that K deficiency results in an inhibition of stomatal guard cell control, decreasing the rate of CO_2 diffusion from the atmosphere into leaves and thus posing the major limitation to photosynthesis. However, recent studies revealed that not stomata but rather the capacity of the leaf mesophyll to conduct CO_2 from the intercellular airspace into chloroplasts causes a substrate limitation to photosynthesis in K deficient plants. Furthermore, K deficiency can impair photochemical and biochemical reactions associated with photosynthesis. We quantified the contribution of photochemical energy conversion (i.e., maxiumum PSII quantum yield F_v/F_m) and biochemical capacity (*i.e.*, RubisCO activity $V_{c,max}$) as well as stomatal and mesophyll CO_2 conductance (g_s and g_m) to the overall limitations of photosynthesis in sunflower, which was grown in nutrient solution under various levels of K supply. A_N, g_s, g_m and $V_{c,max}$ were calculated from photosynthetic leaf gas exchange and F_v/F_m was determined *via* chlorophyll fluorescence imaging. Photochemistry was only impaired when severe K deficiency caused chlorosis. We could demonstrate that the inhibition of photosynthesis in K deficient sunflower was initiated by a significant reduction of g_m, but there was no effect of K supply on stomatal regulation. RubisCO activity additionally decreased when reduced g_m caused low substrate availability in chloroplasts. The study clearly shows that substrate limitation to photosynthesis is caused by impeded mesophyll diffusion of CO_2, most likely initiated by alterations in leaf anatomy. Reduction of g_s under K deficiency is thus an adaptation to low CO_2 utilization by photosynthesis, and stomatal functioning is maintained.

Crop Stress Determines Response of Wheat (Triticum aestivum) to Potassium Fertiliser in a Mediterranean Climate

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Abstract

In the Southwest of West Australia (SWWA), depending on the crop sensitivity, low K soils represent 7-50 % of the cropping area. Rates of K fertiliser application are generally below rates of K removal in grain and hay. In this environment with a Mediterranean climate, drought and frost are common crop stresses. Our aim was to determine whether crop response to K fertiliser was influenced by crop stress. Over a 5-year period, 17 experiments were conducted with 3- 5 rates of K from 0 to 120 kg K/ha. Soil test K by the sodium bicarbonate extraction (Colwell) ranged from 22-140 mg/kg in the 0-10 cm layer. Eight of the sites had Colwell K > 40-45 mg/kg which is the critical range for wheat. Response to K occurred on 9 sites where drought or frost was recorded, but not otherwise. The critical soil test Colwell K level in 0-10 cm or 0-30 cm depths did not predict which sites gave a K fertiliser response. In this environment, leaf K is high during early growth but declines over time, possibly due to low soil K buffering, leaching of K, dryness of surface soils coupled with K stratification close to the soil surface under no-till planting. In addition, both frost and drought stress may coincide with the decline in leaf K. We conclude that K fertiliser provides added protection for cereal crops against crop stress from drought and frost in the mediterranean climate of SWWA.

Elevated Potassium Fertilization Improves Wheat Growth and Yield under Salt Stress

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Abstract
Accumulation of soluble salts in agricultural land only causes osmotic stress, while exchangeable sodium (Na^+) and chloride cause ion toxicity in plants as well. The nutritional disorders in plants, especially reduced uptake of potassium (K^+), has been reported under saline-sodic conditions. Sodium directly competes with K^+ to be taken up by plants. Higher concentration of Na^+ in nutrient medium decreases K^+ uptake and increase Na^+ uptake by plants. Therefore, under salt stress K^+/Na^+ ratio in plant tissue is decreased affecting metabolic activities in plant cell disturbing the enzyme activation, osmoregulation and charge balance. To compete with higher Na^+ concentration in nutrient medium, elevated K-fertilization under Na^+ stress may improve the K^+/Na^+ ratio in plant tissue improving plant metabolism under salt-stress conditions. In this study, the effects of elevated K-fertilization on wheat crop growth, Na^+ and K^+ homeostasis in wheat plant and grain yield under Na^+ stress was determined. It was found that plant growth, physio-chemical attributes and yield was significantly reduced under Na^+ stress and elevated K fertilization improved grain yield by improving K^+/Na^+ ratio in plant tissue. Increased wheat grain yield may also be attributed to improved photosynthetic activity and better water regulation. Wheat growth was reduced at highest level of K fertilization, which may be owing to plants' efforts to stand against high solute concentration in plant tissue. In conclusion, elevated K^+ application could enhance wheat growth and grain yield by mitigating the deleterious effects of Na^+ toxicity, however elevated K fertilization level may not be well responded by vegetative-growth due to increased soluble salts (K^++Na^+) concentration in shoot. Nevertheless, grain yield showed more renounced comeback to higher K levels.

INTRODUCTION

Improved and innovative agricultural practices are the potential source of food production to combat the world crisis of food security owing to ever-decreasing agricultural resources. There is a need to increase the 50% of food production by 2050 to feed the fast-growing population (Rengasamy 2006). Expansion of agricultural land has great economic and environmental concerns, therefore better management and innovation in existing agricultural resources is, perhaps, the only choice to achieve the food production targets.

Salt stress is one of the major stresses mainly caused by irrigation with brackish water and/or by inherited land resources, limiting crop productivity in arid and semi-arid region of the world (Shannon 1994). It is estimated that 20% of the agricultural land worldwide is salt-affected which is about 8×10^8 ha contributing 6% of total land area (Yan 2008). Deleterious effects of salt stress can be categorized in an osmotic phase, which inhibit plant growth due to osmotic stress and an ionic phase in which toxic concentrations of ions deteriorate the plant growth (Munns & Tester, 2008). Salt stress also cause nutritional imbalance of essential elements, especially potassium (K^+), through reducing its uptake by plants (Wakeel 2013).

Potassium uptake by plant cell is mediated by transporters located in the plasma membrane via two mechanisms called as high-affinity transport system (HATS) and a channel-mediated low-affinity transport system (LATS; Epstein, Rains & Elzam 1963). Schachtman & Schroeder (1994) stated that high-affinity K^+ uptake is mediated either by TaHKT1 transporter in wheat or the KT/HAK/KUP family such as the HvHAK1 in barley (Santa-Maria, Danna & Czibener 2000) at low external K^+ concentrations (~0.2 mM). HKT1 is a high affinity K^+ transporter, however is also involved in high-affinity Na^+ uptake in wheat (Rubio, Gassmann & Schroeder 1995). Similarly, AtHKT1 and OsHKT1 (Horie et al. 2007) mediate low affinity Na^+ uptake by arabidopsis and rice plants, respectively. There are several other studies which have explained the Na^+ uptake through K^+ transporters. Furthermore, the Na^+ influx through nonselective cation channels (NSCCs) under saline conditions has also been reported (Kronzucker & Britto 2011).

Higher Na^+ concentration in nutrient medium decrease the K^+/Na^+ ratio in plant tissue competing with K^+ at plasma membrane to be taken up through HKT and NSCC. Na^+ entry into the cell also cause membrane depolarization increasing the leakage of K^+ through activation of outward K-rectifying channels (KOR) (Shabala et al. 2005). Briefly, K^+ has strong interaction with Na^+ for its uptake, translocation, absorption and sequestration into the vacuole (Wakeel et al. 2011). Wakeel (2013) reported that elevated application of K fertilizers may improve its uptake minimizing the Na^+ uptake under salt stress (high Na^+ concentration) conditions and consequently reducing Na^+ toxicity in second phase of salt stress. Furthermore, K also ameliorate plant growth during first phase of salt stress due to its ability of better osmotic adjustments (Nelson 1978). Nevertheless, homeostasis of intracellular K^+/Na^+ maintenance is a critical mechanism for growth and development of plant. Thus, it was hypothesized that application of K fertilizer increased K^+: Na^+ and improve grain yield by improving physiochemical processes in wheat plant under saline-sodic conditions.

MATERIALS AND METHODS

A hydroponic study was conducted in a green house, at the University of Agriculture Faisalabad, Pakistan using wheat (*Triticum aestivum* L., *cv*. Faislabad-2008) as test crop. Seeds were sown in polythene lined steel trays filled with washed sand irrigated with distilled water. After germination in dark, trays were placed in wire house for 15 days to establish the nursery. Seedlings of uniform size were transplanted in foam-plugged holes of polystyrene sheets in 1/2 strength solution [N (4 mM as KNO_3), K (2.2 mM as K_2SO_4), P (0.2 mM as KH_2PO_4), Mg (0.6 mM as $MgSO_4$), Ca (4.0 mM as $Ca(NO_3)_2$), Mn (2.0 µM as $MnCl_2$). Zn (0.5 µM as $ZnSO_4$), Cu (0.3 µM as $CuSO_4$), B (10.0 µM as H_3BO_3), Mo (0.01 µM as $(NH_4)Mo_7O_{24}$), and Fe (0.2 µM as Fe-EDTA)] (Saqib, Zoerb & Schubert 2006). After three days, plants were transferred to the pots having full strength nutrient solution.

Experiment comprised of different levels of K^+ and NaCl. Along with recommended K^+ level (2.2 mM) two higher levels of K^+ (4.4 and 8.8 mM K^+) were established using K_2SO_4, whereas salinity levels were 60 and 120 mM Na^+ along with control having 1 mM Na^+ using NaCl. There were eight replications for each treatment. Seven days after transplantation, salt stress was imposed at 30 mM Na^+ day^{-1} increment to avoid stress shock to plants. The nutrient solutions were changed after every 3 days. Each treatment has eight replications. During first harvest, half of the replications were harvested at vegetative growth just before booting (70 days after sowing) to determine the growth and biochemical parameters, while second harvest was done at maturity when other half replications were harvested to get grain yield data.

Measurement of Physiological, Biochemical, Growth and Yield Parameters

Photosynthetic rate was measured by using the portable infra-red gas analyzer [IRGA (LCA-4)] at 6 weeks after transplanting. These parameters were taken in the morning (08.00-10.00 a.m.) at photosynthetic photon flux density of 1200-1400 µ mol $m^{-2}s^{-1}$ (Ben-Asher et al. 2006). Third fully-expanded leaf from one plant in each replication were selected for the measurement of the data regarding above parameters. At the same stage leaf-osmotic potential was measured by using osmometer (Osmomat

010 Gonatec GMBH.D 10823 Berlin Germany) according to the method of Capell & Doerffling (1993). The water potential of leaf was recorded by a pressure bomb (Scholander et al. 1965). After harvesting, shoot fresh and dry weight was measured using digital balance. Plant samples were air dried and finally kept in oven at 80 °C till constant dry weight was obtained, while other half were kept at -20 °C for enzymatic analyses. Oven-dried plant material was wet-digested by using HNO_3-$HClO_4$ solution to measure Na^+ and K^+ concentrations using Sherwood 360 Flame Photometer (Rashid, 1986). For grain yield, at maturity grains were separated from straw and weighed separately.

Means of four replications were taken for each treatment and statistical significance was calculated by ANOVA using Statistix 8.1 (Analytical Software 2005).

RESULTS

Plant growth

Salt stress significantly reduced the shoot and root dry weight of wheat plants and minimum shoot and root weight was found at 120 mM NaCl stress (Figure 1). Application of elevated levels of K fertilizer (4.4 and 8.8 mM) significantly increased root dry weight as compared to control (2.2 mM K^+), but shoot dry weight did not show significant increase by elevated K fertilizers at 120 mM NaCl. Nevertheless 4.4 mM K^+ at 60 mM NaCl treatment showed significant increase in dry shoot matter. Interestingly, overall highest root dry weight was obtained at 4.4 mM K^+ level at 1 mM NaCl, as well as at 60 mM NaCl and 120 mM NaCl. Higher K fertilization level (8.8 mM K^+) did not produce the highest shoot and root mass. The relative increase due to elevated potassium fertilizers was more at higher salinity levels.

Physiological and water relation parameters

Salt stress significantly reduced the photosynthetic rate, while application of elevated levels of K^+ i.e. 4.4 and 8.8 mM, significantly ameliorated it (Table 1). Maximum photosynthetic rate was observed in not-stressed conditions at 8.8 mM K^+ application, whereas minimum value was observed in 120 mM salt-stressed plants when K level in the nutrient solution was 2.2 mM.

Salt stress lowered the water potential (Ψ_w) in the plant tissue by reducing solute potential (Ψ_s), however pressure potential (Ψ_p) was increased keeping the plants turgid. Application of elevated K^+ fertilizer level under salt stress further increased the Ψ_s as well as Ψ_p probably due to increased uptake of K^+ by plants (Table 1). Maximum water potential was 1.99 MPa in 120 mM salt stressed plants at 8.8 mM K^+ level, whereas minimum was 1.33 MPa in control at 2.2 mM K^+ levels. The differences of Ψ_w, Ψ_s and Ψ_p in all treatments were significant at $p \leq 0.05$. As the Na^+ in plant tissue was replace by K^+ (even higher concentration than Na^+), therefore the impact of elevated K fertilization on water potential is positive.

Na^+ and K^+ concentrations in root and shoot

As the plants were stressed with 60 and 120 mM NaCl, the Na^+ concentration in shoot and root of wheat were significantly (≤ 0.05) increased (Table 2). Application of elevated levels of K^+ significantly reduced the Na^+ concentrations in shoot as well as in root. Maximum Na^+ concentration, 3.79 mg g^{-1} was observed at 120 mM NaCl stress in shoot at low K fertilization (2.2 mM K^+) and increase in K^+ level up to 8.8 mM in nutrient medium reduced the Na^+ concentration to 3.28 mg g^{-1} in shoot.

The concentration of K^+ was significantly (≤ 0.05) reduced in root and shoot, when plants were stressed with 60 and 120 mM NaCl. Elevated K^+ levels (4.4 and 8.8 mM K^+) in nutrient solution increased K^+ concentration in shoot and root of wheat plant. The increase in K^+ concentration due to elevated K levels (8.8 mM K) at 120 mM NaCl stress was from 17.8 mg g^{-1} to 23.62 mg g^{-1} dry mass (Table 2).

Wheat grain yield

The 1000 grains weight and total grain yield per pot was decreased with similar trend. Nevertheless, application of elevated levels of K^+ fertilizer significantly improved 1000 grains weight and total grain

yield under normal and as well as both salt stress levels. At 60 mM NaCl salt stress, 16.8% increase in 1000 grain weight was observed when 8.8 mM K^+ was applied, while 18.4% increase was observed at 120 mM NaCl at highest K^+ level (8.8 mM K^+) compared to control with 2.2 mM K^+ within the respective salt tress level (Figure 2).

DISCUSSION

Salt stress causes osmotic stress in plants which is major factor in reducing growth during first phase and accumulation of higher amount of Na^+ reduced plant growth due to its toxicity in the second phase of salt stress (Munns 2005). Azeem & Ahmad (2011) reported that increased Na^+ uptake and its accumulation in plant tissue caused nutrient imbalance in the plants minimizing the uptake of other nutrients specially K^+ in sunflower (Akram, Athar & Ashraf 2007), canola (Ulfat et al. 2007), cabbage (Jamil et al. 2007) and in wheat (Raza, Athar & Ashraf 2006). Reduced K^+ uptake by plants under salt stress causes the K^+ reduction in shoot as well as in root (Table 2). The other reason for growth reduction under salt stress may be due to ion toxicity owing to accumulation of Na^+ decreasing metabolic activities (Zhu 2002; Table 2). However, at first harvesting Na^+ toxicity symptoms were not clear on plant shoot. Helal & Mengel (1979) also investigated that under saline or sodic condition, K^+ and Na^+ homeostasis shows decisive role in plant growth.

Although water potential was improved by elevated K^+ fertilization during first phase of salt stress, however plant shoot dry weight was not significantly increased. In fact, increased solute (K^++Na^+) concentration (Table 2), at elevated K^+ levels in shoot, improved shoot water-content but not the dry matter. The reason for indistinguishable effect of elevated K fertilization on growth has been explained that the plant utilize energy to produce organic molecules in cytoplasm to adjust the osmotic balance between vacuole and cytoplasm reducing the dry mass production (Taiz & Zeiger 2006). The better water uptake can be beneficial during first phase of salt stress. Whereas better photosynthetic rate may be attributed to better stomatal regulation and enzymatic activities.

Decreased K^+ concentration because of salt stress was improved at elevated K^+ fertilization levels and may be attributed to the enhanced photosynthetic rate and improved metabolic activities in plants (Sun et al. 2011). Hussain et al. (2013) also reported decrease in Na^+ concentration in shoot by application of K_2SO_4 to mitigate Na^+ toxicity in plants under saline and saline-sodic soils. Application of K^+ decreased Na^+ and increased K^+ in leaf and improved K^+/Na^+ ratio may be responsible for improved grain yield under salt stress conditions (Zhu et al. 2016; Table 2).

Elevated K^+ application showed clear improvement in increase in 1000 grain weight and yield in wheat (Sharif & Hussain 1993; Figure 2). The significantly increased grain yield in present study can be credited to the K^+ concentration (Table 2) in shoot and then to an ultimately sugar translocation into the grains due to a phloem loading. Similarly, supplemental K^+ enhanced grain yield of rice too (Bohra & Doerffing 1993).

The increased K^+/Na^+ ratio cannot be translated to plant growth immediately because increased K^++Na^+ concentration in shoot probably increase the metabolic activities against the increased solute concentration in the plant tissue. Nevertheless, clear effects of K fertilization can be seen later on grain yield formation may be due to adaptability of tissue to high solute concentration in tissue, decreased Na^+ toxicity and increase sugar translocation to reproductive part. Therefore, it can be concluded that elevated K^+ nutrition under salt stress mitigates the second phase of salt stress by reducing Na^+ toxicity in plant shoot and improve the grain yield in wheat.

ACKNOWLEDGEMENTS
Prof. Konrad Mengel (Late) is acknowledged because of many thought provoking discussions on this issue, which were the base to plan this study. The financial support from Higher Education Commission Pakistan is acknowledged.

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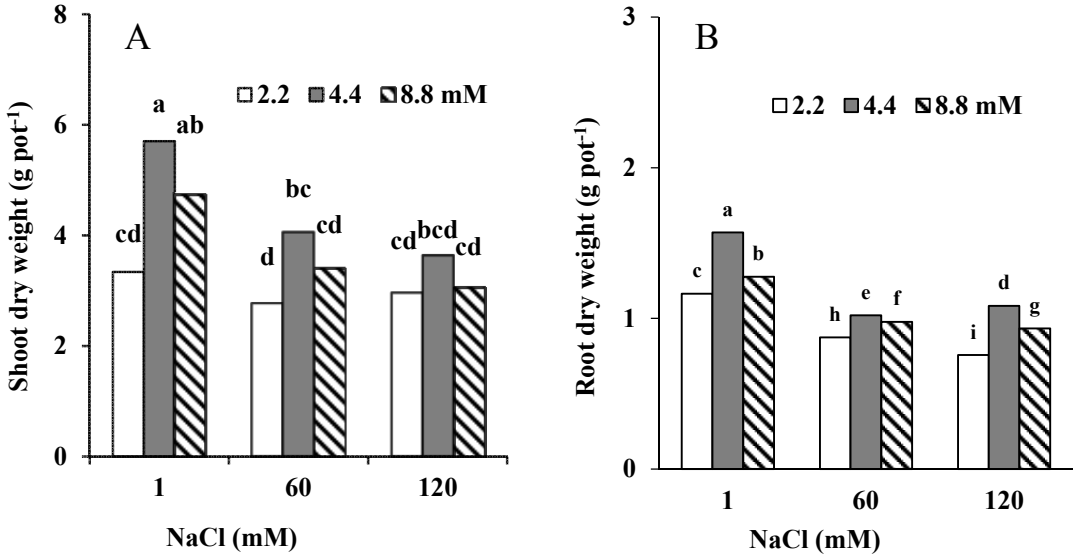

Figure 1: Effect of elevated K^+-fertilization on **(A)** shoot dry weight and **(B)** root dry weight of wheat under salt stress in hydroponic. Columns represent the mean of four replicates and columns not sharing a letter differs significantly at 5% probability by LSD test.

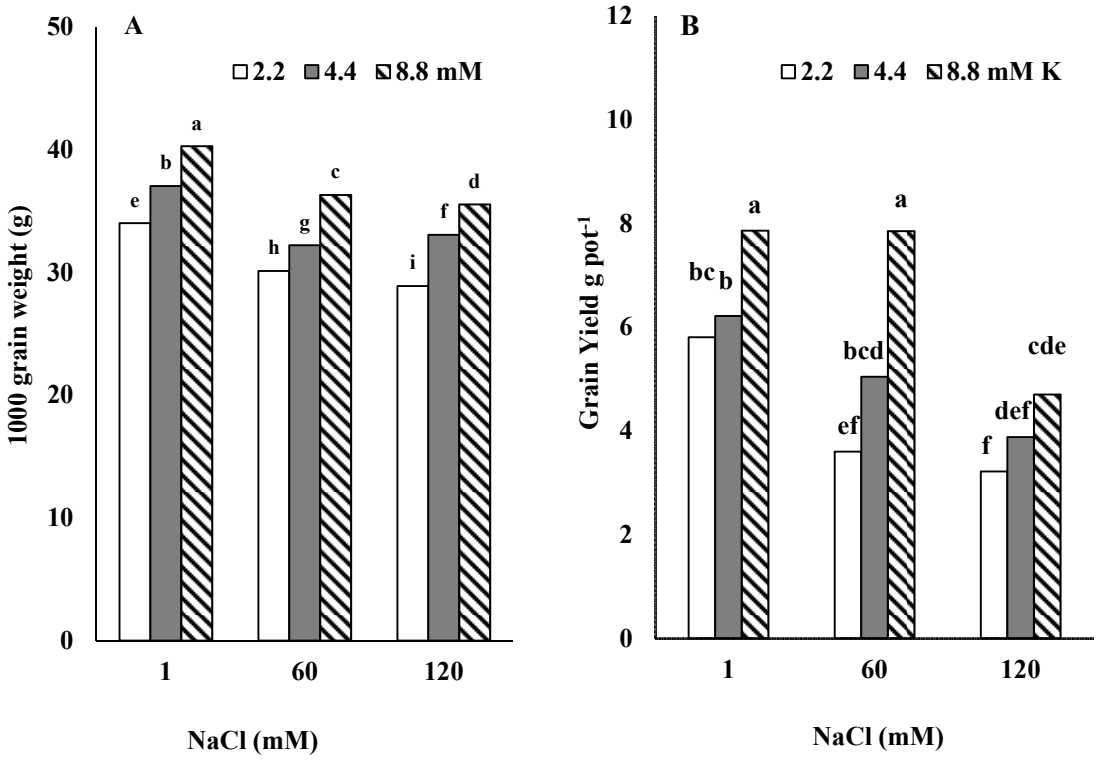

Figure 2: Effect of elevated K^+ fertilization on **(A)** 1000 grain weight (g) and **(B)** yield of wheat under salt stress. Columns represent the mean of four replicates and columns not sharing a letter differs significantly at 5% probability by LSD test.

Table 1: Effect of elevated K application on photosynthetic rate (A), osmotic, water and pressure potential (Mpa) of wheat under salt stress

		Photosynthetic rate (A)	Osmotic potential	Water potential	Pressure potential
NaCl (mM)	**K (mM)**	**(µmol CO_2 m^{-2} s^{-1})**	**(-Mpa)**	**(-Mpa)**	**(-Mpa)**
1	**2.2**	17 bc ± 0.6	0.30 h ± 0.03	1.33 i ± 0.02	1.60 g ± 0.04
	4.4	18 ab ± 0.3	0.49 g ± 0.01	1.58 f ± 0.01	2.07 f ± 0.01
	8.8	19 a ± 0.2	0.71 e ± 0.03	1.79 c ± 0.01	2.49 d ± 0.03
60	**2.2**	14 ef ± 0.7	0.58 f ± 0.01	1.44 h ± 0.01	2.02 f ± 0.01
	4.4	15 de ± 0.6	0.85 c ± 0.01	1.66 e ± 0.01	2.51 d ± 0.02
	8.8	16 cd ± 0.6	0.93 b ±0.01	1.86 b ± 0.01	2.79 b ± 0.01
120	**2.2**	13 f ± 0.9	0.76 d ± 0.02	1.54 g ± 0.01	2.29 e ± 0.01
	4.4	14 ef ± 0.9	0.96 b ± 0.01	1.72 d ± 0.01	2.67 c ± 0.01
	8.8	16 cd ± 0.6	1.16 a ± 0.01	1.99 a ± 0.01	3.14 a ± 0.01

± S.E, Gas exchange and water relation parameters were collected. Each value is average of 4 replicates

Table 2: Effect of elevated K application on Na^+ and K^+ concentration (mg g^{-1}) in shoot and root of wheat under salt stress

NaCl (mM)	K (mM)	Na^+ in shoot (mg g^{-1})	Na^+ in root (mg g^{-1})	K^+ in shoot (mg g^{-1})	K^+ in root (mg g^{-1})
1	2.2	2.44 e ± 0.05	2.02 cd ± 0.03	22.06 d ± 0.21	17.93 d ± 0.19
	4.4	2.26 f ± 0.02	1.78 e ± 0.04	24.54 b ± 0.20	19.58 bc ± 0.18
	8.8	2.12 g ± 0.04	1.42 f ± 0.06	26.78 a ± 0.09	21.35 a ± 0.21
60	2.2	3.43 b ± 0.03	2.37 b ± 0.03	19.93 f ± 0.18	17.10 e ± 0.18
	4.4	3.19 c ± 0.02	2.03 c ± 0.02	23.03 c ± 0.24	19.11 c ± 0.15
	8.8	2.89 d ± 0.04	1.78 e ± 0.03	24.92 b ± 0.20	20.88 a ± 0.11
120	2.2	3.79 a ± 0.02	2.76 a ± 0.02	17.81 g ± 0.23	15.57 f ± 0.31
	4.4	3.48 b ± 0.01	2.39 b ± 0.04	21.23 e ± 0.25	17.49 de ± 0.20
	8.8	3.28 c ± 0.01	1.93 d ± 0.02	23.62 c ± 0.12	19.73 b ± 0.12

± S.E, Na^+ and K^+ concentration in shoot and root were collected. Each value is average of 4 replicates

Enhancement of Germination by Application of Potassium to Tomato Seeds Grown in High Salinity Media

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Abstract
Germination of tomato seeds (*Lycopersicon esculentum* Mill) is a critical factor influencing seedling establishment when seeded directly in fields. The goal of this current study was to develop techniques by adding different concentrations of KNO_3 that may improve seed germination. Tomato seeds (Cv. super Strain B) sawn under salinity of 6000 ppm NaCl, were subjected to five levels of potassium nitrate namely (0, 500, 1000, 1500, and 2000 ppm KNO_3) in petri dishes at 25 °C. This study was conducted in growth chambers at the Faculty of Agriculture and Veterinary Medicine, Qassim University, Kingdom of Saudi Arabia during March 2015. After 14 days, germination percentage was significantly reduced under salinity treatments. Results revealed that at 0 ppm KNO_3, 27% of seeds were emerged, while germination was enhanced significantly at both 1500 and 2000 ppm KNO_3 concentrations to record 77% for both treatments. It was clear that as the K level increased, the seed germination was enhanced. These results indicate that potassium can be used to alleviate salt-induced toxic limitations in tomato plants and improve survival under salt stress conditions.

Key words: Tomato (*Lycopersicon esculentum L.)*, seed germination, salt stress, potassium nitrate, calcium nitrate, growth chambers. NaCl. KNO3.

Soil Shear Stability at the Microscale as Affected by Long-term Potassium Fertilization

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Abstract
Soil stability is determined by the ratio and interaction of the soil's three phases: solid, liquid and gaseous. Fertilizer application alters the chemical properties of the soil solution. A higher concentration of dissolved ions in the soil solution not only affects its osmotic potential but also influences particle-particle interaction via the alteration of electrostatic equilibria. At first glance, potassium might not be considered favorable for soil structure due to the dispersive effect of monovalent cations. However, in the past, a stabilizing effect of potassium has been observed in micro shear tests. In order to determine the impact of potassium fertilization on various levels of soil stability, differently textured soil samples from several long-term potassium fertilization trials in Germany were investigated regarding zeta potential and the amount of readily dispersible clay (RDC). In addition, micro shear tests were conducted in a rheometer at varying matric potentials, accounting for the relevance of soil structure by using both homogenized and undisturbed soil material. Results show that even though zeta potential measurements suggest a shift to less repulsive forces as a result of more intensive potassium fertilization, the amount of RDC increases. Micro shear tests reveal a texture as well as structure dependent reaction of soils with increased fertilization: Undisturbed silt loam is destabilized by potassium, while the homogenized material undergoes stabilization at a moderate fertilization intensity when drained sufficiently. For undisturbed loamy fine sand, the highest values of shear stability are measured at a moderate potassium fertilization intensity but the homogenized sandy material is destabilized by potassium. Further insights regarding the relevance of the chemical properties of the soil solution for soil stability are expected by ongoing measurements as chemical ion exchange processes depending on the valency or concentration are also responsible for differences in soil mechanical strengthening and hydraulic functions.

INTRODUCTION
The ratio and interaction of the solid, liquid and gaseous phases determine the soil's stability. On the one hand, the grain size distribution defines the intensity of swelling and shrinkage and results in the development of soil structure via aggregation. In addition, soil organic matter (SOM) acts as a binding agent strengthening the previously formed aggregates. These factors determine the pore volume and its size distribution. The ratio of solid and liquid phase changes over time. Soil strengthening and the corresponding aggregate formation depend on the formation of water menisci as they enhance soil stability by the contraction of particles and an increased cohesion (Horn & Smucker 2005). However, drainage can only result in stabilization as long as the solid-liquid surface area is large enough to exert the contracting force (Hartge & Horn 2014). Slightly drained sand quickly loses its stability upon further drainage. If the soil is subject to loading exceeding the precompression stress, the pore volume is diminished, forcing pore water to redistribute. In case pores are blocked or if the hydraulic conductivity is not sufficiently high, positive pore water pressure occurs as a result of the incompressibility of water, rendering the soil unable to withstand any shear stress and leading to aggregate disintegration up to complete homogenization. Homogenized soil also exhibits aggregate formation due to shrinkage induced particle contraction but these aggregates are certainly more susceptible to vertical and/or shear stress (Baumgartl 1991; Hartge & Horn 2014; Horn & Dexter 1989; Horn et al. 1994; Horn, Way & Rostek 2003). These processes have been excessively described in the past, however, in recent years, processes taking place at the microscale have come into focus. Rheometry has been established as a tool to

investigate particle interaction at the microscale for different drainage levels in homogenized (Ghezzehei & Or 2001; Holthusen, Peth & Horn 2010; Markgraf 2006; Stoppe 2015) and even structured (Holthusen et al. 2012a) soil material. These methods could also elucidate the strengthening effect of type and concentration of ions adsorbed to soil particles and dissolved in the soil solution as chemical equilibria are altered causing either repulsive or attractive forces between particles. The strengthening – or weakening – of existing micro-, meso-, or macroscale aggregates by the addition of organic or inorganic matter as fertilizer is based on these changes in soil solution composition, too. Particle interactions can be described by the zeta potential, which represents the electrical potential located at the shear plane of a particle in suspension moving in an electric field. The part of the suspension inside the shear plane is electrostatically bound to the particle tightly enough to determine its behavior towards other particles or in an applied electric field (Hunter 1988; Stumm 1992). Apart from the alteration of electrostatic equilibria, flow properties of the soil solution such as surface tension and viscosity may be affected by fertilizer ions (Holthusen et al. 2012b). When it comes to soil (shear) stability, potassium might not be considered favorable due to the dispersive effect of monovalent cations but in fact, Markgraf & Horn (2006a) as well as Holthusen, Peth & Horn (2010) found a positive influence of K^+ on soil microstructural stability. In order to explain these findings, investigations of the effect of potassium on various stages of particle interaction have been conducted and will be shown in the following.

MATERIAL AND METHODS

Characterization of the Investigated Soil Material

Disturbed as well as undisturbed soil material was sampled from topsoils of two long-term potassium fertilization trials in Germany. One of them is conducted on a Chernozem derived from loess in Bernburg (BB), the other one on a Podzol derived from weichselian glacial outwash in Hodenhagen (HH). Standard soil analyses were performed according to the methods described in Blume, Stahr & Leinweber (2011) and are listed in Table 1.

A Brief Remark on the Conducted Measurements

The applied methods are supposed to allow for a distinction between effects of drainage (menisci forces) and physicochemical effects (attractive/repulsive forces). While particle interaction as a result of both, drainage and physicochemistry, is revealed by rheometry, zeta potential and readily dispersible clay allow for a quantification of physicochemical interaction (Fig.1).

Chemical Properties of the Soil Solution

Cation composition (via atomic absorption spectroscopy) was measured in a saturation extract that was produced according to Blume, Stahr & Leinweber (2011).

Zeta Potential

The zeta potential, located at the shear plane of a suspended particle moving in an electric field (Hunter 1988) is a measure for attractive and repulsive forces between particles. It was measured electrophoretically with a ZetaPALS (Brookhaven Instruments Corp., Holtsville, NY USA). 10 mg of air-dried and sieved (< 2 mm) soil were dispersed in 10 ml of ultrapure water in an ultrasonic bath. After 24 h of equilibration, the dispersion was ultrasonicated again. 1.5 ml were pipetted into a small cuvette and – together with the measuring cell – inserted into the ZetaPALS.

Readily Dispersible Clay

The turbidity of a soil suspension, representing the amount of readily dispersible clay (RDC), was measured in a 2100AN IS Laboratory Turbidimeter (ISO7072; Hach, USA). The measurement is conducted according to Dexter et al. (2011) and Voelkner, Holthusen & Horn (2015). The turbidity of the suspension is measured and displayed in Nephelometric Turbidity Units, NTU [g L^{-1}]. As the turbidity is a function of the mass concentration of particles in the suspension, the mass of dry soil particles in the plastic bottle is calculated via Eq. 1

$$M_d = \frac{M_m}{1+w} \quad (1)$$

with dry (M_d) and moist (M_m) mass of the weighed in soil material and the gravimetric water content w, which is determined by oven-drying an additional subsample of the material at 105°C. The measured turbidity is finally normalized accounting for the initial water content and mass of soil in the plastic bottle using Eq. 2.

$$Normalized\ turbidity\ NTU_{norm} = \frac{NTU\ [g\ L^{-1}]}{M_d\ [g\ L^{-1}]} \quad (2)$$

Rheometry

Preparation of Soil Samples for Rheometry

In order to reveal the effect of fertilization as well as drainage on soil structure and resulting changes in soil micro stability, samples were prepared from both homogenized and undisturbed soil material. For the homogenized version, air-dried material was sieved < 2 mm and moistened to obtain a gravimetric water content of approximately 10 %. After overnight equilibration, the soil was manually repacked into small cylinders (0.9 cm high and 3.6 cm in diameter) at a defined bulk density of 1.4 g cm^{-3}. The samples with intact soil structure were carefully cut out from larger soil cores and transferred to the same small cylinders.

The samples were saturated with purified water by capillary rise before five replications of each fertilization intensity were drained to a matric potential of -6 and -15 kPa, respectively. Just prior to the measurement, each sample was trimmed to a height of 4.5 mm and a diameter of 2.5 cm in order to fit into the measuring gap of the rheometer. The part of the sample that is removed in the course of trimming is used to detect its water content prior to the measurement by oven-drying the material at 105°C for 16 h.

Rheological Measurements

The soil samples were carefully placed in a rheometer MCR 300 (Anton Paar, Stuttgart, Germany) with a 2.5 cm profiled parallel plate measuring system. In order to determine the soil's response to shear stress, an amplitude sweep test (AST) with controlled shear deformation was conducted. Here, the sample to be tested is enclosed between a fixed lower plate and the upper measuring bob which is moving in an oscillating manner with increasing amplitude at a constant frequency of 0.5 Hz. The deformation ranging from 10^{-4} to 100 % is related to the height of the measuring gap, resulting in a maximum deflection of the upper plate of 4 cm in both directions at the end of the test. A constant temperature is maintained by a Peltier unit. Fig. 2 shows a representative depiction of possible results of such a test.

While the deformation is applied via the deflection of the upper plate against the fixed lower one, the torque M needed to achieve the desired deformation is logged by the software and used to calculate the shear stress τ according to Eq. 3 (Holthusen, Peth & Horn 2010)

$$\tau(t, M) = \frac{2M}{\pi r^3} \quad (3)$$

with radius r of the oscillating upper plate. It represents the capability of the soil to withstand deformation, making it possible to compare data from rheological measurements to those collected in frame shear tests (Holthusen et al. 2012c). Furthermore, from the given deformation, the resulting shear stress and the delay of the response of the sample related to the applied distortion, which is recorded as phase shift angle δ, storage modulus G' and loss modulus G'' can be derived. Fig. 1 (left-hand side) depicts the possible course of G' and G'' with increasing deformation. The storage modulus, G', is a measure for the elasticity of the soil sample. It represents the energy that is available to reverse the previous deformation, while the loss modulus, G'', equals the energy dissipated during the deformation of

the sample (Mezger 2012). For very small deflection values, both G' and G'' remain constant and parallel to each other. In this so-called linear viscoelastic (LVE) range, there are no significant changes in the structure of the sample. Exceeding the LVE range the elastic behavior of the sample predominates as long as G' exceeds G'' and the deformation is partly reversible. Beyond the point where G' = G'', viscous behavior outweighs the elastic component of the deformation and the structural integrity of the sample is irreversibly destroyed which may lead to creeping or flowing depending on the water content of the sample (Holthusen, Peth & Horn 2010; Markgraf & Horn 2006a, b; Mezger 2012; Stoppe 2015). However, as the measurement itself only yields the two independent parameters M and δ from which all other rheological parameters are derived, the two results τ and G'/G'' in Fig. 2 can only be regarded as a supplement to each other showing the measured data in another format (Mezger 2012). To enable reference to be made to classical soil shear stability measurements, results from AST are going to be presented in the form of shear stress versus deformation.

Additional information regarding the measuring configuration can be found in Markgraf, Horn & Peth (2006).

RESULTS

Chemical Properties of the Soil Solution

Table 2 clarifies that fertilization chemically alters the soil solution. The concentrations of readily soluble cations in the saturation extract of the Chernozem material rise with increasing fertilization intensity, with the exception of Na^+ and K^+, which exhibit a slight decrease for fertilization according to 50 % of plant K^+ withdrawal. For the sandy Podzol, K^+ contents escalate for fertilization intensities amounting to 100 and 150 % of plant K^+ withdrawal, while the concentration of the remaining cations appears not to be fertilization dependent.

Zeta Potential

Zeta potential measurements reveal a less distinct effect of soil K^+ content on particle-particle interactions (Fig. 3). The more the zeta potential values approach zero, the more dominant are attractive forces in particle interaction. While there is a slight drop in zeta potential from zero fertilization (75 mg K_2O kg soil^{-1}) to 50 kg K_2O (ha a)$^{-1}$ (160 mg K_2O kg soil^{-1}) in the loess material of the Chernozem, zeta potentials rise with increasing fertilization intensity from that point on, indicating a slight shift to less repulsive forces.

In the sandy Podzol, however, fertilization leads to more repulsive forces, only the highest fertilization level results in a decline of particle repulsion.

Readily Dispersible Clay

There is less readily dispersible clay in the sandy Podzol than in the Chernozem derived from loess (cf. Fig. 4), as was anticipated due to the markedly lower clay content in the sandy material. However, contrary to expectations, there is less RDC in sand when the zeta potential attains lower values (cf. Fig. 3). In contrast, the pattern of RDC in loess is in exact accordance with the zeta potential measurements. When the zeta potential drops (more negative values, i.e. increase in repulsive forces), there is more readily dispersible clay in the soil-water-suspension, whereas the turbidity of said suspension decreases with increasing zeta potential emphasizing a slight tendency to more aggregation with intensifying K^+ fertilization.

Rheometry

Rheological measurements reveal that soil shear strength at the microscale depends on a variety of factors (Fig. 5). Drainage improves soil strength, regardless of whether the soil is homogenized or soil structure is intact (with the exception of moderately fertilized undisturbed sand, cf. Fig. 5 B str).

However, the degree of shear strength improvement due to menisci forces depends on soil structure, the effect being more distinct for homogenized soil material for both sand and loess. Furthermore, the pattern of the shear strength curves is much more steady for the homogenized loess, where the texture is more uniform and aggregates are no larger than 2 mm. In sand, on the contrary, irregularities can be observed even in homogenized material. Intensive fertilization appears to act as a damping factor for the stabilizing effect of drainage, observable especially for the structured samples. The unfertilized loess almost always displays the highest shear stability. Nevertheless, the homogenized material appears to undergo stabilization at moderate fertilization rates when drained sufficiently. In sand, where there are considerably more relatively large particles compared to the size of the measuring gap, the effect of fertilization is more heterogeneous than in the more finely grained loess.

Table 3 informs about the water content of the samples before measurement in the rheometer at the respective matric potentials. The more intensively loess (Chernozem) is fertilized, the higher is its water content at a given matric potential. Furthermore, the difference between -6 and -15 kPa is distinctly greater for homogenized than for structured material, irrespective of the soil type, which is attributable to a markedly higher water content at -6 kPa. Other than that, the sandy soil (Podzol) does not show such a consistent behavior with a clear effect of K^+ fertilization on soil water content.

DISCUSSION

Soil (shear) stability is the result of a complex interplay of physical as well as physicochemical forces at different scales. If a suspension of clay particles is considered, the balance of attraction and repulsion determines whether the particles coagulate or stay in a dispersed state. Particle interaction in suspensions may be characterized according to the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory (Derjaguin & Landau 1941; Verwey & Overbeek 1948). Due to the negative charge of clay minerals as a result of isomorphous substitution, a suspended clay particle is surrounded by counter- (cations) and co-ions (anions) in a characteristic manner. At the clay surface, located in the so-called Stern Layer, cations compensate part of the negative charge. In the diffuse layer, their concentration diminishes into the direction of the bulk solution, whereas the concentration of anions increases. Interference of this double layer of two or more particles results in repulsion. Upon addition of electrolytes to the solution, the diffuse layer is compressed; hence the particles may approach to a closer distance. The compression of the double layer is more pronounced for di- and polyvalent cations than for monovalent ones. Opposed to the double layer repulsion is the attracting van der Waals force, which is widely unaffected by electrolyte concentration (Lagaly, Schulz & Zimehl 1997; van Olphen 1977) but determined by the particle distance. If the thickness of the double layer is reduced sufficiently, the particles are more likely to approach closely enough to reach the range of van der Waals-attraction when they collide as a result of Brownian motion (Stumm 1992). The loess material originating from the Chernozem shows a distinct increase of monovalent (Na^+ and K^+) but also of divalent (Ca^{2+} and Mg^{2+}) ions in the soil solution, which accounts for a decrease in repulsive forces as can be seen in the zeta potential values for the three fertilized plots. Containing considerably less clay and with that providing a suspension with a markedly lower particle concentration, the sandy Podzol material yields results that support the statement of dilution increasing repulsion due to a more extended double layer thickness. Even though the low pH of the sand would increase positive charges of variable charge bearing particles (SOM and edges of clay minerals) (Plaza et al. 2015; Tombácz & Szekeres 2004 2006) and the SOM content is more than twice as high as in the loess material, the zeta potential values of the sand are distinctly lower. The less dominant attractive van der Waals forces are, the easier it is to convert a flocculated suspension back into a dispersed state, e.g. by stirring or shaking (van Olphen 1977), which is reflected in a higher amount of readily dispersible clay in loess (Fig. 4). The reason for the Podzol not containing more RDC with increasing fertilization although the zeta potential measurements suggest more repulsive forces might be found in the preparation of the samples for the respective measurement. Table 1 shows comparably high contents of SOM in the sandy material. Especially in soils poor in clay, the majority of SOM is accumulated within the fine silt and clay fraction and more precisely in primary **o**rgano**m**ineral **c**omplexes (OMCs) (featuring the size of primary

mineral particles) and secondary mineral complexes (aggregates consisting of primary OMCs) (Christensen 1992). By barely shaking a sample with water, only limited dispersion is provided, causing small secondary OMCs to settle. Consequently, the clay incorporated in these micro aggregates is not captured in the turbidity measurement. The samples for the zeta potential analyses, however, are ultrasonicated in order to ensure thorough dispersion, causing secondary OMCs to disrupt into primary OMCs (Schmidt, Rumpel & Kögel-Knabner 1999). Attraction and repulsion on a particle-to-particle scale may be reflected in the soil's shear behavior for small aggregates. If repulsive forces increase for example, clay particles may be separated from aggregates, leading to aggregate disruption eventually. However, upon drying, clay minerals, possibly together with ions of the soil solution, accumulate at the contact points of aggregates and are able to act as a cementing agent (Horn & Dexter 1989; Kay & Dexter 1992). Ion concentration of the soil solution not only plays an important role concerning electrostatic particle interaction but also when it comes to characteristics of the soil solution itself. Holthusen et al. (2012b) found surface tension as well as viscosity of aqueous salt solutions to be affected by type and concentration of the dissolved salts. The properties of the soil solution, especially surface tension and contact angle, but also viscosity, are included in equations such as the Young-Laplace equation (capillary rise) or the Hagen-Poiseuille equation (saturated flow in a cylindric capillary). Consistent with Becher (2001), who calculated a decreasing water retention for decreasing surface tension of the fluid, the water retention is enhanced with an increase of soluble cations in the soil solution, which, according to Holthusen et al. (2012b), augments surface tension. The apparently fertilization-induced damping of the stabilizing effect of a reduced matric potential (Fig. 5) can be ascribed to an increasing water content at a given matric potential (Table 3) which is presumably a result of the drainage itself being hampered by a rise in surface tension of the soil solution. The higher the degree of saturation of the pore space, in turn, the more likely is the occurrence of positive pore water pressure during deformation resulting in the destabilization of the soil (Hartge & Horn 2014). The patterns visible for the results of zeta potential and RDC measurements (Fig. 3 and 4, respectively) are not visible in the micromechanical shear strength (Fig. 5), leading to the assumption that the effect of pore water pressure (negative as well as positive) outweighs the electrostatic interactions. This is especially prominent for loess, showing decreasing shear resistance with increasing fertilization although zeta potential and RDC results would suggest less repulsive forces.

CONCLUSION

Soil shear stability at the microscale is distinctly affected by soil texture and structure as well as water content. Drainage leads to higher shear stresses regardless of texture or structure, although the effect is more pronounced for homogenized material. Furthermore, a fertilization induced change in the ion concentration of the soil aqueous phase leads to the formation of a new electrochemical equilibrium between particles, altering the ratio of attractive and repulsive forces. Electrostatic interactions gain relevance, the higher the clay content of a sample is. However, the effect of water content via menisci forces (stabilizing) or positive pore water pressure (destabilizing) appears to outweigh electrostatic forces, although the magnitude of the effect of matric potential is affected by fertilization.

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Table 1: Selected characteristics of the investigated soil material. The four fertilization intensities at the respective site correspond to 0, 50, 100 and 150 % of plant withdrawal. Soil K^+ content = double lactate extracted K^+; SOM = Soil organic matter.

	Fertilization [kg K_2O $ha^{-1}a^{-1}$]	Soil K^+ content [mg K_2O kg^{-1}]	Texture % Sand	% Silt	% Clay	pH [-]	SOM [% w/w]
Cherno-zem	0	75	5	72	23	7.3	2.6
	50	160	5	72	23	7.3	2.6
	100	205	5	71	24	7.3	2.6
	150	250	5	72	23	7.4	2.6
Podzol	0	45	86	9	5	4.3	5.4
	70	50	84	9	7	4.7	6.3
	140	90	85	10	5	4.4	6.1
	210	145	85	9	6	4.3	6.1

Table 2: Soil K^+ content (double lactate extracted) and resulting concentrations of sodium, potassium, calcium and magnesium measured in the saturation extract. n=3.

	Soil K^+ content [mg K_2O kg^{-1}]	Na^+_{sat}	K^+_{sat}	Ca^{2+}_{sat}	Mg^{2+}_{sat}
		[mg L^{-1}]			
Cherno-zem	75	4.0 ± 0.7	1.9 ± 0.6	151.3 ± 33.4	8.6 ± 1.6
	160	3.9 ± 0.4	1.5 ± 0.0	177.6 ± 8.9	9.7 ± 0.2
	205	6.8 ± 2.2	7.6 ± 0.2	206.8 ± 12.9	12.7 ± 0.9
	250	9.0 ± 1.9	10.1 ± 0.7	228.1 ± 15.6	14.8 ± 0.9
Podzol	45	3.9 ± 0.1	3.0 ± 0.1	253.1 ± 8.6	15.4 ± 0.2
	50	5.9 ± 0.5	7.4 ± 0.6	180.7 ± 14.6	13.3 ± 1.0
	90	4.5 ± 0.1	32.4 ± 0.8	195.0 ± 7.2	20.3 ± 0.8
	145	6.2 ± 0.2	59.8 ± 2.0	231.5 ± 11.5	13.0 ± 0.7

Table 3: Water content of soil samples for rheology made of homogenized (hom) and structured (str) material at matric potentials of -6 and -15 kPa, respectively. Values represent arithmetic means and standard deviations of 5 (hom) and 10 (str) samples.

Soil K^+ content [mg kg^{-1}]		hom		str	
		-6 kPa	-15 kPa	-6 kPa	-15 kPa
		Water content [% w/w]			
Cherno-zem	75	32.2 ± 1.1	22.1 ± 0.3	24.7 ± 1.9	23.6 ± 0.8
	160	32.6 ± 1.9	24.2 ± 0.2	25.6 ± 1.2	24.2 ± 1.3
	205	33.0 ± 0.4	23.3 ± 0.2	25.6 ± 1.5	24.4 ± 0.7
	250	34.2 ± 0.5	25.5 ± 0.3	26.4 ± 1.5	24.9 ± 0.6
Podzol	45	23.5 ± 0.5	11.8 ± 0.2	19.0 ± 2.0	14.8 ± 1.4
	50	29.2 ± 0.5	15.7 ± 0.4	20.8 ± 2.2	15.7 ± 2.2
	90	27.3 ± 0.2	14.5 ± 0.3	18.5 ± 3.1	16.0 ± 1.7
	145	28.1 ± 0.3	15.6 ± 0.2	17.9 ± 1.0	15.6 ± 1.6

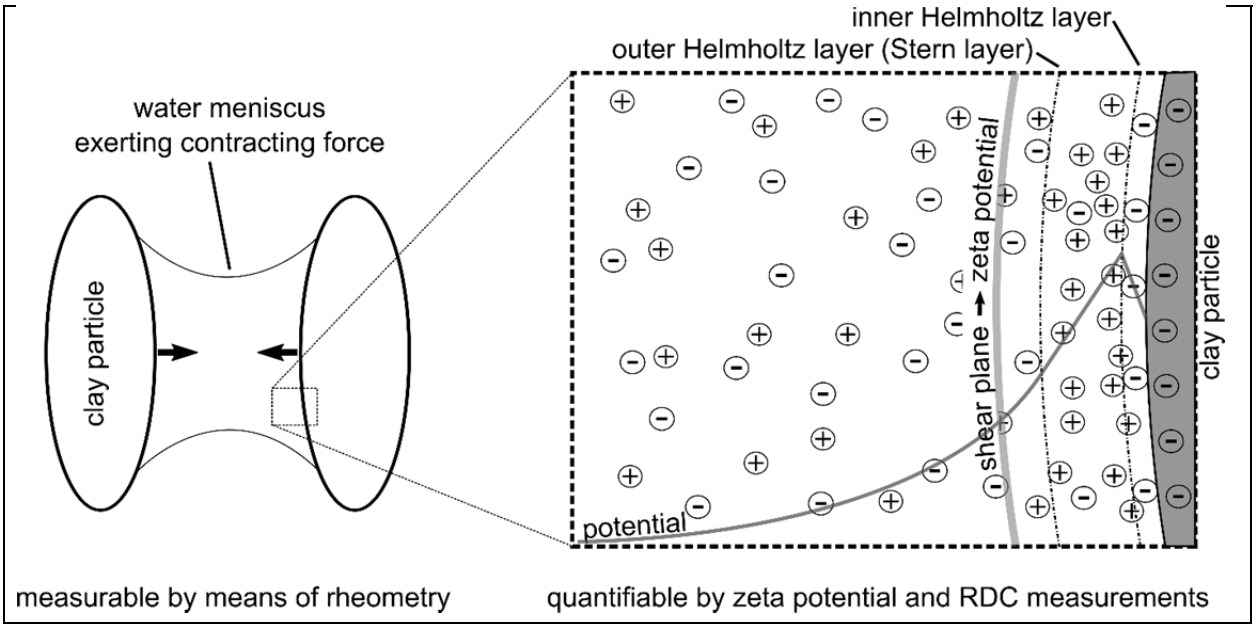

Figure 1: Connection between drainage (left-hand side) and physicochemical (right-hand side) effects on particle interaction. While rheometry is a tool to characterize particle interaction as a result of menisci forces as well as attraction and repulsion, zeta potential and readily dispersible clay (RDC) measurements allow a closer look on the latter two (double layer model on the right-hand side redrawn and modified for the sake of simplicity after Baumgarten (2013)).

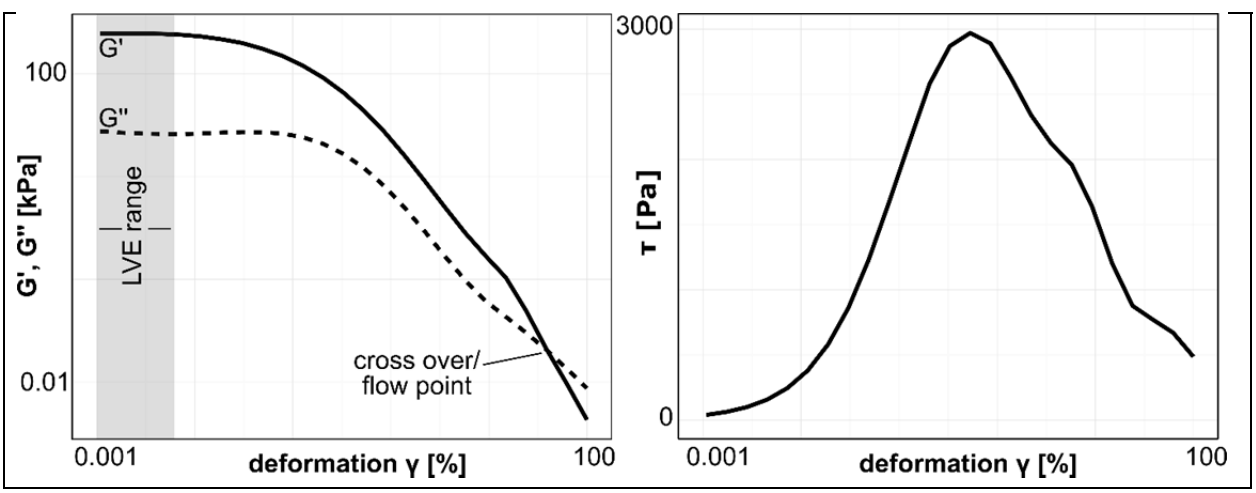

Figure 2: Schematic representation of possible results of an amplitude sweep test. Left-hand side depicts storage (G') and loss (G'') modulus alongside the linear viscoelastic (LVE) range (deformation is reversible to full extent) as well as the flow point (microstructural breakdown) during gradual depletion of soil microstructural stiffness. Right-hand side shows the course of the shear stress (τ), visualizing the resistance of the soil sample to the applied deformation.

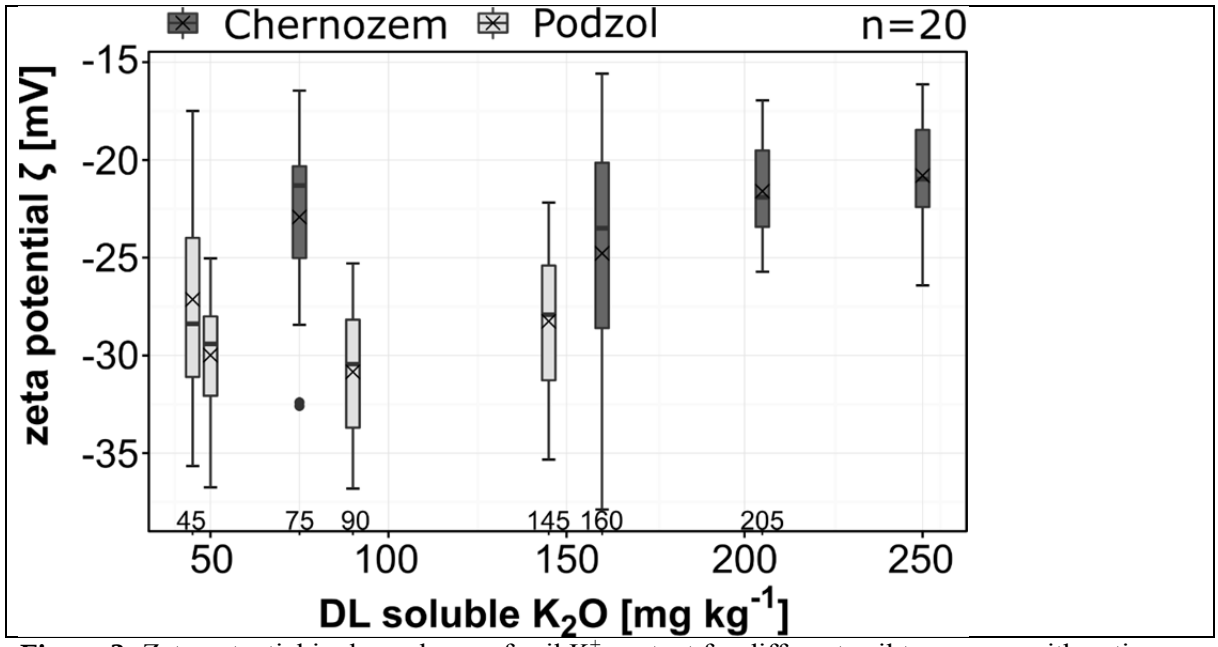

Figure 3: Zeta potential in dependence of soil K^+ content for different soil types. x = arithmetic mean values, dots represent outliers.

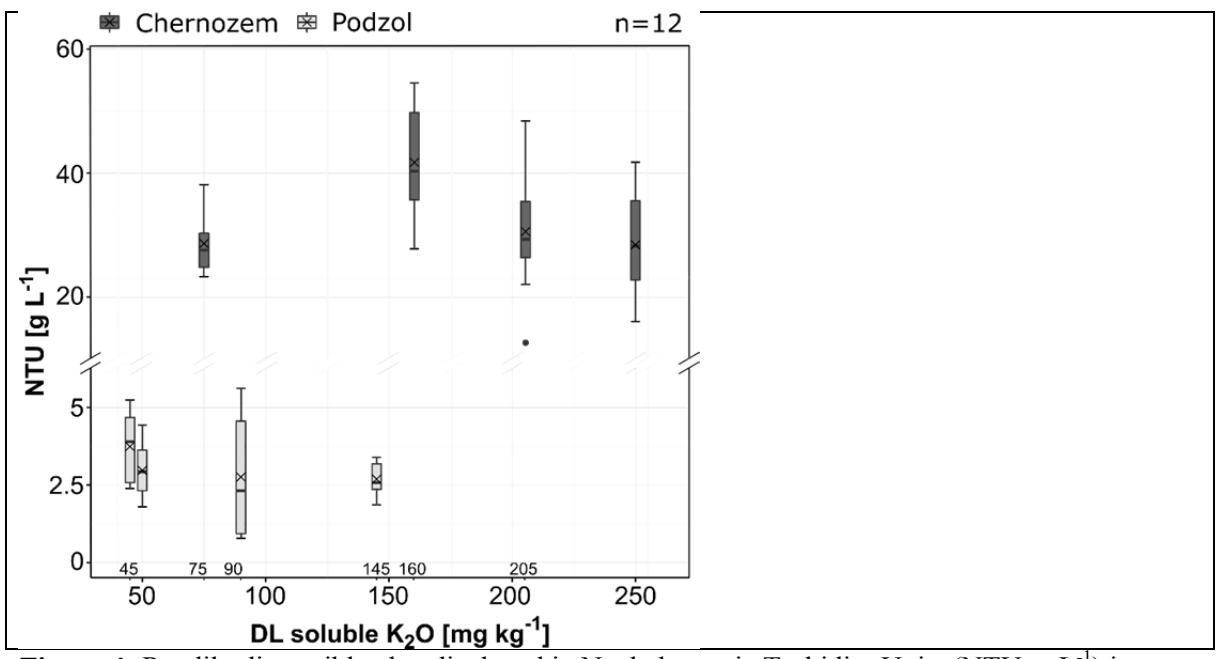

Figure 4: Readily dispersible clay displayed in Nephelometric Turbidity Units (NTU, g L^{-1}) in dependence of soil K^+ content for the two soil types. x = arithmetic mean, dots represent outliers.

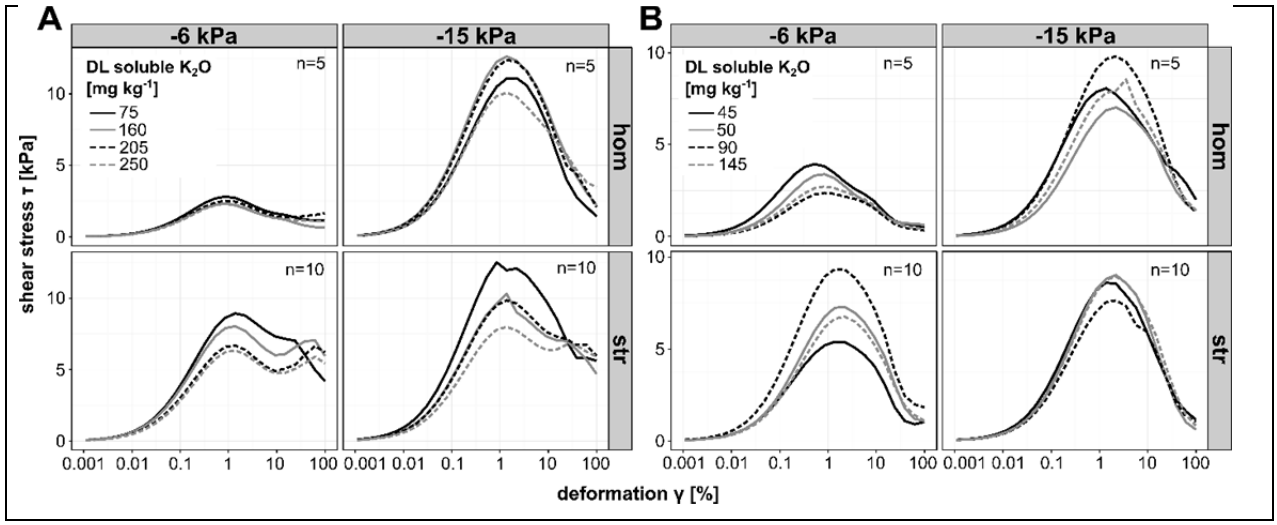

Figure 5: Shear stress at the microscale revealed by rheometry in dependence of deformation for different drainage levels (-6 kPa, -15 kPa) as well as for homogenized (hom) samples and samples with intact soil structure (str). **A:** Chernozem derived from loess, **B:** Podzol derived from weichselian glacial outwash (sand).

Selecting the Proper Source of Potassium Fertilizer

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Abstract
Many agricultural soils are deficient in adequate K to meet crop demands. Potassium deficiency commonly results in decreased crop yields and loss of quality. Many essential plant biochemical and physiological functions are impaired by a lack of sufficient K. Although K is a relatively abundant geologic material, most rocks and minerals are too insoluble to meet the needs of rapidly growing crops. There are many geologic resources of soluble K minerals that are processed into a variety of soluble fertilizers. Selection of the most appropriate K fertilizer for a specific crop and soil requires a knowledge of the chemical and physical properties of the materials. Most K fertilizers begin as sylvite or sylvinite minerals, which are converted to a variety of other soluble K materials. Other K fertilizers, such as langbeinite and polyhalite are mined directly from the earth. Most common K fertilizers are readily soluble and become available for plant uptake when adequate soil moisture is present. Since all K fertilizers provide the same K nutrition, the selection of the proper source depends on the associated anions or cations in the particle, and other properties such as solubility, pH, and salt index. The nutritional needs of the crop should be of primary importance during the K fertilizer selection process, but practical issues such as the form and compatibility of various nutrients, available application equipment, and fertilizer price will also be considered. Certain crops may have a sensitivity to various nutrients, but this limitation can often be overcome with careful fertilizer management.

INTRODUCTION

Potassium (K) is the seventh most common element in the earth's crust, yet crop K deficiency is growing worldwide. For example, in India, 50 to 70% of agricultural soils are estimated to be K deficient and input-output balances for K are negative in most states (Dutta et al., 2013; FAI, 2015). In the early 1980s, the Second National Soil Survey in China indicated that 42% of agricultural soils were deficient in available K. M more recently, analysis of 43,000 soil samples from across China showed that 55% were below critical levels (CAAS-IPNI), but there is great variation in soil K concentrations across regions. For cash crops receiving higher K fertilizer application, soil K concentrations have shown an increasing trend from 1990 to 2012, but have remained flat or decreased for grain crops and remain short of critical values (He et al., 2015) and about half the cropland China still has a negative K budget (Liu et al. 2017). In Brazil, 85% of the soils in the Cerrado region test low in available K (Lopes, 1977) and more than 60% of the agricultural soils are responsive to K fertilization (Prochnow, personal communication). Even in North America, where good fertilizer practices are common, median levels for soil test K are currently 150 ppm and are frequently below critical levels (IPNI, 2015).

Potassium in Plant Metabolism

Potassium is the most important and abundant cation in plant tissue. It has numerous biochemical and physiological functions within plants, which have been well documented and described in detail by Marschner (1995), Mengel and Kirkby, (2001) and Epstein and Bloom (2005). Potassium activates many enzymes, including those needed for carbohydrate metabolism and starch synthesis, and is involved in protein synthesis, photosynthesis, osmoregulation, cell extension, stomatal movement, and phloem transport. Potassium is important to water relations within the plant. It protects the plant from dehydration and wilting and maintains cell turgor through regulation of stomatal opening and closing, which limits water loss.

The value of K in increasing the quality of plant products is well known. For example, K has been shown to increase protein content in maize and wheat, oil content and isoflavone concentration in soybeans, nutritional quality of potato, and lint quality in cotton (Zörb et al., 2013; Pettigrew, 2008). It is commonly accepted that K decreases the incidence of plant disease and pests (Prabhu et al., 2007; Amtmann et al, 2008). While not always the case, K application tends to diminish the incidence of fungal and bacterial disease as well as insects damage in crops. This beneficial effect of K is attributed to synthesis of proteins, starch and cellulose which depress the concentrations of soluble sugars, organic acids, amino acids, and amides in plant tissues, which are necessary for feeding pathogens and insects (Römheld and Kirkby, 2010). However, because of variability in disease susceptibility and metabolic profiles, it is difficult to prove a consistent causal relationship with K.

The K concentrations in crops can range from 0.4% to more than 4% depending on the crop species, soil and climatic conditions, and fertilizer inputs (Zörb et al. 2013). Root cells have a high and efficient rate of K uptake due to active uptake mechanisms, even when K is in short supply (Ashley et al., 2006). Much research has addressed the mechanisms of how K is absorbed by plant roots (see reviews of Leonard, 1985; Maathuis, 1998).

Environmental stress from drought, chilling, frost, temperature extremes, soil salinity, soil acidity, diseases, etc. are increasing and contributing to reduced crop yields. Some estimates of yield reductions, relative to ideal conditions, associated with abiotic stress factors have been reported to range between 54 and 82% (Bray et al., 2000). The role of K in biotic and abiotic stress mitigation has been recognized and reviewed by Cakmak (2005) and Wang et al. (2013). Studies from molecular biology, summarized by Römheld and Kirkby (2010), suggest K has a specific role in regulating plant stress responses.

With the many and vital roles of K in plant biochemistry and physiology, an adequate K supply is clearly essential for optimizing crop productivity. The scientific literature contains thousands of examples of positive crop response (yield and quality) to appropriate applications of K fertilizer.

Crops grown on soils with insufficient K produce less than optimum yields; they fail to use water efficiently, for reasons outlined above, and use N less efficiently. For example, a maize study in Ohio that included a range of soil test K concentrations and N fertilizer rates demonstrated that N recovery efficiency is increased by reducing N rates below optimum levels, but at the expense of crop yield. However, application of fertilizer N at high soil K levels produced higher yields with less N; 13.1 t/ha with 213 kg N/ha with soil K level of 139 mg/kg vs. 10.5 t/ha with 308 kg N/ha with 80 mg K/ha in the soil. (Johnson et al., 1997). Interactions between K and N in crops have been reviewed by Johnston and Milford (2012).

Potassium in Soil

Supplemental K is often required to maximize crop yields, especially on soils testing low in plant-available K. The total amount of K in the soil (0-20 cm) can range from 3,000 to 100,000 kg/ha, depending on parent material and mineralogy (Sparks, 1987). However, availability of K to plants depends on the soils' ability to release K and the also the crop itself (Öborn et al., 2005). Micas and K-feldspars are the most abundant source of K in soils. Weathering of these minerals produce secondary micaceous clay minerals, such as illite, mixed-layer minerals, and vermiculite (Bertsch and Thomas, 1985; Mengel and Kirkby, 2001). Soils rich in clay tend to be rich in K. Silt and sand fractions contain more feldspars. Availability of K in these soils is dependent on the degree of weathering, biological activity, and rhizosphere processes.

The weathering and leaching of relatively insoluble K-containing feldspars, micas and other aluminosilicates over a geologic time frame produced water-soluble K minerals which occur as dissolved

salts in natural brines or precipitate from the evaporation of shallow seas. These deposits are usually mined from some depth in the earth's mantle and processed into commercial K fertilizers.

Selecting the appropriate source of K fertilizer for specific crops and environments requires an understanding of their basic properties. Most commercial K fertilizers are quite soluble and they rapidly dissolve when adequate soil moisture is present. As potash fertilizers dissolve, the K fraction is identical for all sources. The major difference between K sources is in the accompanying anions and cations within the fertilizer material. In the geologic deposits, the most abundant of these soluble salts, and the major source of K for fertilizer, is potassium chloride (KCl). It occurs as pure KCl, in the mineral sylvite, in combination with sodium chloride (sylvinite), or in combination with magnesium and sulfate salts as carnallite ($KCl{\bullet}MgCl_2{\bullet}2H_2O$), kainite ($KCl{\bullet}MgSO_4{\bullet}3H_2O$), langbeinite ($K_2SO_4{\bullet}2MgSO_4$), polyhalite ($K_2SO_4{\bullet}MgSO_4{\bullet}2CaSO_4{\bullet}2H_2O$) and other salts. A small amount of K comes from potassium nitrate (KNO_3) deposits in Chile, where it is codeposited with sodium nitrate ($NaNO_3$).

SELECTING THE APPROPRIATE POTASH SOURCE

All potash fertilizers are identical in their supply of K for plant nutrition, however their accompanying nutrients will change their solubility, pH, salt index, and the conditions for their most appropriate use. The form of fertilizer that will be used will also factor into the selection process. There are circumstances where bulk blends of nutrients, compound single-granule fertilizers, fluid fertilizers, or fertilizer suspensions are most appropriate depending on cropping conditions, the availability of blending and application equipment, and fertilizer prices.

There are many examples of benefits from a particular source of K fertilizer on yield and harvest quality, but the findings are not consistent. Some of these conflicting results stem from differences in the fertilization technique, the application rate and timing, and the comparisons between specific K fertilizer sources. Additionally, there may be restrictions on the selection of K fertilizers for organic crop production (Mikkelsen, 2007).

It has been suggested that the effect of a particular K fertilizer source is more evident on crops with a harvested fruit. To evaluate this hypothesis, Lester et al. (2010) compiled a summary of 20 years of published research examining the effects of K source and application method on fruit attributes. The majority of the papers they reviewed reported a positive response on some crop quality parameter due to K fertilization, but there was wide variation. A positive response to foliar K applications was frequently noted, but this was also not consistent among all studies and for all K fertilizer sources. Their review illustrates the need to utilize scientific principles to adjust the selection of the most appropriate K fertilizer source for specific crop and soil conditions.

In addition to plant nutrition, in some soils it may important to maintain proper amounts of S, Ca, and Mg by selecting an appropriate mixed salt K fertilizer such as langbeinite or polyhalite. An overemphasis on K fertilization alone can lead to an emerging plant deficiency of divalent cations and unbalanced plant nutrition (Jakobsen, 1993), as well as negative impacts on soil permeability (Oster et al., 2016).

An understanding of the chemical and physical properties of important K fertilizers is essential for making the selection of the right source. A very brief summary is provided here:

Characteristics of Common K Sources

Potassium Chloride: KCl (muriate of potash, MOP); 0-0-60; Water solubility (20°C) 344 g/L; Solution pH approx. 7

Potassium chloride is the most widely used K fertilizer due to its relatively low cost and because it contains more K than most other sources. Potassium chloride is often spread onto the soil surface prior to

tillage and planting or applied in a concentrated band near the seed. Since all dissolving K fertilizers will increase the soluble salt concentration, banded KCl is placed to the side of the seed to avoid damaging the germinating plant. Potassium chloride rapidly dissolves in soil water and a pure grade of KCl can be solubilized for fluid fertilizers or applied through irrigation systems.

Potassium Sulfate: K_2SO_4 (sulfate of potash, SOP); 0-0-50; 17 to 18% S: Water solubility (25ºC) 120 g/L; Solution pH approx. 7

Potassium sulfate is an excellent source of both K and S nutrition for plants. There may be certain soils and crops where the addition of Cl should be avoided. In these cases, K_2SO_4 makes a very useful K source. Potassium sulfate is only one-third as soluble as KCl, so it is not as commonly dissolved for addition through irrigation water unless there is a need for additional S. Fine particles are used for making solutions for irrigation or foliar sprays since the small particles are more rapid to dissolve. Foliar sprays of K_2SO_4 are a convenient way to apply additional K and S to plants, supplementing the nutrients taken up from the soil.

Potassium Nitrate: KNO_3 (nitrate of potash, NOP); 13.5-0-45.5; Water solubility (20°C) 316 g/L; Solution pH 7 to 10

The use of KNO_3 is often desirable in conditions where a highly soluble, chloride-free source of both K and N is needed. Potassium nitrate contains a relatively high proportion of K, with a N to K ratio of approximately 1:3. Applications of KNO_3 are commonly made to the soil or as a dilute solution sprayed on to plant foliage.

Potassium Thiosulfate: $K_2S_2O_3$ (KTS); 0-0-25; 17% S. Solution pH 7.5 to 8.

This clear fluid fertilizer is used for direct soil application, applied with irrigation water, or used as a foliar fertilizer. The thiosulfate portion of the molecule will oxidize in soil to form sulfate in an acid-forming process.

Langbeinite: $K_2SO_4 \cdot 2MgSO_4$; 0-0-21; 21% S, 10% Mg; Water solubility (20ºC) 240 g/L; Solution pH approx. 7

Langbeinite has K, Mg, and S all contained within a single particle, which helps provide a uniform distribution of nutrients. Langbeinite is totally water soluble, but is slower to dissolve than some other common K fertilizers because the particles are denser than other K sources. It is frequently used where a fertilizer free of Cl is desirable. Langbeinite is a nutrient-rich fertilizer with a relatively low overall salt index.

Polyhalite: $K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$; 0-0-14; 19% S, 12% Ca, 3% Mg

This soluble geologic mineral contains four essential plant nutrients in one particle, making convenient application in fields. It is also used in situations where a chloride-free fertilizer is desirable.

Potassium Hydroxide: KOH; 0-0-83

This strongly alkaline material is commonly used as a component of fluid fertilizers to provide a low-salt index, chloride-free source of K. It is useful to neutralize acidity in liquid fertilizer blends, irrigation water, or soil. Extreme safety measures must be used when handling this caustic material.

Potassium Phosphate: KH_2PO_4 (Monopotassium Phosphate, MKP) 0-52-34; Water solubility (20ºC) 226 g/L; Solution pH 4.2 to 4.7

This highly soluble product is commonly used where a source of both P and K is desired, without additional N. This K source is most commonly used in fertigation and for foliar applications.

Mineral/Silicate K:

Many geologic minerals contain K, but their solubility is generally too low for agronomic use.

Considerable research has been conducted on developing various K-bearing minerals as fertilizers and techniques to accelerate their dissolution through chemical and biological processes in the soil. Transportation limitations may restrict use of these materials to fields near their production site.

Manure K:
Got itGPotassium is not a structural component of plant cells and remains highly soluble in animal manure and urine. The nutrient value of K in animal manures is generally equivalent to soluble K fertilizers. The chemical composition of manures must be known to apply material at rates that avoid excessive or insufficient application of nutrients to the field. Solid manures frequently contain between 5 to 25 kg K_2O/ton, while liquid pit manures typically contain 1 to 4 kg K_2O/1000 L. Lagoon liquids have an even lower K concentration due to their dilute nature.

Fertilizer Salt Index
Most modern fertilizers are chemically classified as salts, and all salts can inhibit the ability of plant roots to absorb water. High concentrations of dissolved fertilizer (salt) can cause desiccation and "burn" can occur for seedlings and plant tissues that lose their moisture due to osmotic stress. Some fertilizer materials have higher salt index (osmotic potential) than others. The salt index of N and K fertilizers is generally greater than P fertilizers, and sulfate forms of fertilizer generally have a lower salt index than Cl-based fertilizers.

There are differences in laboratory methodology for determining salt index, but the relative rankings are well established. Placement of any fertilizer with a high salt index in close proximity to seeds should be avoided to minimize osmotic damage during germination. However, in addition to the salt index measurement, the soil, weather, and crop conditions often have a greater impact on potential fertilizer damage to seedlings than the fertilizer salt index rating alone.

Potential Concerns with Excessive Chloride
The selection of a particular source of K fertilizer is sometimes based on the presence of Cl. There is a wide range of Cl sensitivity among plant species and cultivars. As a broad classification, many woody plant species, vegetables, and beans are more susceptible to Cl toxicity, whereas many non-woody crops tolerate higher concentrations of Cl in the rootzone (Maas, 1986).

There is a large body of literature related to the effects of Cl on crop performance (Fixen, 1993). Chloride is an essential plant nutrient and it is routinely added in some environments to enhance plant growth and disease resistance (Ren et al., 2015). However, excessively high Cl concentrations are linked to decreased crop growth and quality due to osmotic effects and specific ion toxicity.

The effect of K fertilizer source on potato growth and quality has likely received more attention than any other crop. There are multiple reports of reduction in specific gravity (% dry matter) in potatoes receiving various K fertilizers. Some researchers have observed no differences in potato specific gravity between various K fertilizer sources, while others have measured a decrease in specific gravity when using KCl compared with K_2SO_4 (e.g. Davenport, 2001). This reduction in specific gravity may not be directly due to the presence of Cl, but due to greater K uptake from KCl and a higher salt index. These factors can cause the tubers to absorb more water than when fertilized with another K source. Other research shows that the total K application rate has a greater impact on reducing specific gravity than the individual K fertilizer source. (Westerman et al., 1994). Additionally, when KCl is split into multiple applications, or if KCl is applied in the autumn (with adequate winter rain) for a spring-planted potato crop, any negative impact on specific gravity is eliminated. Factors such as the climate and the potato variety can also influence the effect of fertilization on potato specific gravity. These many interacting factors illustrate the difficulty in making generalizations for selecting a proper K source for all conditions.

There are many excellent choices available for meeting the K requirements of crops. Selecting the appropriate K source starts with understanding the properties of the fertilizer material and knowing the specific needs of the crop. There is no single K fertilizer that is always superior to another, but the decision of the best K source also needs to be made in consideration of the timing of application, the rate of application, and the fertilizer placement.

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Selecting the Right Source of Potassium for Fertigation

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Absract
Fertigation is the application of fertilizers through irrigation water. Fertigation is commonly practiced under arid and semiarid conditions with drip irrigation system, the most efficient irrigation method. To ensure efficient fertigation, one should select the right source of nutrient. For fertigation, source must be completely water soluble, compatible with other nutrient sources and with irrigation water quality. Besides, the source should be suitable for the soil chemical and physical properties and finally should be affordable and environmentally and economically acceptable. Potassium is an essential nutrient and can be supplied from various sources. The common sources of potassium that can be injected into fertigation system include potassium chloride (MOP), potassium sulfate (SOP), potassium nitrate (NOP), monopotassium phosphate (MKP) and potassium thiosulfate (KTS). Each of these sources contains at least two essential nutrients and none of them contain harmful nutrients at normally-used concentrations. MOP is a good choice for fertigation in soils with a good drainage system, for shloride-tolerant crops, and when hard water is used in fertigation where other sources such as SOP cannot be used. Besides, MOP is the most soluble, least expensive and contains the highest level of potassium. MOP is not recommended for chloride sensitive crops. SOP is a good source that can be used under saline conditions but it is not recommended for fertigation when irrigation water contains more than 3 meq Ca and Mg to avoid precipitation and clogging problems. NOP is a good source that supplies both N and K and can be used under saline condition but sometimes its use is economically not feasible due to its higher price. Besides, NOP is not recommended under conditions susceptible to contamination of ground water, nor when accumulation of nitrate is undesired in crop products. Other sources of K are also discussed.

Keywords: Fertigation; Potassium Source; Solubility; Compatibility

INTRODUCTION

The most limiting factors of agricultural production in irrigated agriculture are nutrients and water supply. Therefore, in modern agriculture, both fertilization and irrigation are important management factors for controlling yield quantity and quality (Bar-Yosef 1999; Rusan & Malkawi 2016). Application of plant nutrients through irrigation system is called fertigation. Fertigation is an efficient tool for management of fertilization and irrigation and is essential for today's agriculture to cope with the critical situation of limited water resources in many countries (Mohammad 2004; Mikkelsen et al., 2015).

Modern irrigation systems, such as drip irrigation, are widely used in arid and semi-arid regions and are considered the most efficient irrigation method (Sharmasarkar et al. 2001). Additionally, drip irrigation is ideally suited for controlling the placement, time and rate of fertilizer application, thus enhancing water and nutrient utilization efficiency (Kafkafi & Tarchitzky 2011; Papadopoulos, 2000). With drip irrigation, the wetted soil volume and thus the active root zone is reduced under drippers and therefore, addition of all fertilizers required in one single dose is not possible (Kafkafi & Tarchitzky 2011; (Mikkelsen et al., 2015). Instead, fertilizers should be applied frequently in small amounts with each irrigation - a practice that can only be achieved with fertigation (Mohammad 2000). Adopting the 4R nutrient stewardship concept, which defines the right source, rate, time, and place for plant nutrient application (IPNI, 2013) is very crucial for nutrient management in the small wetted soil volume under drippers. Fertigation is the

most efficient tool for applying the 4R nutrient stewardship concept and ensures the nutrient best management practices.

Research has shown that fertigation resulted in higher yield and quality of various vegetable crops such as tomato (Bar-Yousef, et al. 1995); potato (Mohammad et al. 1999); garlic (Mohammad & Zuraiqui 2003) and pepper (Qawasmi et al., 1999). In addition, fertigation minimizes leaching of water and mobile nutrients from the rhizosphere, thus minimizing groundwater contamination and improving fertilizer and water use efficiency (Hagin et al., 2002). In a field study by Mohammad, M. (2004), using a ^{15}N isotope it was found that fertigation enhanced all components of nutrient utilization efficiency including physiological and agronomic recovery efficiencies as well as partial factor productivity. The recovery of immobile nutrients such as P and K, applied conventionally, is low due to losses by fixation, adsorption and erosion, while their uptake was enhanced with fertigation (Mohammad et al. 2004).

There are several factors that are prerequisite for successful fertigation. The use of good quality irrigation water, soluble and compatible fertilizers and application of the actual crop water and nutrient requirements are the main prerequisites for successful and efficient fertigation (Mohammad 2004; (Mikkelsen et al., 2015). One of the most critical prerequisites for successful fertigation is the selection of the right source of nutrients. For fertigation, the sources need to be completely soluble in irrigation water and compatible with other fertilizer sources as well as with the irrigation water quality (Mohammad 2003). This article discusses the guidelines to be considered to select the right source of K under various conditions of fertigation farming system

SELECTING THE RIGHT SOURCE OF POTASSIUM FOR FERTIGATION

There are several sources of potassium that can be used with fertigation systems. The following are the main sources:

Muriate of potash (MOP) = Potassium chloride, KCl (0-0-60)

Potassium chloride is the most commonly and widely used source of K mainly due to its relatively low cost and its high K content. Potassium chloride has the highest K content (60% K_2O), is generally the least expensive source of potassium and is the most popular and most water soluble K fertilizer. It may not be desirable for use under saline conditions and for chloride sensitive crops.

Color of MOP:

The color of MOP can vary from dark red to pink to white, depending on the source of the sylvinite ore and the recovery processes. The reddish tint comes from trace amounts of iron oxide. However, both red and white KCl have the same agronomic effectiveness and the same nutrient availability; however white potash can have a slightly higher K content (0-0-62). MOP is an excellent source not only for potassium but also for chloride which is the only K source containing chloride.

Sulfate of potash (SOP) = Potassium sulfate, K_2SO_4 (0-0-50)

Potassium sulfate is the least soluble source among all common K fertilizers used in fertigation. Compared to MOP, SOP is less soluble, more expensive and contains less K (50% K_2O). SOP tends to cause precipitation of $CaSO_4$ in the irrigation system creating a clogging problem. Therefore, SOP should not be injected into micro irrigation systems where irrigation waters contain more than 2 to 3 meq/l, of Ca and Mg. This source is a good option when used on chloride-sensitive crops.

Potassium Nitrate (NOP) (13-0-46)

It is an excellent choice of potassium fertilizer for areas where irrigation water salinity problems are present as it has the lowest salt index. It is less soluble than MOP, but more soluble than SOP. NOP is the most expensive source of K, but the grower benefits from both the nitrogen and the potassium in the product when both are needed.

Monopotassium phosphate (MKP), KH_2PO_4 (0-52-34)
Monopotassium phosphate is highly soluble with high contents of P and K. It is relatively expensive. When both P and K are required, this source can be a good option.

Potassium thiosulfate (KTS), $K_2S_2O_3$ (0-0-25-17) and (0-0-22-23)
Potassium thiosulfate (KTS), usually available in two grades, is a neutral to basic, clear, liquid solution. This fertilizer can be blended with other fertilizers, except with those containing Ca and Mg. KTS blends should not be acidified below pH 6.0. Upon application, the thiosulfate component will be oxidized into sulfuric acid by the bacteria (Thiobacillus thiooxidance), causing acidification of the soil. This acid under calcareous soil will favor the solubility of insoluble P and micronutrient compounds in the soil enhancing their availability to the plant.

Plant nutrients supplied with the different sources of potassium:
Besides potassium, common potassium fertilizers supply other nutrients such as nitrogen, sulfur and chloride. All these accompanying ions associated with the potassium are also considered essential nutrients. The following are the major functions of these essential nutrients:

Potassium (K):
1. Important to regulatory mechanisms like photosynthesis, carbohydrate translocation, and protein synthesis
2. Critical for osmoregulation.
3. Increases resistance to biotic and abiotic stress conditions
4. Improves quality of yield and harvested products

Nitrogen (N):
1. Is a constituent of all proteins, chlorophyll, coenzymes and nucleic acids
2. Important for building plant tissue, growth of sprouts, leaves, branches and stems and stimulating vegetative growth.

Sulfur (S):
1. Important constituent in plant proteins and necessary for the synthesis of proteins and enzymes. Disulfide bond (S-S) is responsible for protein folding the necessary step to convert nonfunctional to functional protein
2. Is a component of cysteine and methionine (the only amino acids containing sulfur)
3. Important in synthesis of vitamins, hormones, and other plant metabolites
4. Is a component of glycosides, which give odor to onions, mustard, etc.

Chloride (Cl):
1. Activates system for production of O2 in photosynthesis
2. Plays an essential role in enzyme activation and osmotic regulation
3. Plays a role with K in plant water balance and regulating stomata opening
4. Important in disease resistance

Potassium can be obtained from a variety of sources. Selection of the right source of potassium is an important step for effective and successful fertigation. There are many factors and considerations governing the selection of the right source of potassium for fertigation. These include the following:
1. The source of potassium must supply the soil and subsequently the crops with all potassium needed in a balanced way and in an available form when needed.
2. The source must be in the right combination with the rate, time and placement of fertilizer application.
3. The source must be water soluble and compatible with the irrigation water quality used to prepare the stock fertigation solutions. It should be noted that solubility is significantly temperature-dependent, where it decreases with decreasing temperature. The solubility of most commonly used potassium fertilizers is shown in Table 1 (Elam et al., 1995; Wolf et al., 1985). It should be noted

that dissolving more than one fertilizer will increase the ionic strength of the fertilizer solution and may reduce the reported solubility values. Most potassium fertilizers are soluble in water. The solubility of the most common K fertilizers at 20 °C are 34% for KCl, 31% for KNO_3 and 11% for K_2SO_4. SOP is the least soluble in water and may precipitate as $CaSO_4$ if irrigation water contains more than 2-3 meq Ca. Such precipitates caused by K_2SO_4 may clog the drippers. NOP on the other hand, has higher solubility than SOP Finally, The most soluble KCl should be used with precaution under saline conditions and for chloride sensitive crops (Mass and Hoffman 1977). When precipitation and clogging problems are of concern then the NOP is the best choice. It is fair to mention that chloride from applied KCl contributes relatively very little to the overall chloride provided by the saline irrigation water. Besides, chloride excess will be leached away from the root system, when sufficient irrigation water is applied on soils where leaching is favorable.

4. The source of potassium should be compatible with the sources of other nutrients in the fertilizer solution. Sources that contain sulfate and phosphate should not be mixed with fertilizers containing Ca or Mg to avoid precipitation of calcium sulfate and calcium phosphate which clog the drippers and filters (Table 2) (Burt et al., 1998).
5. The source should have a low salt index (SI) and its solution should have a low electrical conductivity (EC), since the fertigation solution is applied to a small volume of soil where the roots are. The fertilizer salt index is a measure of salt concentration that fertilizers induce in soil solution, which is expressed as a ratio of the osmotic pressure of the soil solution produced by the fertilizer to that of the same weight of sodium nitrate, expressed as a percentage (Kamburova & Kirilov 2008). Na-nitrate was chosen as the standard because it is 100 % water-soluble and because it was a commonly used N-fertilizer when the SI concept was first proposed in 1943. At equal product weight, SOP has a lower SI value (Table 4). Besides the SI there is another indicator, used to express the potential risk of soil salinity, which is related to the effect of fertilizer solutions on EC. The EC of an electrolyte solution is a measure of its ability to conduct electricity. The EC-value of a fertilizer salt is expressed in milliSiemens/cm or deciSiemens/m, measured at a temperature of 25 °C after dissolving 1 gram of fertilizer salt per liter of water. The SI for KCl, KNO_3 and K_2SO_4 are 116, 74 and 46, respectively. However, the EC of solutions of KCl, K_2SO_4 and KNO_3 are 1.79, 1.54 and 1.35 dS/m, respectively (Kamburova & Kirilov 2008). Note that the SI for K_2SO_4 is lowest since sulfate would precipitate in the soil, while its solution has higher EC than that of KNO_3 since it has more charges/aqueous ions. The solution for KCl has higher EC than K_2SO_4 since it has higher solubility. It should be noted that liquid fertilizers will produce a lower osmotic pressure in the soil solution than granular products of the same grade, since granular products will use soil water to dissolve.
6. In summary, the SI for SOP is lowest since sulfate would precipitate in the soil, however, K_2SO_4 solution has higher EC than KNO_3 since it has more charges aqueous ions. The solution of KCl has higher EC than that of K_2SO_4 since it has higher solubility and its ions will not form any precipitates. It should also be noted that the choice of materials having a low SI is most important for localized placement of fertilizers when fertilizers are applied as a starter or in band near the seeds or seedlings. The liquid fertilizer will always have lower SI than the dry solid fertilizers.
7. The source of nutrients must suit soil characteristics. For example, chloride-containing sources should be avoided under saline condition, while nitrate-containing sources should be avoided in coarse textures soil, or where the water table is shallow, to avoid contamination of ground water by nitrate.
8. The source should be affordable and its use economically feasible. The sources of potassium should be evaluated in part based on the comparative costs per unit of nutrient as this will significantly affect the farmer's income. In this regard, KCl has the lowest cost as compared with KNO_3 or K_2SO_4 (Burt et al ., 1998).
9. Interaction between nutrients should be considered when selecting the source of fertilizers. There is an antagonistic interaction for example between Cl^- and NO_3^-, where one reduces the absorption of the other. This can be employed in fertigation management to avoid the

accumulation of either Cl^- or NO_3^- as required. Therefore, under saline conditions, KNO_3 can be applied to reduces the absorption of the Cl^-. On the other hand, when accumulation of NO_3^- in agricultural products and contamination of ground water are of concern, then KCl can be applied to reduce the absorption of NO_3^-. When the chloride concentration in the soil solution increases, plants take up chloride on the account of essential anionic nutrients, especially nitrate, which has been attributed to the non-specific replacement effects (Mengel & Kirkby 1982). Uptake of high concentration of Cl^- by salt sensitive crops can be harmful to the crop. Nukaya et al. (1991) found that tomato yield was not affected by Cl^- uptake upto 13 mmol (450 ppm) when EC of the root environment was kept at 3.5 dS/m. On the other hand, a concentration of 3.8 mmol/l SO_4 causes significant increase of blossom end-rot phenomena in fruit.

10. Recognize any possible impact of the accompanying ions on the environment (soil, water, air), quality of the product, and public health

CHLORIDE IONS IN KCl VERSUS THAT IN IRRIGATION WATER:

Controversial discussion is ongoing regarding how significant the effect is of the accompanying Cl^- ions provided with MOP versus that provided with the irrigation water. To clarify this debate, the following example provides quantitative estimates on the magnitude of Cl^- provided with MOP vs that from the irrigation water with reference to the permissible level of Cl^- in irrigation. The permissible maximum level of Cl^- provided by the irrigation water with no harmful effect to the soil or crops is 4 meq Cl^-/L (142 mg/L) (Table 3) (Ayers & Westcot 1994). Assume a farmer using such water is cultivating a tomato crop which has a water requirement of about 5000 m^3/ha. This means that this amount of water will supply the soil with 710 kg Cl^- [(142*5000)/100] per season per ha. Assume instead that the farmer will fertilize his tomato crop with 200 kg K_2O /ha. This will provide the soil with 200 x 40/100 = 80 kg Cl^-. Thus, 80 kg Cl^- provided by the KCl / 710 kg Cl provided by the irrigation water = 11.3%. Thus, the contribution of the Cl^- supply to the soil from KCl equals 11.3% of that supplied by the irrigation water and will not have any negative impact on the soil according to the FAO guidelines. Based on the above discussion, KCl can be successfully used when irrigation water is not saline and the fruit taste, shelf life, and fruit firmness need to be improved. Besides, it can be used when the costs of fertilization need to be decreased, when the use of nitrate needs to be reduced (e.g. in NO_3 susceptible zones), or when K_2SO_4 use is restricted where irrigation water contains more than 2 meq Ca/L. It should be noted that there are chloride tolerant crops such as sugar (fodder) beet, celery and coconut and chloride sensitive crops such as starch potato, strawberry, pepper, beans, melon, onion, lettuce, and transplants. Other chloride tolerant crops include cereals, maize, oil seed rape, asparagus, cabbage, beetroot, oil palm, rice, banana, cotton, sunflower, grape wines, stone fruits, potato, tomato, carrots, kiwi, coffee and pineapple

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Table 1. Solubility of various fertilizers at different temperature, g/100 g water (Wolf et al., 1985)

Temperature, ^{o}C	KCl	K_2SO_4	KNO_3	KH_2PO_4	$K_2S_2O_3$
	Potassium Chloride	Potassium Sulfate	Potassium Nitrate	Monopotassium Phosphate	Potassium Thiosulfate
10	31	9	21	18	120
20	34	11	31	22	150
30	37	13	46	28	175

Table. 2. Fertigation Compatibility Table: Fertilizers that can and cannot be mixed in the same fertigation tank

Nutrient source	NH_4NO_3	$CO(NH_2)_2$	$(NH_4)_2SO_4$	$(NH_4)_2HPO_4$	KCl	K_2SO_4	KNO_3	KH_2PO_4	$K_2S_2O_3$	$Ca(NO_3)_2$
NH_4NO_3	_	_	_	_	_	_	_			_
$CO(NH_2)_2$	C	_	_	_	_	_	_			_
$(NH_4)_2SO_4$	C	C	_	_	_	_	_			_
$(NH_4)_2HPO_4$	C	C	C	_	_	_	_			_
KCl	C	C	C	C	_	_	_			_
K_2SO_4	C	C	C	C	C	_	_			_
KNO_3	C	C	C	C	C	C	_	_		_
KH_2PO_4	C	C	C	C	C	C	C	_		_
$K_2S_2O_3$	C	C	C	C	C	C	C	C	_	_
$Ca(NO_3)_2$	C	C	I	I	C	I	C	I	I	_

C = Compatible I = Incompatible

Table 3. Guidelines for interpretation of water quality for irrigation (Ayers and Westcot, 1985)

		Degree of restriction on use		
Potential irrigation problems	Unit	None	Moderate	Severe
ECw	dS m^{-1}	<0.7	0.7 – 3.0	>3.0
TDS	mg L^{-1}	<450	450 - 2000	>2000
Specific ion toxicity (affects sensitive crops)				
Chloride:				
Surface irrigation	meq L^{-1}	<4	4 – 10	>10
Sprinkler irrigation	meq L^{-1}	<3	>3	-
Boron	mg L^{-1}	<0.7	0.7 – 3.0	>3.0

Table 4. Salt Index **(**Kamburova, K & Kirilov, Pl 2008)

Potassium Fertilizers	Salt Index	Salt Index/unit of K_2O	EC (1 g/l at 25°C; dS/m)	Max. solubility at 10°C, g/l	Max. solubility at 20°C, g/l
Sodium Nitrate (reference)	100	6.1 N	=	=	=
MOP (Potassium chloride)	116.2	1.9	1.79	312	342
NOP (Potassium Nitrate)	73.6	1.6	1.35	219	315
SOP (Potassium Sulfate)	46.1	0.9	1.54	93	111
KTS (Potassium Thiosulfate)	68	2.7	=	=	=
MKP (Monopotassium phosphate)	8.4	0.1	=	=	=
Sulfate of Potash Magnesia	43.2	1.9	=	=	=

Differences in Crop Growth and Productivity Relating to the Potassium Source used in Fertigation

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Abstract

Fertigation solutions having nitrate concentrations that are maximized, but balanced to ideally supply nutrients for crop growth and development were found in various experiments to provide superior results in considering growth and productivity. To maximize nitrate, potassium nitrate as opposed the other potassium sources to meet the potassium need is required. Pot trials were carried out using a number of crops.

Peach, Apple: Nursery peach (Golden Magic) and apple trees (Anna) were planted into 2.7 l pots containing river sand, and treated with one of three nutrient solutions in irrigating. The solutions were made up using the same fertilizers except for those supplying potassium. The potassium source was KCl, K_2SO_4 or KNO_3. As a consequence the ammonium to nitrate ratio differed between solutions as well as the chloride or sulphate content. Elemental nutrient content except for that of S and Cl was equal. An identical experiment was performed on each fruit type. One new shoot was permitted to develop per tree after heading the trees back to above the graft union. New shoot length was measured weekly from mid- or late December, 2013, until late January, 2014. On the last date of measurement, the new shoots were cut from the trees, and number of leaves initiated and fresh and dry weight determined. Growth was most vigorous in the trees treated with the solution made up with KNO_3. Vigour differences relating to KCl or K_2SO_4 as the K source were not apparent. Leaf number per shoot, or shoot fresh or dry weight bore a direct relationship to shoot length. This signifies that differences in length were not solely due to differences in the extent of inter-node extension, and also occurred as a result of differences in dry matter accumulation.

Orange, banana, tomato: The benefit of ameliorating the effects of salinity in using KNO_3 as opposed to KCl or K_2SO_4 as the potassium source in making up fertigation solutions was demonstrated. An identical experiment was performed on each fruit type. Nursery Valencia orange trees, and Williams banana and Rodade tomato plants, were transplanted into 2.7 l pots containing river sand or river sand/calcium carbonate (80:20 v/v), and treated with one of four nutrient solutions. One solution contained only $Ca(NO_3)_2$ and NaCl, and was applied to all the plants. The remaining three solutions were made up using the same fertilizers except for that supplying K. The K source was KCl, K_2SO_4 or KNO_3. As a consequence the NO_3^- to NH_4^+ ratio differed between solutions as well as the Cl^- or SO_4^{-2} content. NaCl was added to every solution to impose salinity stress. Elemental content except for that of S and Cl was equal in the K-containing nutrient solutions. In each experiment, growth was most vigorous in the plants treated with the solution made up with KNO_3 and least vigorous in the plants treated with the solution made up with KCl. This was reflected by height increases, and fresh weight and number of leaf differences when the plants were lifted. Number of primary roots in banana was commensurate with vigour. Number of leaves showing marginal necrosis in banana or number of wilted leaves in tomato indicated greatest salinity stress following fertigation with the solution made up with K_2SO_4. In tomato, number of flower trusses, fruit number and yield were greatest where the KNO_3 solution was applied and least where KCl solution was applied. Differences in individual fruit weight were not observed.

Further research can be carried out to assess the inclusion of KNO_3 as opposed to K_2SO_4 or KCl in a number of other crops. The trials already carried out consistently show superior performance of fertigation solutions where KNO_3 is used as the K source under saline or non-saline conditions.

Potassium Sulfate as a Key to Crop Quality

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Abstract
Applying the right amount of potassium (K), at the right time and the right placement – while sticking to balanced fertilization – has many positive impacts on crop yield and quality. Furthermore, concerning crop yield and particularly crop quality, one of the main factors to be considered in nutrient management is the right source of potassium.

Generally, potassium fertilizers are available in the form of potassium chloride (KCl- , muriate of potash – MOP) and potassium sulfate (K_2SO_4, sulfate of potash – SOP). While a wide range of crops is tolerant to chloride, other crops such as potato, vegetables or fruits are chloride-sensitive. These crops accumulate excessive amounts of chloride in their cells and the strong osmotic effect causes toxicities or reduces the transport and storage of assimilates.

In potato, MOP, compared to SOP, increases the content of free amino acids and phenolic components which lead to processes of enzymatic browning. Also, SOP results in higher starch contents of the tubers due to the better translocation and storage of assimilates.

Within the citrus crop, fruits are heavier, contain more juice and sugar when fertilized with potassium in the form of SOP.

Pineapple is also a crop that profits from potassium fertilization in the form of SOP. It has been found that chloride negatively affects fruit yield and size and some internal fruit characteristics, such as sugar-acidity ratio or flesh color.

Furthermore, by delivering a balanced amount of potassium and sulfur, SOP is very suitable to increase the yield and quality of oil crops such as rapeseed or sunflower.

The aim of this paper is to describe the role of potassium and under which situations SOP is recommended for (i) a partly chloride tolerant crop, such as pineapple, (ii) chloride sensitive crops, such as potato, citrus and grapes, and (iii) high sulfur demand crops, such as oilseed crops.

Keywords: potassium chloride, potassium sulfate, crop quality, chloride sensitivity

INTRODUCTION

Since the 1960s, food production has increased greatly. The “Green Revolution” raised cereal yields due to new crop selection and the use of pesticides and fertilizers. Nowadays the global population reaches six billion people, but it is estimated it will be doubled by 2050. Restoring soil fertility is amongst the agronomic practices that has to be continued and improved in order to be able to attain future nutritional demands in a sustainable way (Tilman et al. 2002).

Potassium (K) is a macronutrient needed for plant growth, drought tolerance and fruit or seed quality. Although this element is present in many soils, its release is slower than the amount demanded by current high yielding crops. Fertilizer use complements the nutrients supply. Generally, K fertilizers are presented

in the form of potassium chloride (KCl^- , muriate of potash – MOP) and potassium sulfate (K_2SO_4, sulfate of potash – SOP), amongst others. Chloride is one of the essential plant nutrients, but might cause negative effects if applied above the plants requirements. While a wide range of crops is tolerant to chloride, other crops are chloride-sensitive. These crops accumulate excessive amounts of chloride in their cells and the strong osmotic effect causes toxicities or reduces the transport and storage of assimilates.

In addition to be a chloride free fertilizer, SOP is very suitable to increase yield and quality of oil crops such as rapeseed or sunflower by delivering a balanced amount of potassium and sulfur. The aim of this paper is to describe the role of potassium and under which situations SOP is recommended for a (i) partly chloride tolerant crop, such as pineapple, (ii) chloride sensitive crops, such as potato, citrus and grapes, and (iii) high sulfur demand crops, such as oilseed crops.

SENSITIVITY OF CROPS TO CHLORIDE

Chloride (Cl) is a micronutrient. With a minimum of 1 g/kg^{-1} dry matter, plants fulfill their requirement for vegetative growth (Marschner 2012; White & Broadley 2001). Nevertheless, according to the existing amount of Cl on soils, and the sensitivity of the crop, its presence may harm plants.

Excessive concentration of chlorine in the root zone may cause osmotic stress (Lamond & Leikam 2002). Moreover, a large amount of Cl in the cytoplasm may shift other ions from the binding site of enzymes compromising the cellular functioning (George, Horst & Neumann 2012). In addition, it may interfere with the translocation and accumulation of assimilates, and the synthesis of chlorophyll and photosynthesis (Beckerman &Lerner 2015) and obstruct the uptake of other nutrients (George, Horst & Neumann 2012).

The reaction to chloride accumulation varies according to the plant species. In saline sensitive plants, even low concentrations of salt may limit growth and produce leaf necrosis (George, Horst & Neumann 2012; Maas 1993; Sykes 1992). This kind of response is divided into four categories: “chloride loving”, “chloride tolerant”, “partly chloride tolerant” and “chloride sensitive” crops (K+S n.d.).

Amongst the “chloride loving”, we find celery, sugar beet, fodder beet, coconut and swiss chard. In the “chloride tolerant” group, cereals, maize, rice, oilseed rape, soy bean, sugar cane, oil palm, cotton and banana stand out. In this case, Cl based fertilizers may be used, although many vegetables would benefit from sulfur fertilizers, due to the high uptake of this element.

Crops considered “partly chloride tolerant” include sunflower, stone fruits, grape vines, seed potatoes, potatoes for human consumption, tomatoes, carrots, tea, coffee and pineapple. MOP may be used if it is applied prior to vegetative growth. The “chloride sensitive” group consists of starch potatoes, potatoes for processing, citrus, berries, mango, pomes and stone fruits, broad beans, early vegetables, and crops growing under glasshouse, amongst others.

PINEAPPLE

Pineapple (*Ananas comosus*) is ranked as the third major tropical fruit worldwide after banana and citrus (Bartholomew, Paull & Rohrbach 2003). It can be consumed fresh, sliced and as juice. Costa Rica, Brazil and Thailand were the greatest pineapple producers in 2013, harvesting 2.69, 2.48 and 2.46 million tons respectively (FAO STAT 2016).

Potassium is the highest required nutrient for pineapple production. It has positive effects for plant growth, fruit yield, fruit quality and boosts the synthesis of sugars and acids (Lacoeuilhe 1978, 1984; Nanayakkara, Herath & Senanayake 2005; Spironello et al. 2004; Teixeira, Quaggio & Mellis 2011b). This macronutrient increases total acidity, preventing internal browning during storage at chilling

temperatures (Marchal, Pinon & Teisson 1981; Nanayakkara, Herath & Senanayake 2005). Moreover, ascorbic acid is fostered by this element, thus the fruit color of the pulp is intensified (SOPIB 2015). The amount of K required by this production doubles the nitrogen demand (SOPIB 2015).

The source of potassium applied to pineapple may affect its production. Some authors consider this tropical plant to be a chloride sensitive crop. Although MOP is the most frequently used source of K because it is cheaper than SOP, the chlorine presence in MOP may have some negative effects. In addition, sulfur requirements are high. Due to this two conditions, SOP may be, in many circumstances, the most appropriate source of K for pineapple production (SOPIB 2015).

Large amounts of Cl may obstruct the uptake of K, leading to symptoms that are alike to those present in extreme potassium deficiency, such as reduction in fruit size, decrease in dry extract, a measurement of sugar content (Fig. 1) (Lacoeuilhe 1978; Manica et al. 1984; Marchal, Pinon & Teisson 1981; SOPIB 2015; Teixeira et al. 2011a). In addition, the excess of this element in the tissue, may cause leaf necrosis (SOPIB 2015). Fertilization with MOP is not harmful if the concentration of chlorine in the "D" leaf, the most recent fully developed leaf, is not higher than 17 g kg^{-1} (Py, Lacoeuilhe & Teisson 1984; Teixeira, Quaggio & Mellis 2011b).

Biomass accumulation diminishes linearly when the amount of Cl increases in the "D" leaf (SOPIB 2015; Teixeira, Quaggio & Mellis 2011b). This may be the case in MOP or MOP plus SOP applications. In addition, when SOP or MOP plus SOP are applied, pineapple yield response is linear, whereas in MOP fertilization the response is quadratic. This means that, at high rate of muriate of potash applications, yields do not increase significantly. This might be related with chloride toxicity at high KCl rates (SOPIB 2015; Teixeira, Quaggio & Mellis 2011b).

With regard to fruit quality parameters, it was found that SOP increases 18.5 % fruit weight, 17.8 % weight of fruit flesh and 24.4 % sugar/acidity ratio (Figure 1) (Manica et al. 1984). In the case of fruit weight, other studies agree with the positive results SOP has compared to MOP (Lacoeuilhe 1978; Manica et al. 1984; Samuels & Gandia-Diaz 1960; Sanford 1968; Su & Li 1963; Tay 1972).

Under certain conditions, it is not clear whether sulfate of potash presents advantages over muriate of potash and visceversa. In order to lower internal browning during storage and transport, acidity in the fruit should be high (Gething 1991). On the one hand, some studies show that in fields were fruits have low acidity, MOP is recommended rather than SOP, because acidity is fostered by MOP fertilization (Gething 1991; Marchal, Pinon & Teisson 1981; Teixeira et al. 2011a). Fruits applied with MOP increased their acidity rate from 25 to 33 % of the total acidity rate, compared to those with SOP (Py, Lacoeuilhe & Teisson 1984). On the other hand, another experiment showed a reduction in internal browning when, in presence of light, 5% SOP was sprayed at pre and post harvest plus 5% Ca(OH) and10 ppm ABA. Since MOP was not used, no comparison can be made between the two fertilizers (Nanayakkara, Herath & Senanayake 2005). Finally, in a trial conducted in Brazil, there were no significant differences amongst the fertilizers regarding acidity (Figure 1) (Manica et al. 1984).

POTATOES

Potatoes (*Solanum tubersosum* L.) are known to be one of the major food crop in the world. In 2014, 385 million tons of tubers were produced worldwide (FAO STAT 2016). Because of its high dry matter production, potatoes are a cheap source of energy due to its large content of carbohydrate. This tuber also provides us with essential vitamins as well as important macro and micro nutrients.

Potato has different uses. They may be used for French fries production, chips, fresh consumption and "potato seed," pieces of tubers used to propagate potato. Thus, according to the market use, the recommendation on the amount and source of nutrients application differs.

Potassium is of great importance for potatoes. It not only increases tuber yields, but also improves tuber quality (Marschner 2012) and it is essential for risk management under stress conditions such as drought. Potassium increases starch, citric acid and vitamin content (Imas & Bansal 1999). It decreases the incidence of discoloration such as internal blackening and black spot (Beringer, Haeder & Linhauer 1983). Furthermore, K reduces the amount of reducing sugars (Herlihy & Carrol 1969; Kumar, Singh & Kumar 2004). These, when fried, are responsible for the darkening of potato chips and fries and the synthesis of acrylamide, a potential toxic substance (Kumar, Singh & Kumar 2004).

Due to its high yielding capacity and tuber formation, K requirements in potato are high, thus the recommended quantities of potassium to apply (Bansal & Umar 1998; Panique et al. 1997). Nevertheless, the rate varies according to the use. While potato for fresh consumption has high K rate applications in order to increases tuber size, potato tubers destined for seed production should not be so heavily fertilized, because the aim is to obtain small tubers. Potato destined to chips production should not be very highly fertilized. Excessive K concentrations may reduce dry matter content, hence industry standards would not be complied (Imas & Bansal 1999).

Potassium expedites the transport of assimilates from the leaves to the tubers (Beringer, Haeder & Linhauer 1983) and is therefore essential for the synthesis of starch. Research shows that there is a difference in the applied K source as muriate or sulfate of potash on starch content of tubers. MOP significantly decreases starch content compared to SOP. Potato plants fertilized with SOP have a higher rate of transport of assimilates into the tubers compared to those with MOP (Beringer, Koch & Lindhauer 1990; Haeder 1976). The application of MOP can lower the starch content from 1.5% (Orlovius 1996) to 2% (Lampe 2007) compared to SOP treated plants.

For chips production, potatoes with high dry matter content are needed because this provides crunchiness to the snack (Imas & Bansal 1999; SOPIB 2015). Dry matter content increases with SOP fertilization, due to a higher tuber: shoot ratio (Beringer, Koch & Lindhauer 1990). In plants fertilized with MOP, there is uptake of Cl^-. Consequently, the plant stimulates shoot growth in order to enclose this element in the shoot. Thus, the tuber: shoot ratio in plants treated with MOP is lower than in SOP. Leaves collected at three different days exhibit lower osmotic potentials and higher amount of water (Beringer, Koch & Lindhauer 1990). For French fries production, the content of dry matter is not as relevant as in chips production and for table production this parameter is not significant (Imas and Bansal, 1999). In order to obtain tubers with high yield, potato should be fertilized with K_2SO_4 rather than KCl (Bansal 2003).

Potassium fertilization increases tuber mechanical stress resistance. Hence, incidence of black spot injuries decrease (Beringer, Haeder & Linhauer 1983; SOPIB 2015). Concentration of K in the cell sap becomes higher, promoting turgor pressure. Higher firmness of the tuber lowers the risk of lesions in the skin during harvest and handling. The exposure of some phenolic components and free amino acids to oxygen, result in an undesired brown coloring (Beringer, Koch & Lindhauer 1990; Mondy & Munshi, 1993). The source of K has an influence in this response. Potato plants applied with SOP have less content of free amino acids and phenolic components compared to those fertilized with MOP (Singh, Marwha & Grewal 1996), hence they are less susceptible to browning.

For the production of french fries and chips is necessary that the content of reducing sugars is low. When heated, glucose and fructose go through the Maillard reaction, a non-enzymatic process that causes discoloring and changes in flavor. In addition, when fried, reducing sugars react with free amino acids producing potential toxic substances such as acrylamide (Kolbe & Haase 1997).

There are different studies that analyze the effect of MOP and SOP on reducing sugars with different results. On the one hand, some papers argue that there is no difference between the chloride based and the sulfur based fertilizer with regard to the reducing sugar content (Kumar, Singh & Kumar 2004; Stanley &

Jewell 1989). Others detected that when the K amounts are high, there is less unwanted browning coloration, no matter the source (Kumar, Singh & Kumar 2004; Murphy & Goven 1966). On the other hand it is discussed that when SOP is applied, the concentration of reducing sugars increases (Singh, Marwha & Grewal 1996). Finally there are studies that show that SOP may decrease the reducing sugars content but when compared the chip score, the higher the amount of K applied, the difference amongst the sources vanishes (Anonymous 2000; Bansal & Trehan 2011).

CITRUS

The large amount of different varieties of citrus fruits hold a great contribution of consumed fruits worldwide. By the year 2013, 136 million tons of citrus were produced, 53% correspond to oranges, 21% tangarines, mandarins, clementines and satsumas, and 11% lemons and limes (FAOSTAT 2016). They are well known for being a natural source of vitamin C and vitamin B complex.

Potassium plays a major role in different aspects of citrus fruit production. On the one hand it is involved in the production and transport of essential metabolites such as sugar, starch and protein (Ashraf et al. 2013; Liu et al. 2000). Since synthesis of vitamin C is influenced by sugar metabolism, an adequate K nutrition management may foster the production of this important biomolecule. On the other hand, potassium directly affects fruit quality. Many studies show that it is positively correlated to fruit size, juice volume per fruit, color and yield (Abd-Allah 2006; Alva & Tucker 2006; Ashraf et al. 2010; Quaggio, Junior & Boaretto 2011).

Potassium not only enhances fruit quality aspects. It is also essential for increasing water use efficiency (WUE) under saline conditions (Marchand 2007). An experiment conducted in Turkey compared WUE of two rootstocks (*Troyer citrange* and *Poncirus trifoliate*) for Satsuma mandarin (*Citrus unshiu*) fertilized with different rates of SOP (0, 600 and 1200 g K_20/tree) and irrigated with saline and highly saline water (3.5 and 6.5 dS/m). In the case of *Poncirus trifoliate*, WUE increased under optimum and high doses of K when the water was highly saline, but in the saline irrigation treatment, only high amounts of K improved this characteristic. In the case of *Troyer citrange*, WUE increased with K under saline conditions, but for highly saline treatments, WUE increased till the optimum application, 600 g K_20/tree, further fertilization did not improve WUE for this rootstock (Marchand 2007).

The use of MOP as source of potassium in citrus plantations is widely extended. Nevertheless, citrus is a chloride sensitive crop and this kind of fertilizer may be harmful for the trees (Bañuls & Primo-Millo 1992). The degree of sensitivity depends on the species, for example, lemons are more sensitive to Cl than oranges (Lloyd et al. 1989). Potassium application in citrus is high. If citrus under saline soils are fertilized with MOP, uptake of chlorides may be in large amounts. Thus, the concentration of Cl in the tissue will be sufficiently large to decrease tree growth and fruit quality. Due to this drawback, citrus production under saline soils can be fertilized with SOP to avoid this disadvantage (SOPIB 2015). Nevertheless, for some quality parameters, in some species, there are no differences based on the source of potassium.

Considering quality parameters such as color, total soluble sugars (TSS) and juice content, the combination of sources and rates of potassium have different effects on these parameters. Although K enhances color, large amounts may produce the opposite effect. Fruit remains green under high K concentrations (Hamza et al. 2012; Koo 1988). Fruit coloration was delayed in clementines fertilized twice with 4% K_2SO_4. High K concentrations increase TSS, but the impact from source is minimum, KNO_3 slightly rises TSS compared to K_2SO_4 (Hamza et al. 2012). In Kinnow (Citrus deliciosa x Citrus nobilis), SOP application may enhance juice content per fruit, compared to MOP (Ashraf et al. 2013).

Regarding fruit weight, the results of fertilization with MOP and SOP vary according to the citrus species. In Kinnow (Citrus deliciosa x Citrus nobilis), trees with SOP applications gave heavier fruits compared to

those with MOP. In Clementine var. Cadoux, under low and medium foliar K rates, higher yields were obtained with KNO_3. Meanwhile, under high K fertilization, fruits were heavier when K_2SO_4 was applied (Hamza et al. 2012). In Nagpur mandarin (Citrus reticulate cv. Blanco), the average fruit weight was higher when mono-potassium phosphate (MKP) was applied, followed by SOP and MOP, respectively (Shirgure & Srivastava 2013). On the contrary, in oranges (Citrus sinensis L.) and Marsh' grapefruit, the average fruit weight was similar amongst trees treated with either MOP or SOP (Koo & Reese 1972; Quaggio, Junior & Boaretto 2011).

GRAPES

Grapes are consumed as table grapes or as the input for wine production. In 2013 France, Italy, United States of America and Spain were the main producing countries, and 27.4 million tons of wine were produced worldwide (FAOSTAT 2016).

Due to its participation in carbohydrate synthesis, K plays a significant role in wine, juice and fresh grape production. This metabolic process affects pH, acid balance in grape juice and the color of wine (Christensen, Kasimatis & Jensen 1978; Hale 1977; Morris, Cawthon & Fleming 1980; Somers 1977). The higher the color density of wines, the better quality ranking position (Delgado et al. 2004; Somers and Verette 1988). Moreover, TSS in grape juice and acid content increase with greater K fertilizations (Dhillon, Bindra & Brar 1999). Color and astringency of wines is boosted by potassium applications, due to the higher content of phenols, anthocyanins and tannins (Delgado et al. 2004).

A precise balance between nutrient requirements, root growth and time of soil reactivity is the key to obtain high yield and quality table grapes (Ruiz & Sadzawka 2005; SOPIB 2015). To achieve this aim, the timing for potassium fertilization is essential. Before plant growth and root competition start, 67% of the yearly demanded total K should be applied. In this way, this nutrient will be available during flowering and fruit formation. The other 33% should be provided after controlling the concentration levels in leaves, at the time grapes are coloring or at the end of the summer. Hence, the K supply will be sufficient for the post-harvest period (SOPIB 2015). In the case of wine grapes, the demand for this element is lingered, from coloring berry stage to harvest (Rodríguez et al. 1974; SOPIB 2015).

Grape vines are partly chloride sensitive. This means that Cl based fertilizers may be used if they are applied before vegetative growth and on time (K+S n.d.). Nevertheless, SOP may be an interesting option for grapes vines under soils with high calcium carbonate concentrations and to enhance wine quality.

The application of SOP may be beneficial for wine production under calcareous soils. The sulfate anion in SOP lowers the pH in the soil. If the calcium concentration is really high and phosphorus is insoluble, SOP acidifies the soil, releasing it from the soil matrix (SOPIB 2015).

Sugar content, the alcoholic degree and quality of wine can be improved by SOP fertilization (Table 1). In addition, SOP reduces potassium deficiency risk, and preserves the soil as a result of its low salinity index. The color of wine is intensified when SOP is applied. Under the French experts to taste / test wine quality standards, optimum results are obtained when 120 kg K_20 of SOP are applied (SOPIB n.d., 2015). Finally, grape yield increases with the use of SOP, by rising the number and weight of fruit bunches (Figure 2) (Edelbauer 1979).

OILSEED CROPS

Oilseed crops are used for human consumption, animal fodder and for industrial activities. In 2013, 42.7 tonnes of soybean oil were produced, whereas 24.7 tonnes of oil rapeseed and 12.6 tonnes of sunflower. Soybean, rapeseed and sunflower ranked as the first, third and fourth major vegetable oil producers respectively (FAOSTAT 2016).

Oilseed crops have a high sulfur demand. This nutrient plays an important role in the setting up of sulfur based amino acids, and therefore of protein formation, synthesis of plant resistance precursors, such as pythoalexines and glutathione, triggering of enzymatic reactions in the metabolism of energy and fatty acids, and promotes nitrogen use efficiency. The demand of sulfur is higher in oilseed crops than in cereals, approximately four times more in order to produce one ton of produce (SOPIB 2015). Nevertheless, S application should be within a well-adjusted fertilization plan together with other nutrients with the intention of harvesting high quality and large amount of oilseed rape (Ahmad, Abraham & Abdin 1999).

Crops cannot directly uptake elemental S because it is not plant-available. Sulfur needs to be oxidized into sulfate-S in order to be absorbed by plants (Bettany & Janzen 1984; Malhi, Schoenau & Grant 2005; Solberg and Nyborg 1983; Wen et al. 2001). Although elemental S fertilizers have higher amounts of nutrient per weight of product, due to the slow release of S, annual crops grown on depleted S soils won't benefit from this source (Malhi, Schoenau & Grant 2005; Noellemeyer, Bettany & Henry 1981). Due to the high demands of S, canola crops have higher yields when the soil has S in the form of sulfate (Malhi, Schoenau & Grant 2005; Nyborg 1968).

In rapeseed, some studies performed in Canada compared different sulfate based fertilizers with elemental S applications (Malhi, Schoenau & Grant 2005). Although elemental S may increase seed yield, sulfate-S fertilizers have a bigger impact, even after four yearly applications. This difference is larger if it is applied in spring at sowing time (Table 2) (Malhi & Leach 2003; Malhi, Schoenau & Grant 2005). In addition, a study carried out in India indicates that an equilibrium between N and S is needed in order to achieve high quality yield. Under deficient amounts of S, synthesis of proteins and enzymes is inadequate. A balance nutrition lessens the amount of toxic concentrations of non-protein N. The maximum oil content was achieved with 60 kg S ha^{-1} and 100 kg N ha^{-1} (Table 3) (Ahmad, Abraham & Abdin 1999; Malhi, Schoenau & Grant 2005).

In France, SOP application on rapeseed at the end of winter increases yield. The amount of rainfall during the winter months in the regions of Poitou-Charente and Centre of France indicates the S deficiency risk. Under balance nutrition of NPK, a top dressing with SOP at the end of winter seems to satisfy S and K demands of rapeseed (Fauconnier 1983; Kemmler & Tandon 1987).

In the United States of America, in Kansas, soybean grown under conservation tillage has a higher yield when less than 100 lb/A of SOP is applied at planting in furrow compared to MOP. When the fertilizer is close to the seed, the probability of salt injury is higher with MOP compared to SOP due to its high salt index. Moreover, the larger the amount of fertilizer applied in furrow, the higher the probability of damaging the seedling. This disadvantage is avoided when the fertilizer is applied two inches to the side and two inches below the seed (2x2) at sowing. Under this practice, there is no difference in yield with either source of K fertilizer (Table 4) (Gordon 1999).

CONCLUSIONS

In this paper, we describe the role of potassium on different crops and define under which situations SOP is recommended for pineapple, potato, citrus, grapes, and oilseed crops. These are our conclusions:

- Potassium enhances fruit or seeds quality attributes such as amount of sugars, color and juice content in pineapple, citrus and wine production. In the case of potato, it also increases starch content.
- Sulfur demand in oilseed production is high. It is approximately four times the Sulfur demand of cereals. This element is essential for the synthesis of S-based amino acids and proteins and plant resistance precursors.

- Due to the fact that SOP is a chloride free fertilizer, its use is recommended under saline conditions or saline irrigation systems. In addition, the sulfate anion present in potassium sulfate lowers the pH and releases the P in highly calcareous soils.
- Chloride sensitive crops may benefit from the application of SOP when fertilization rates are high. Large amounts of MOP increase Cl content in the root zone. This might interfere with the uptake of K or harm tissues due to the presence of toxic concentration of this element.
- In in-furrow soy bean crop systems, under low and optimum K rates, SOP is recommended. Its lower salt index reduces the probability to harm the seed during germination.
- In potato, SOP increases starch content, reduces browning and improves resistance to mechanical stress. Concerning the amount of reducing sugars, it is not yet clear whether SOP or MOP has better results to reduce their content in tubers.
- In oilseed crops, it is recommended the use of sulfate based S fertilizers, such as SOP, compared to element S fertilizers in order to facilitate sulfur uptake and increase yields. In order to obtain high quality seeds, the amount of N and S should be balanced. In canola, maximum oil content is achieved with 60 kg S ha^{-1} and 100 kg N ha^{-1}.

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TABLES AND FIGURES

Table 1. The effect of different potash fertilizers on grapes on sugar concentration, titratable acid, tannin content and frost sensitivity at flowering (Edelbauer 1979)

Potash fertilizer	Sugar content		Tritable acid		Tannin content		Frost sensitivity	
	(g/l)	rel.	%	rel.	(mg/l)	rel.	(%)	(rel.)
Muriate of potash (MOP)	153.8	100	7.3	100	185	100	30.8	100
Sulfate of potash (SOP)	160.2	104	7.65	105	208	112	28.6	93

Table 2. Seed yield from various S fertilizers applied at two rates in autumn and spring to canola near Tidsale in northeastern Saskatchewan (Adapted from Malhi et al. 2005; Malhi & Leach 2003).

Treatment			Seed yield (kg ha^{-1})			
Fertilizer †	Rate of S (kg ha^{-1})	Time of application	1999	2000	2001	2002
			Source of S x rate of S			
ES-90	10		26	196	222	727
	20		40	370	337	797
ES-95	10		41	175	173	562
	20		68	421	257	760
AP	10		96	616	383	945
	20		394	859	478	1073
AS	10		251	744	435	968
	20		587	861	448	1165
	SEM ‡		29.2§	43.9 ns	22.7 ns	40.2 ns
			Source of S x time of application			
ES-90		Autumn	48	466	344	898
		Spring	18	99	215	626
ES-95		Autumn	88	459	282	753
		Spring	21	137	148	569
AP		Autumn	189	750	414	1036
		Spring	300	725	447	983
AS		Autumn	214	734	446	1030
		Spring	624	870	438	1103
		SEM ‡	29.2§	43.9§	22.7§	40.2§

†ES: Elemental S; AP: Sulphate Plus containing elemental S and sulfate-S; AS:ammonium sulfate
‡SEM: standard error of the mean
§ Significant treatment in ANOVA at $P \leq 0.001$
ns: not significant

Table 3. Interactive effects of nitrogen and sulfur on seed and oil yields of rapeseed (Brassica campestris cv. Pusa Gold) (Adapted from Ahmad et al. 1999).

Treatments (T) †	Seed yield (t ha^{-1})	Oil yield (q ha^{-1})
T_1	2.81	12.9
T_2	4.52	22.6
T_3	6.94	33.6
T_4	6.12	29.6
T_5	6.58	31.6
LSD (0.05) Treatments (T)	0.317	1.097

† T1 = 0S + 100N; T2 = 40S + 60N; T3 = 40S + 100N; T4 = 40S + 100N; T5 = 60S + 150 N
‡ LSD: least significant difference

Table 4. Effect of starter (7-21-7) placement, rate and potassium source on soybean yield (Adapted from Gordon 1999).

	Placement			
	In-furrow		2 x 2	
	SOP	MOP	SOP	MOP
0	197	197	197	197
50	196	160	198	198
75	196	158	198	198
100	192	152	198	198
150	154	142	199	197
200	152	139	198	197

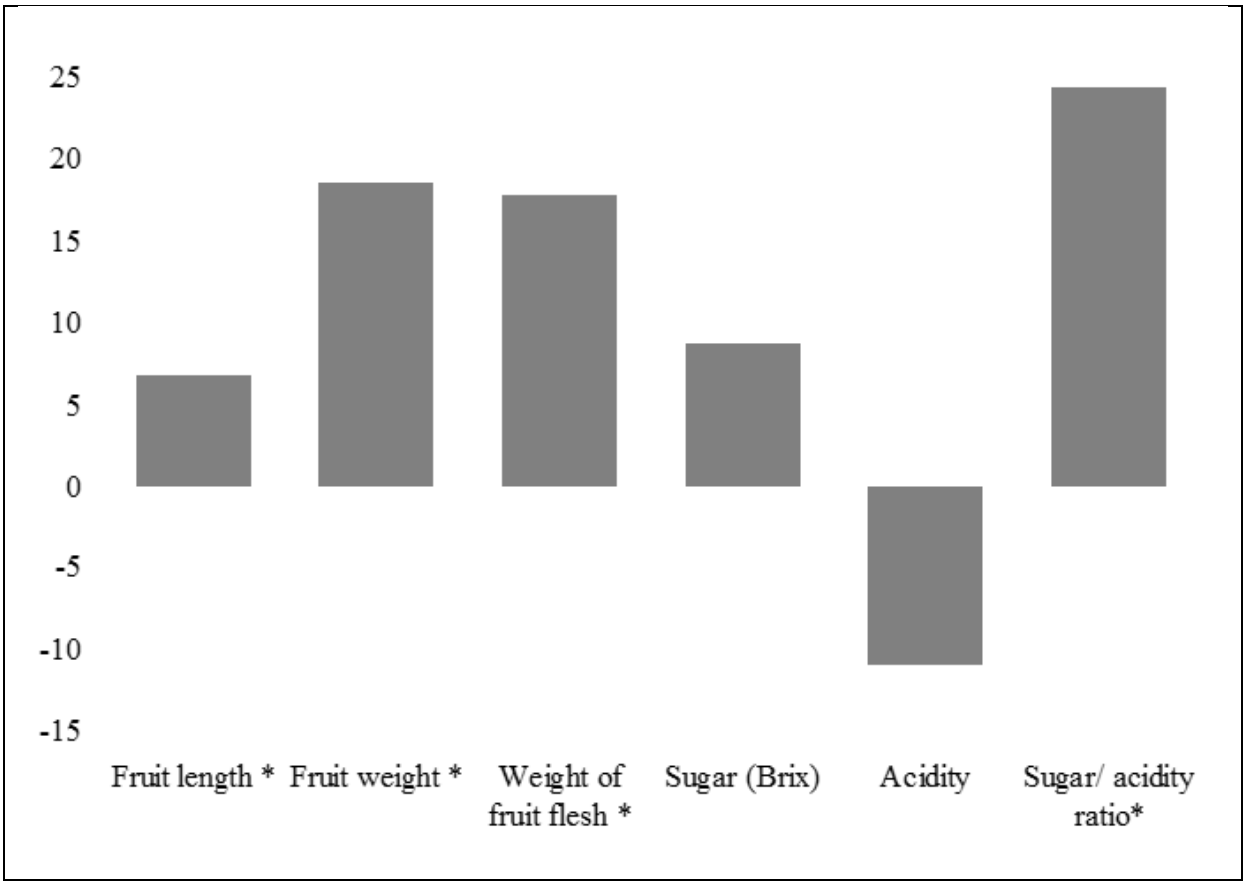

Figure 1. Effect of replacement of potassium chloride by potassium sulfate on size, weight and quality aspects of pineapple (Adapted from Manica et al. 1984)

* Not significant (Duncan test α=5%)

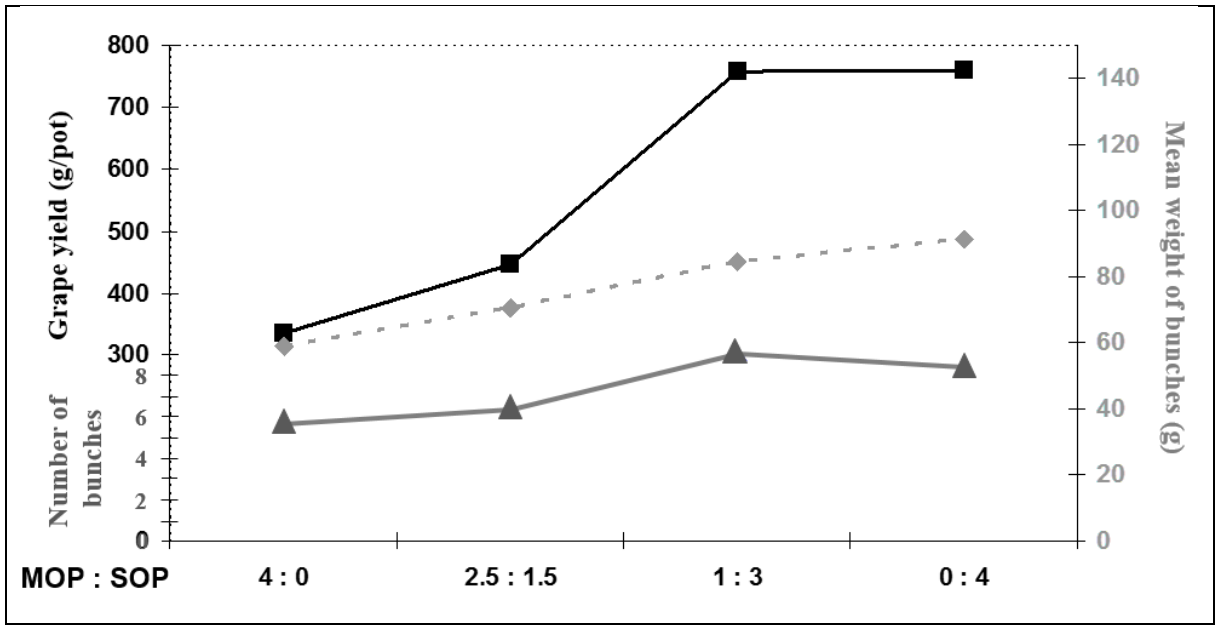

Figure 2. Effect of SOP on grape yield by increasing number and weight of fruit bunches (Edelbauer 1979)

A Novel Potassium Fertilizer Derived from K-Feldspar

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Abstract
The most widely used ingredient of potassium fertilizers is KCl. While relatively cheap and abundantly available in the northern hemisphere, supplies of KCl in the Global South can be expensive and/or scarce, mainly due to the logistics required for North-South transportation. An additional important limitation is that soils around the world present remarkably different physico-chemical characteristics, but only one type of fertilizer available at large scale exist, i.e. KCl. This is particularly problematic in tropical soils, where the high solubility of KCl results in non-negligible leaching losses and low residual effect. Here, we propose a novel fertilizer derived by hydrothermal processing of K-feldspar in presence of CaO. A detailed characterization of the hydrothermal product is proposed, which include X-rays diffraction (XRD), Particle Size Distribution (PSD), and bench-top leaching tests. Preliminary results on agronomic yields for maize are also presented. Such promising results coupled with a simple economic model suggest a new opportunity to re-think potassium fertilization in tropical soils.

Keywords: potassium chloride (KCl), K-feldspar, tropical soils, materials characterization

How can Resins be Utilized to Improve K Rate Recommendations

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Abstract

Ion exchange resins have been used in some countries to extract ions from soils for agronomic and environmental assessments. In Brazil over 100 commercial laboratories adopt ion-exchange resin on a routine basis and more than 2 million soil samples are analyzed every year, attesting the method's feasibility. Resin beads (~0.4 mm) are used in Brazil, which are mixed with the soil samples and stirred overnight for 16 h before ion determination. This shaking period is necessary especially for P and Ca extraction; around 4 h are usually sufficient to extract exchangeable K from organic matter and the 1:1 mineral fractions or Fe and Al oxides that predominate in the highly weathered Brazilian soils. Although the Brazilian experience with 2:1-type minerals is rather limited it can be expected that the long shaking time may favor the extraction of K forms in addition to easily removed exchangeable fraction but this remains to be tested. Initially the resin procedure was introduced because it gives a better diagnosis of P availability than other soil extractants for Brazilian soils. However, early work showed that K, Ca, and Mg extracted by resin was equivalent to the soil exchangeable fractions of these elements; therefore, this is an advantage of extracting four nutrients at once. The error or variability of resin-K determination in commercial laboratories is low: only 2% of the results of grade A laboratories in the proficiency test (65% of a total of 114 laboratories) are outside the confidence interval. The calibrations for resin soil K used for fertilizer recommendation are basically the same for exchangeable K developed in the 1970's to 1990's; however, more recent work allowed successful soil K calibrations with ion resins. Therefore, the resin method is a feasible and proven option to assess soil available K and guide fertilizer recommendations for agricultural crops.

INTRODUCTION

Potassium fertilization is important in Brazil because of the predominance of soils of low CEC and low fertility, especially in the central region where most of the grain is produced nowadays.

Soils analysis has always played an important role in guiding fertilizer recommendations in Brazil. Exchangeable K correlates well with plant responses to K and is the main criteria, in addition to crop export, to determine K rates to be applied to most crops. Extensive field calibration studies for exchangeable K were done in in Brazil in the 1960s to 1990s with crops such as cotton, maize, soybeans, sugarcane, and citrus (Cantarella et al., 1998). Recently Schlindwein et al. (2011) updated soil K calibration for no-till in Southern Brazil.

Phosphorus deficiency and soil acidity are the major fertility constraints in Brazilian soils (Lopes and Guilherme, 2016). The development of a reliable method for the determination of plant available P in tropical soil has always been a matter of interest in Brazil. An ion exchange resin procedure was developed in the early 1980's and since then is used in routine in this country.

Ion exchange resin has been known as an extractant of soil nutrients for a long time. Following the pioneer work on the resin method for P extraction in soil by Amer et al. (1955) the topic soon called the attention of other authors (Sibbesen, 1977, Smith, 1979, Moser et al., 1959, Raij and van Diest, 1980) and the several variations of the resin procedure continue to raise interest of soil scientists (Schlindwein et al., 2013, Datta et al., 2012, Bortolon et al., 2010, Schlindwein and Gianello, 2009, Schlindwein and

Gianello, 2008, Vandecar et al., 2011). Reviews on the subject highlighting the advantages of the resin procedure for P extraction includes the works of (Raij, 1994, Raij et al., 2009, Silva and Raij, 1999).

Ion exchange resins can also extract other elements from the soil. There are several variations of resin methods, which include resin beads that are mixed with soil (Raij et al., 1986), resin capsules or bags shaken or incubated with soil (Dobermann et al., 1996, Smith, 1979), ion membranes that can be either shaken with soil samples in the laboratory (Qian et al., 1992) or inserted in the soil directly in the field or in laboratory and retrieved for analysis later (Mallarino and Atia, 2005, Schlindwein and Gianello, 2009, Qian et al., 1996), and resin disks (Datta et al., 2012). A comprehensive review on the subject was written by Skogley and Dobermann (1996)

In the case of Brazil, the main interest in the resin method was for P extraction, which requires anionic resins. However, previously work indicated that the addition of cationic resins improved P extraction as compared to the anionic resin alone (Vaidyanathan and Talibudeen, 1970). Therefore, the procedure developed and used in Brazil included a mixture of anionic and cationic resins, allowing the simultaneous extraction of P, Ca, Mg, and K (Raij et al., 1986), which is advantageous for routine laboratories. Prochnow et al. (1998) showed that SO_4^{2-}-S can also be effectively extracted with resin. In Canada, Qian et al. (1992) used ion exchange resin membranes to extract P, K, N, and S, and concluded that the results of the resin procedure were better correlated with plant nutrient uptake than the conventional methods tested.

The resin method in the low CEC soils of Brazil has been quite effective to provide an index of K availability. In soils with 2:1 clay minerals resins have been used to extract nonexchangeable K and in kinetic studies, but a method suitable for routine laboratories to measure plant available K remains a challenge.

USE OF K FERTILIZER IN BRAZIL

Once the great majority of the Brazilian soils are extremely weathered, with clay fractions containing high amounts of secondary minerals such as kaolinite, gibbsite, goethite, and hematite, the available potassium in agricultural soils tend to be low (Resende et al., 2002), except for some costal soils, Vertisols in the south of the country, and some small portion of soils containing high amounts of K primary minerals (Benites et al., 2010). In a survey of soil properties in the Cerrado region in the 1970s, 85% of the samples of topsoil were shown to have low available K (Lopes and Guilherme, 2016). Therefore, the fast development of that region into the Brazilian food basket was dependent on proper soil management, including K application.

Potassium is the most used nutrient in the Brazil. In the year of 2015 the consumption reached 3.7, 4.7 and 5.4 million tons of respectively N, P_2O_5 and K_2O (ANDA, 2015). Figure 1 shows the increase in the consumption of all three main nutrients since 1960 in the Brazil. A sharp increase in the use of all nutrients was observed, with K_2O almost doubling in the last fifteen years. Brazil ranks second in the world in K consumption, 90% of which are imported, but is the first worldwide in annual geometric growth since the early 1990's (6.3% per year).

About 70% of the fertilizer consumption in Brazil is for three crops, i.e., soybean, maize and sugarcane. These crops are responsible for exporting around 10.6 million tons of K_2O, which represents 80% of the nutrient export by the 18 most important crops in Brazil. Therefore, proper fertilization, based on sound diagnostic criteria is of utmost relevance for Brazilian agriculture. A nutrient budget calculated by the International Plant Nutrition Institute in Brazil indicates that about 82% of the K_2O added as fertilizer is exported from the fields by the main crops (Cunha et al., 2014), which is a relatively good recovery rate when compared to other regions.

DEVELOPMENT OF THE RESIN METHOD

Best alternative for P diagnosis

Until the early 1980's, P extraction was based either on 0.025M H_2SO_4 or 0.05M HCl in 0.125M H_2SO_4 solutions in Brazil. Both methods give similar values. Phosphorus extraction with dilute strong acid solutions is often inadequate for tropical soils rich in iron and aluminum oxides – which predominates in Brazil – giving results frequently too low, even in soils well supplied with P (Raij et al., 1986). An example is shown in Figure 2, comparing the relation between soil extractable P and response of cotton to applied P fertilizer in 28 field experiments. When soil P was extracted with an acid solution it was difficult to separate sites that responded to fertilization (low relative yields, RY) from sites with no response (RY equal or close to 100) as soil analysis showed P values around 5 mg P dm^{-3} for RY ranging from 65 to 100. When the same soils were analyzed with the resin procedure the results of the non-responsive sites increased, producing a much better relation between soil analysis and plant response.

Soils treated with rock phosphates show high P results when extracted with acid solutions (Freitas et al., 2013, Raij and van Diest, 1980), which do not always reflect P availability for plants. Both situations – soils high in Fe and Al oxides and soils fertilized with rock phosphate - may result in inadequate P fertilizer recommendations.

The procedure developed by Raij et al. (1986) involves the simultaneous extraction of four nutrients from the soil samples by a mixture of equal proportion of strong basic anion exchange resin (Amberlite IRA 400) and strong acid cation-exchange resin (Amberlite IR-120). The resins need to be pre-conditioned during two weeks, using a diluted and slightly acidic solution containing K, Ca, Mg, S and P salts to obstruct the nonexchangeable sites inside the resin particles. The resins are maintained saturated with NH_4Cl and prior to use, are saturated with NH_4HCO_3. The mixed resin (2.5 cm^3) is added to 5 cm^3 of soil in a water medium and shaken for 16 hours. The resins are separated from the soil by sieving and the nutrients are extracted with a NH_4Cl solution and determined by various procedures.

An important step of the procedure is the disaggregation of soil by shaking in water during 15 minutes with a glass marble. It permits the rupture of very stable soil aggregates, increasing the diffusivity of the ions adsorbed inside this soil particles to the extracting solution. This step, associated with the lengthy shaking time (16 h, overnight) is fundamental to improve the nutrient extraction by resin in clayed soils. The 16-h extraction is necessary for P and Ca; preliminary tests indicated that K extraction from most soils was complete after about 4 h

Methods involving the use of resin are normally time-consuming and their adoption by routine laboratories is limited. In Brazil, following a long research effort that indicated that ion exchange resin provided better diagnosis of soil P availability, it was decided that the method should be adopted. Practical problems were overcome with the development of equipment and procedures to turn if feasible (Raij and Quaggio, 2001, Raij et al., 1986) and, in 1983 this method was introduced in routine laboratories. Nowadays, 114 laboratories, public and private, make use of this procedure (Cantarella et al., 2017). The performance of these laboratories for resin K in an interlaboratorial ring test indicated that only 2 and 4% of the samples analyzed were outside the established confidence interval, for laboratories graded A and B, respectively – those considered suitable according with the ring test rules (Table 1). Outside Brazil, other commercial use of a resin method for soil analysis is that developed at the University of Saskatchewan, Canada, in which a resin membrane is inserted in the soil for extraction of P, S, K, Ca, and Mg (Bremer et al., 2014).

Resin and soil K extraction

Exchangeable K, extracted with neutral 1 mol L^{-1} NH_4OAc solution, the standard for exchangeable cations, but also with ammonium chloride, calcium chloride and Mehlich 1 or Mehlich 3 solutions, is

widely used to estimate K availability to crops (Zörb et al., 2014, Helmke and Sparks, 1996). In Brazil, where the clay fractions are predominantly composed by 1:1 layer minerals or Fe and Fe oxides, exchangeable K provides a good estimate of soil available K (Cantarella et al, 1998; Nachtingall and Raij, 2005) and is the basis for K fertilizer recommendations. Raij and Quaggio (1984) cultivated three crops of brachiaria grass in a greenhouse in 24 soil samples which included B horizons of soils containing mica and feldspars. They found that brachiaria extracted more K than the exchangeable fraction especially from B horizons but, nonetheless there was a high correlation between exchangeable K and K uptake by the three cuttings of grass.

Resin-extracted K by the method developed by Raij et al. (1986) shows close relation with the exchangeable fraction extracted with neutral NH_4OAc solution (Figure 3); therefore, the calibration curves for exchangeable K calculated in previous years are also used for resin K, i.e. the range of soil interpretation values of soil K in the fertilizer recommendations tables are the same for exchangeable and resin K. Hence, K fertilizer recommendations in Brazil have been made using the resin method since 1984 by the laboratories that have adopted that procedure. The first soil calibration for K using resin in Brazil was elaborated by Quaggio et al. (1998), using data of a network of field experiments with citrus (Figure 4). In fact, that was the first calibration of soil analysis for citrus using field data. The equation calculated by Quaggio et al. (1998) for resin was very close to those obtained for exchangeable K for maize and cotton (Cantarella et al., 1998)

The extractants to measure exchangeable K are not always efficient in soils with 2:1 layer clay minerals that may have interlayer K fixation and nonexchangeable K fractions (Mengel and Kirkby, 2001; Zörb et al., 2014). Despite its shortcomings, exchangeable K is the most common indicator of soil K availability used (Helmke & Sparks, 1996). For instance, Havlin and Westfall (1985) concluded that NH_4OAc was a good indicator of long term K supply in calcareous soils even in soils that had nonexchangeable K. Several methods are used for the determination of nonexchangeable K in soils, including boiling HNO_3, hot HCl, sodium tetraphenylboron (NaTPB), and ion exchange resins (Helmke and Sparks, 1996). The hot HNO_3 method is the most commonly used method for nonexchangeable K but it is cumbersome and hardly adopted in routine (Zörb et al., 2014); in addition, nonexchangeable K may be only moderately available to crops (Helmke and Sparks, 1996) and sometimes show low correlation with plant uptake (Dobermann et al., 1996). Rayment (2013) argued that the exchangeable and nonexchangeable fractions combined offer more information than either separately but they do not unequivocally indicate situations in which soil K could supply enough nutrient for sugarcane in Australian soils. The author suggested that total K should occasionally be determined to help to guide K application, instead of relying only on labile and exchangeable fractions, and that K fertilizer should be applied when the ratio of total to exchangeable K are below 2 or 3. Total K is also a complex determination for routine analysis.

Ion exchange resins can also be used to determine nonexchangeable K in soils (Helmke and Sparks, 1996). In fact, since the early work of Arnold (1958) resins have been used for that purpose and were considered of promising value for soil fertility evaluations. Several authors used resins to determine the rate of release of fixed or structural mineral K and to study the kinetics of nonexchangeable K in soils (Feigenbaum et al., 1981, Martin and Sparks, 1983, Havlin and Westfall, 1985, Havlin et al., 1985, Dobermann et al., 1996). Although the K fractions extracted with resin in these studies helped to characterize K forms that are available to plants other than exchangeable K, the extraction procedures were generally long – days or weeks – to be used in routine. Albeit in some studies the authors pointed out that the K fractions extracted with resin correlated well with plant K uptake (Havlin and Westfall, 1985, Dobermann et al., 1996) the use in routine was not generally the purpose of the investigations.

Yang et al., (1991a, b) developed a phytoavailability soil test (PTS) for simultaneous determination of K, P, and S, in which ion anionic and cationic exchange resins were confined in 2.5 cm diameter bags stirred with soil, but, in those cases, the time for equilibration was relatively long. Qian et al. (1992), Qian et al.

(1996), and Qian et al. (1998) used ion exchange membranes to simultaneously extract N, P, S, and K from soils and found that their procedure yielded results that were equal or better than conventional methods. These studies led to the development of a commercial application of the membrane method for multinutrient extraction from soils, including K (Bremer et al., 2014). However, Woods et al (2006) pointed out that the results of K of these probe membranes inserted into the soil are sometimes difficult to interpret and to classify as low, medium, or high, but allowed a good understating of K status for turf grass, the plants used in that study.

The successful case of large-scale soil diagnosis of nutrient availability, including K, and its use for fertilizer recommendation in Brazil suggests that ion exchange resin deserves attention. Although the weathered soil of Brazil differs from many soils of temperate regions, the results shown above of investigations with such soils indicate that resin can be useful to characterize nonexchangeable K availability and that such fractions usually correlate well with plant uptake. The soil extraction procedure used in Brazil may not be automatically adapted or suitable for temperate climate soils because soil properties are different and there are many details and options regarding resin use that must be taken into account (Skogley and Dobermann, 1996). However, the longtime known theory behind resin as a soil extractant (Arnold, 1958, Martin and Sparks, 1983, Havlin and Westfall, 1985, Skogley and Dobermann, 1996, Raij et al., 1986), in special its way of functioning as a sink for nutrients that mimic the natural process of diffusion toward plant roots, offers a potential that cannot be disregarded for the diagnosis of K availability in a variety of soils. Some of the procedures developed to implement the resin method in routine in Brazil, notably the grinding of soil samples to disrupt soil microaggregates, the long (16 h) and intense shaking process, and the high ratio of electric charges of resin to soil (Raij and Quaggio, 2001), were intended to facilitate the diffusion of tightly held nutrients such as P and Ca from the soil to the soil solution and then to the resin. These procedures may suggest the direction for future development of a method of soil analysis that goes beyond exchangeable K for soils that fix K.

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Table 1. Error in laboratories using ion-exchange resin in Brazil (Times New Roman, 11 pt.)

Grade of laboratory in the Ring Test (n=114 labs) †	Samples outside the confidence interval							
	P	MO	pH	K	Ca	Mg	H+Al	All determinations (n=180 per lab)
	---------- % ----------							
Average of all labs	12	6	5	9	10	7	9	8
Grade A labs	5	1	1	2	3	4	3	3
Grades A and B labs‡	8	3	2	4	4	5	5	5

† 114 laboratories fulfilled the Proficiency test requirements during the whole year and were included in the evaluation (Cantarella et al., 2017)

‡ Laboratories approved in the Proficiency test according with the rules (Quaggio et al., 1994)

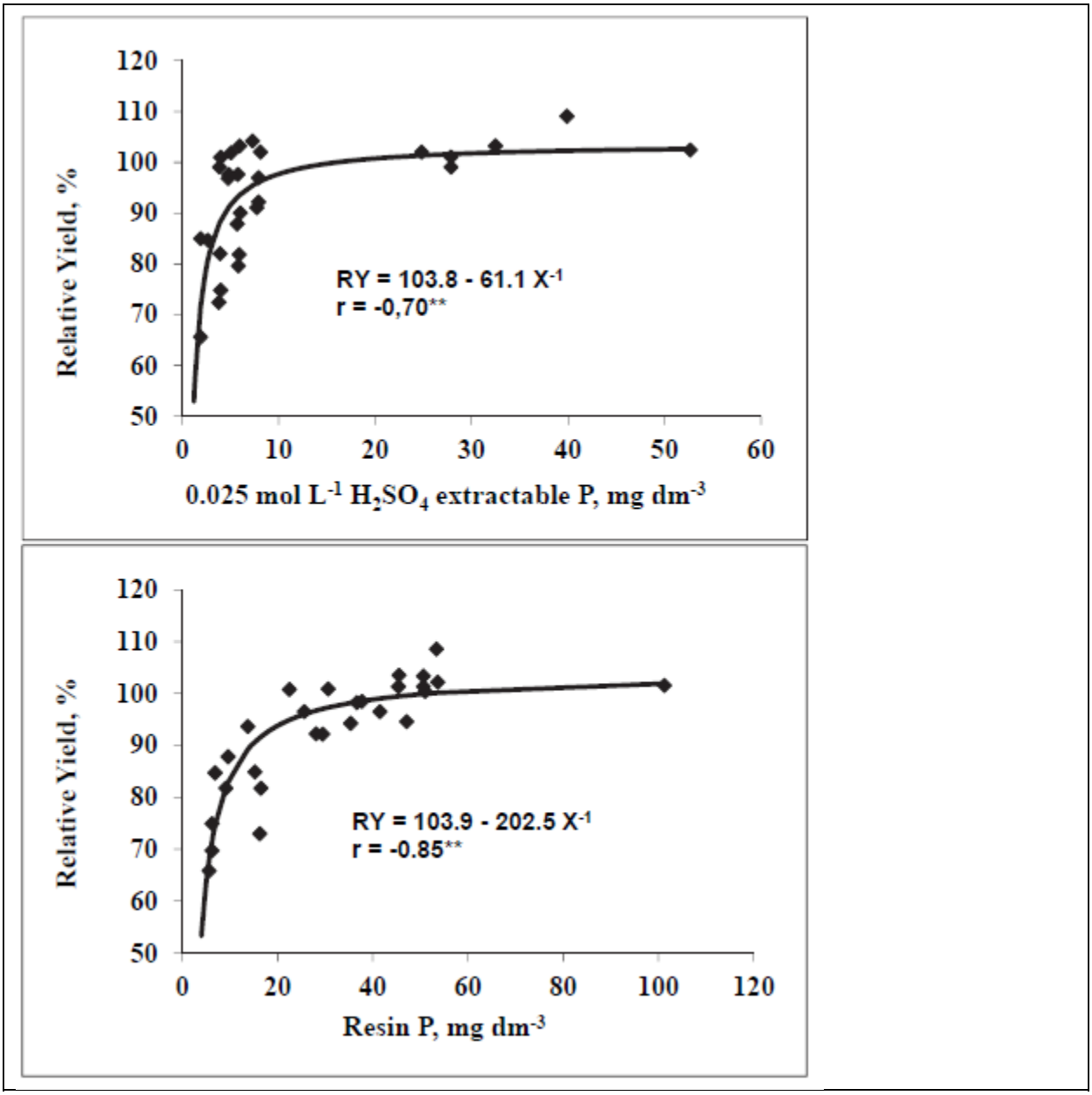

Figure 1. Relationship between cotton response to P fertilizer and P extracted by an acid solution or by ion exchange resin. Each dot represents one field experiment (n=28) with fertilizer P response in cotton. Relative yield was calculated as RY = (yield of control plot (no P)/yield of fertilized plot)*100. Source: Raij et al. (1986)

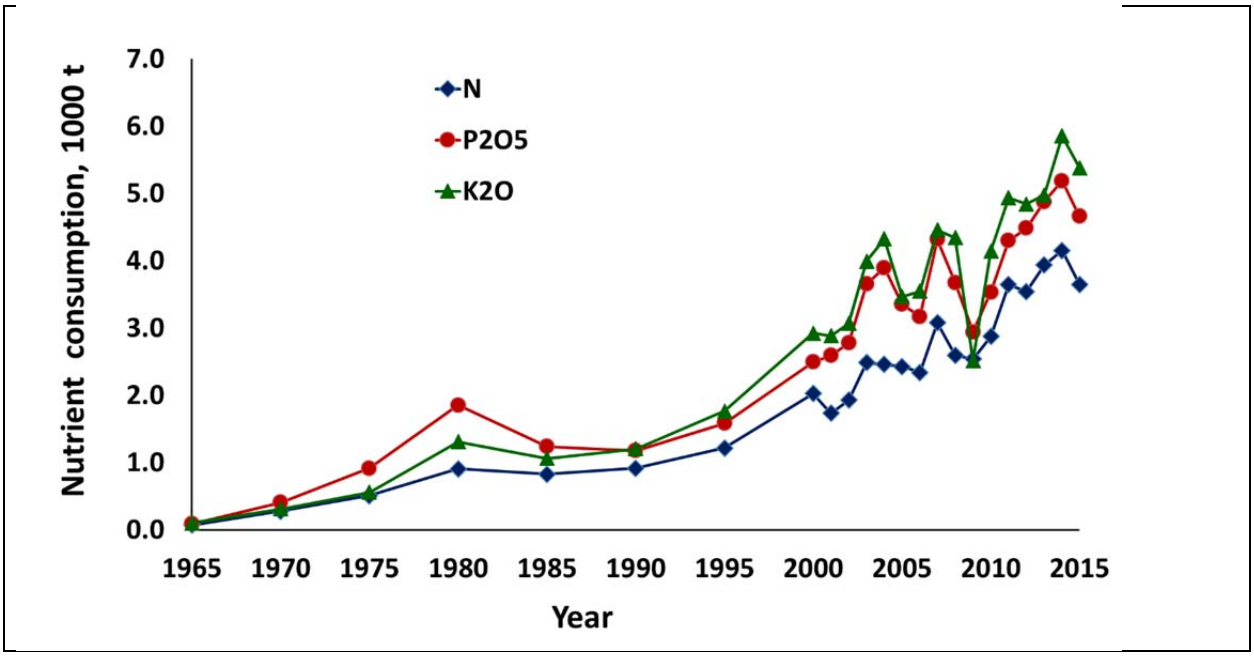

Figure 2. Apparent consumption of nutrients in Brazil: 1965-2015.

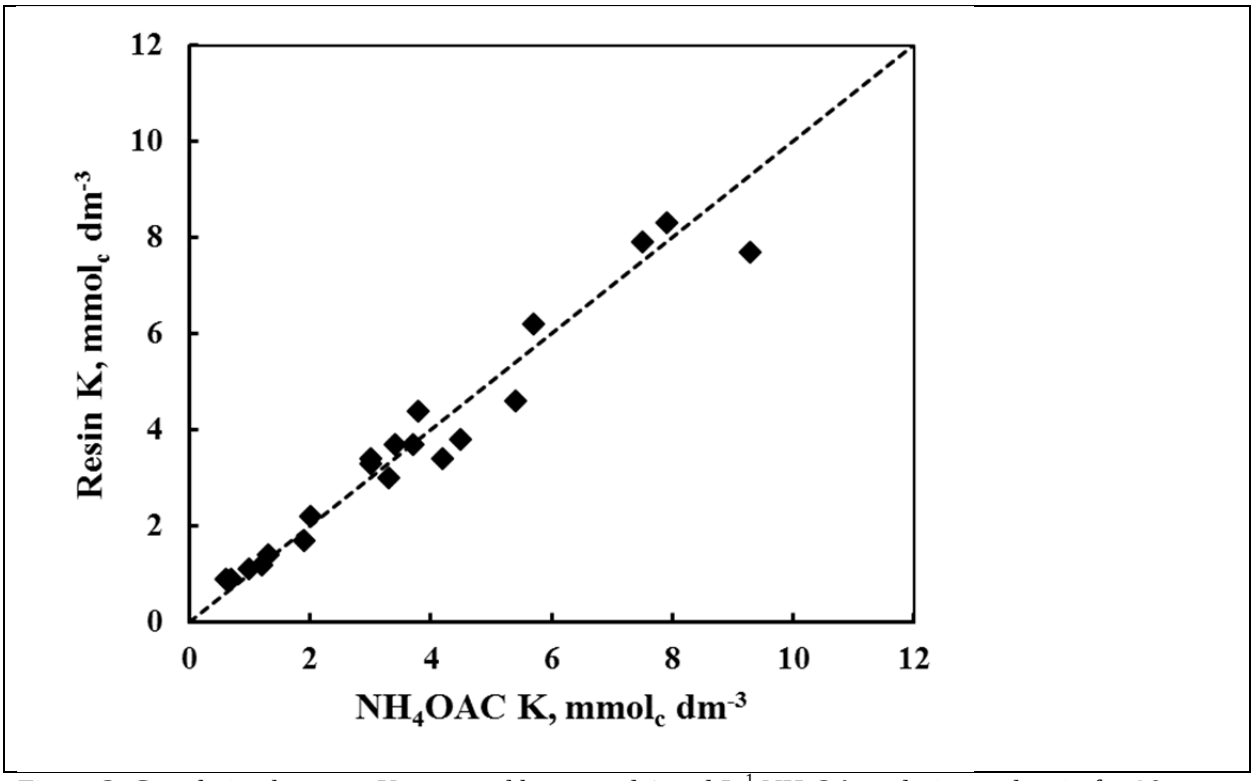

Figure 3. Correlation between K extracted by neutral 1 mol L^{-1} NH_4OAc solution and resin for 20 representative soils from the state of São Paulo, Brazil. Source: Raij et al. (1986)

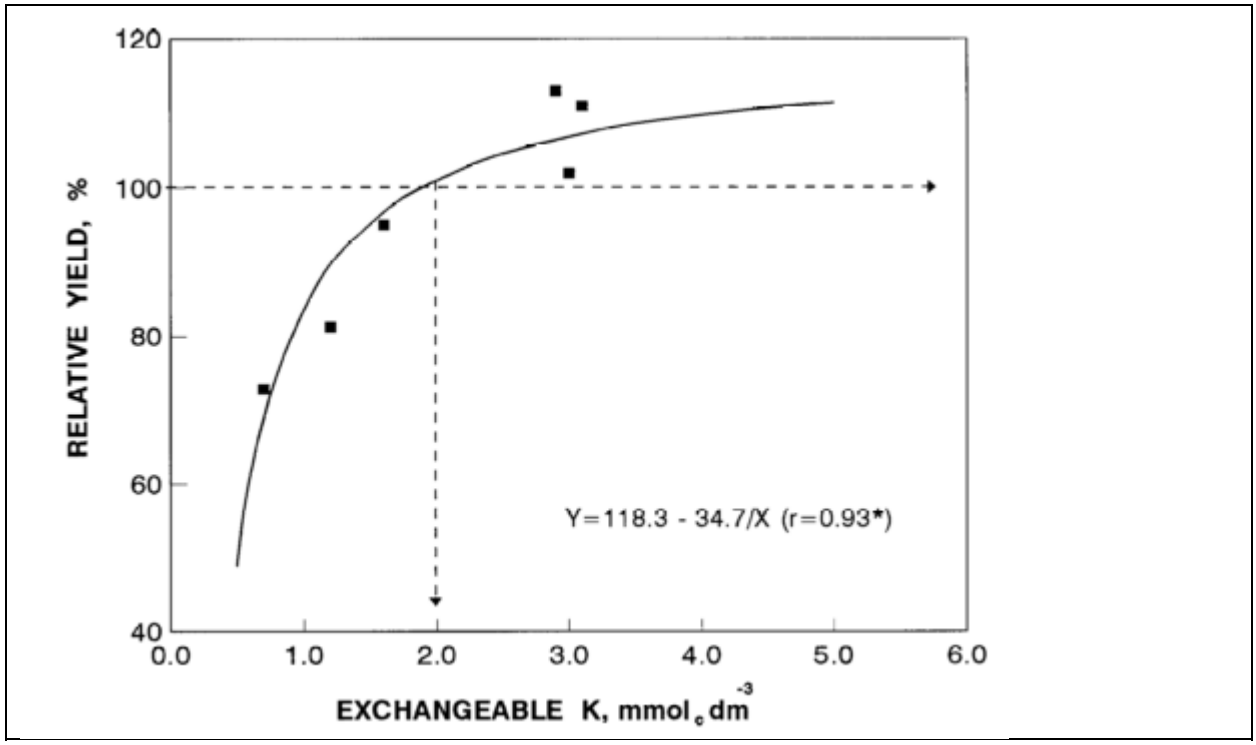

Figure 4. Calibration of resin-K for citrus. Source: Quaggio et al. (1998)

Rates and Residual Effect of Potassium Fertilization in a Brazilian Oxisol

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Abstract

Potassium (K) fertilizers are commonly a must in terms of plant nutrition in acid soils of the tropics, including Brazil. In many areas farmers cut back on fertilizer expenses, which could compromise good yields, profit and food safety in the future. Studying the impacts of K fertilizer cut back on Brazilian soils is important to demonstrate the effects in the medium to long run and this was the main objective of this study. The field trial was carried out for six years in a clay Oxisol in Itiquira, MT, growing soybeans every summer and maize 2nd crop or Brachiaria grass during the fall/winter. Treatments involved: (1) four rates of K_2O (22.5, 45.0, 90.0, and 135.0 kg K_2O ha^{-1}), plus a control with no K_2O added, in interaction with suppression or not of K after the third year, (2) three levels of base saturation (40% 55%, and 70%), (3) three rates of phosphogypsum application (0, 2, and 4 ton ha^{-1}), (4) two times of K_2O application, and (5) two localities of application. Responses to K_2O were frequent along the years but relatively small. The negative effect on grain yield of both crops from the suppression of K_2O was in the order of 300 kg ha^{-1} for soybeans and 800 kg ha^{-1} for maize 2nd crop, yearly, comparing the K recommended rate of 90.0 Kg ha^{-1} and the control. Cutting back K rate after the third year still did not affect much soybean and maize 2nd crop. In certain years yields of both crops was positively affected by phosphogypsum application, while maize 2nd crop yield was also positively affected by liming. The experiment has shown the soil to have a high buffering capacity in K and P. It will be interesting to note how much longer the soil can provide such nutrients without dramatically impacting yields.

INTRODUCTION

The requirement for worldwide abundant food, feed, fiber, and more recently biofuel, leads to requirements for higher amounts of fertilizer utilized in agriculture in diverse parts of the globe. Potassium (K) is, most generally, the second nutrient in terms of plant demand (after nitrogen, N). Potassium is highly mobile in most soils and relatively mobile in the plants (Havlin et al., 1999). This nutrient is responsible for several vital mechanisms for plant development and high yields (enzyme activation, translocation and stock of compounds, osmotic regulation, water maintenance, etc; Hawkesford et al., 2012). Potassium fertilizers are very commonly a must in terms of plant nutrition in acid soils of the tropics, including Brazil. In many areas farmers cut back on fertilizer expenses, which could compromise good yields, profit and food safety in the future. Farmers expect that the soil supply will be sufficient to provide the ideal conditions for plant development and yield, even with lower or no supply of K fertilizers. Studying the impacts of K fertilizer cut back on Brazilian soils is important to demonstrate the effects in the medium to long run. With that in mind the main objective of this study is to verify the effects of cutting back K fertilizer rates in a Brazilian Oxisol. Also, the experimental design was prepared to study other important factors which may affect the K fertilizer effectiveness in tropical soils.

MATERIAL AND METHODS

General Information

The experiment takes place having soybean as the main crop and is located in Itiquira, Mato Grosso at the experiment station of Research Foundation MT. The study was initially planned for six years. The winter crop is defined annually depending on conditions in the area, most

specially related to time of soybean harvest and climatic conditions. In six years of the project four years had maize during the winter and one time Brachiaria grass. The differences in treatments were performed only to the soybean (summer crop), with fertilization being the same across all treatments for the winter crop. Table 1 presents the chemical and granulometric properties for the soil. Methods for soil analysis followed the principles described by Embrapa, 1997. Potassium level was considered medium before starting the experiment.

Table 1. Chemical and physical soil properties, 0 to 20 cm.

Soil pH		**P**	**K**	**S**	**Ca**	**Mg**	**Al**	**H**	**V**	**OM**	**Clay**	**Sand**	**Silt**
H_2O	$CaCl_2$	— mg dm^{-3} —			— $cmol_c$ dm^{-3} ——				%	g dm^{-3}	—— g kg^{-1} ——		
5.6	4.9	20.4	57	18.6	2.9	0.7	0.0	5.4	41.0	38.9	639	152	209

Zn	**Cu**	**Fe**	**Mn**	**B**
mg dm^{-3}				
4.4	1.3	91	26.3	0.46

Treatments

The treatments are shown on Table 2 and legends for the variables studied can be found in Table 3. In summary, the experiment outline includes: (1) four rates of K in interaction with suppression or not of K after third year, (2) three rates of base saturation (BS), (3) three rates of phosphogypsum application (PG), (4) suppression of P in different levels after third year, (5) two levels of time of application, and (6) two levels of locality effect. The experiment is designed mainly to study K rates and its residual effect after the third year. Secondarily, the experiment is designed to evaluate other important variables that affect K fertilization, having the regular rate of K (K3) as a standard. The experiment was designed to study the residual effect of K fertilization in interaction with liming and phosphogypsum. Also, the outline should make possible to investigate the phosphorus (P) residual effect and the effect of K, regarding time of K application and locality effect. Table 4 summarizes the variables studied. Important to note that the experiment uses KCl, the most common K fertilizer used in Brazil, and studies all other variables considered in the 4R Potassium Stewardship (rate, time and place). The regular practices in terms of rates, time of application, locality effect, liming and phosphogypsum application will be N3, P3, K3, TA1, LE1, BS L2 and PG L2. Nitrogen is of course not a problem for soybean (due to N fixation when seeds are properly inoculated with *Bradyrhizobium japonicum*) and will not be studied. Variations in rates and other variables should permit several important comparisons as outlined in Table 5.

Some important local decisions related to the input variables for the treatments were made. They are:

1. *Rates of K_2O*: K3 was defined as 90 Kg ha^{-1}. K_2O was applied in all treatments, except 23 and 24, by splitting the proper rate in two applications: half at seeding and half in top dressing right after plant emergency.
2. *Rate of N*: not applicable to soybean (inoculation) and 60 Kg ha^{-1} for corn 2nd crop.
3. *Rate of P_2O_5*: P3 was defined as 45 Kg ha^{-1}.
4. *Lime rates*: Defined along the years to have three scenarios of base saturation (40%, 55% and 70%).
5. *Phosphogypsum rates (PG)*: No lime, recommended rate based on soil clay content and double of the recommended rate (0, 2.0 and 4.0 t ha^{-1}).
6. *Time of application (TA)*: Regular TA was to regularly split the K_2O rates in two applications (half at seeding and half right after plant emergency). The alternative (treatment 23) was to split in three applications (1/3 at seeding, 1/3 at emergency and 1/3 fifteen days after emergency).
7. *Locality effect (LE)*: Regular LE with half of the K_2O rate at seeding (5 cm besides and 5 cm bellow the seeds) and half in top dressing right after plant emergency. The alternative (treatment 24) received all of the K_2O rate at the soil surface right after plant emergency.

The above decisions were based on soil, crop and regional knowledge (previous agronomic experimentation).

Plots, replicates and statistics

The plot size was of 6.3 m x 9.5 m (59.85 m^2). The number of replicates is four per treatment. The statistics was performed by SAS to gain information about each of the comparisons outlined in Table 5.

Evaluations (Output variables)

The main evaluation discussed in this article is grain yield for soybean and maize but some inferences are also made, mainly for soil K availability along the time.

RESULTS AND DISCUSSION

The results from cultivating six years of soybean in summer (2010-11, 2011-12, 2012-13, 2013-14, 2014-15 and 2015-16), four years of corn in winter (2011, 2013, 2014 and 2015) and one year of Brachiaria grass in winter (2016) show response to K application in most of the years and conditions. This can be visualized in Figure 1 that shows the gap in yield of soybean and corn when comparing application of 90 Kg K_2O per hectare (usual rate) with the control, which received no application of K. Also, it can be visualized by the response curves of total grain yield of soybean and corn when adding all harvests (Figures 2 and 3).

Differences in soil K availability were expected with time due to differences in K_2O rates. Figure 4 confirms this trend with clearly higher rates of K_2O leading to higher amounts of available K by the Mehlich methodology.

Although responses to K_2O are clear in terms of K soil availability and yields of soybean and corn, it has to be noted that such responses are still relatively small (Figures 2 and 3), with the first rate of K_2O already providing the maximum yield. This should be related to a high buffering capacity of this soil in terms of K availability. It is expected that differences among rates of K_2O applied will increase with time (experiment to be continued), which will make possible conclusions also about cutting back on K. Similarly, to what happened with K_2O, responses to P_2O_5 were also small.

Lime and phosphogypsum application favored yields in some specific years. For example, lime increased corn yield by 660 Kg per hectare in 2015, while phosphogypsum increased soybean yield by 354 Kg per hectare in 2016. Some other differences existed for other variables studied but results were not so conclusive in terms of final recommendation related to effect of timing or placement of K_2O.

This is a long term agronomic trial designed to show results along the years. It is expected that in years to come higher difference in treatments will allow more definitive conclusions related to the 4R Potassium Stewardship in these types of soil of the tropics.

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Table 2. Experiment outline.

Treat #	Treat #	Year 1	2	3	4	5	6	Year 1	2	3	4	5	6	Year 1	2	3	4	5	6	Time App (TA)	Locality Effect (LE)	Liming BS Level	PG Level
		Rates of N						Rates of P_2O_5						Rates of K_2O									
1	1	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	0	0	0	0	0	0	TA 1	LE 1	BS L2	PG L2
2	2A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K1	K1	K1	K1	K1	K1	TA 1	LE 1	BS L2	PG L2
3	2B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K1	K1	K1	0	0	0	TA 1	LE 1	BS L2	PG L2
4	3A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K2	K2	K2	K2	K2	K2	TA 1	LE 1	BS L2	PG L2
5	3B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K2	K2	K2	0	0	0	TA 1	LE 1	BS L2	PG L2
6	4A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BS L2	PG L2
7	4B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	0	0	0	TA 1	LE 1	BS L2	PG L2
8	4C	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K1	K1	K1	TA 1	LE 1	BS L2	PG L2
9	4D	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K2	K2	K2	TA 1	LE 1	BS L2	PG L2
10	5A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K4	K4	K4	K4	K4	K4	TA 1	LE 1	BS L2	PG L2
11	5B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K4	K4	K4	0	0	0	TA 1	LE 1	BS L2	PG L2
12	6A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BS L1	PG L2
13	6B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	0	0	0	TA 1	LE 1	BS L1	PG L2
14	7A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BS L3	PG L2
15	7B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	0	0	0	TA 1	LE 1	BS L3	PG L2
16	8A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BSL 2	PG L1
17	8B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	0	0	0	TA 1	LE 1	BS L2	PG L1
18	9A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BS L2	PG L3
19	9B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	0	0	0	TA 1	LE 1	BSL 2	PG L3
20	11A	N3	N3	N3	N3	N3	N3	P3	P3	P3	0	0	0	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BS L2	PG L2
21	11B	N3	N3	N3	N3	N3	N3	P3	P3	P3	P1	P1	P1	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BS L2	PG L2
22	11C	N3	N3	N3	N3	N3	N3	P3	P3	P3	P2	P2	P2	K3	K3	K3	K3	K3	K3	TA 1	LE 1	BSL 2	PG L2
23	12A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 2	LE 1	BS L2	PG L2
24	13A	N3	N3	N3	N3	N3	N3	P3	P3	P3	P3	P3	P3	K3	K3	K3	K3	K3	K3	TA 1	LE 2	BSL 2	PG L2

Table 3. Legends for variables in Table 2.

Variable	Specification	Definitions/Observations
Treat	Treatment	
N	Nitrogen	N3 = ideal rate of N for specific crop and region.
P	Phosphorus	Rates of P_2O_5 = 0, P1, P2, P3, with P3 = ideal rate of P_2O_5 for specific crop and region. P1 = P3/4, P2 = P3/2.
K	Potassium	Rates of K_2O = 0, K1, K2, K3, K4, with K3 = ideal rate of K_2O for specific crop and region. K1 = K3/4, K2 = K3/2, K4 = 1.5*K3.
TA	Time of Applicaton	TA 1 = regular practice (seeding and fifteen days after); TA 2 = variation for time of application (1/3 at planting and two top dressings of 1/3 K3 each).
Year		1 to 6
LE	Locality Effect = Placement of K as related to the seed	LE 1 = regular practice (ex.: ½ 5 cm besides and bellow the seeds at planting and ½ at plant emergency); LE 2 = variation for locality effect (all quantity at soil surface).
BS	Base Saturation	Levels of liming for BS of 40%, 55% and 70%.
PG	Phosphogypsum	Levels of Phosphogypsum of 0, 2 and 4 ton ha^{-1}.

Table 4. Summary of variables studied at the present experiment outline.

Var #	Specification
1	K rate
2	K residual effect
3	K and base saturation/liming
4	K and phosphogypsum application
5	P rate and P residual effect
6	K time of application
7	K placement

Table 5. Possible comparisons with experiment outline suggested in Table 2.

Comp #	Comparison	Treatments Involved
1	Response curve to K_2O with continuous application of K and regular practices for N, P, K time of application, K locality effect, liming and PG level.	T1, T2, T4, T6 and T10 (A).
2	Response curve to K_2O with K application up to 3rd year and regular practices for N, P, K time of application, K locality effect, liming and PG level (B)	T1, T3, T5, T7 and T11 (B).
3	A vs B = Effect of suspension of K application after 3rd year at regular practices	
4	Effect of different rates of K in residual effect as related to ideal rate (K3)	T6, T7, T8 and T9 (C).
5	Effect of liming on K fertilization with continuous application of K and regular practices	T12, T6 and T14 (D).
6	Effect of liming on K fertilization with application of K up to 3rd year and regular practices	T13, T7 and T15 (E).
7	D vs E = Effect of liming on suspension of K application after 3rd year at regular practices	
8	Effect of phosphogypsum on K fertilization with continuous applicaton of K at regular practices	T16, T6 and T18 (F).
9	Effect of phosphogypsum on K fertilization with application of K up to 3rd year at regular practices	T17, T7 and T19 (G).
10	F vs G = Effect of phosphogypsum on suspension of K application after 3rd year at regular practices.	
11	Response curve to P with full P only up to 3rd year and regular practices	T20, T21, T22 and T6.
12	Effect of timing of K application at regular practices	T6 and T23.
13	Placement effect of K application at regular practices	T6 and T24.

Regular practices = N3, P3, K3, TA1, LE1, BS L2 and PG L2

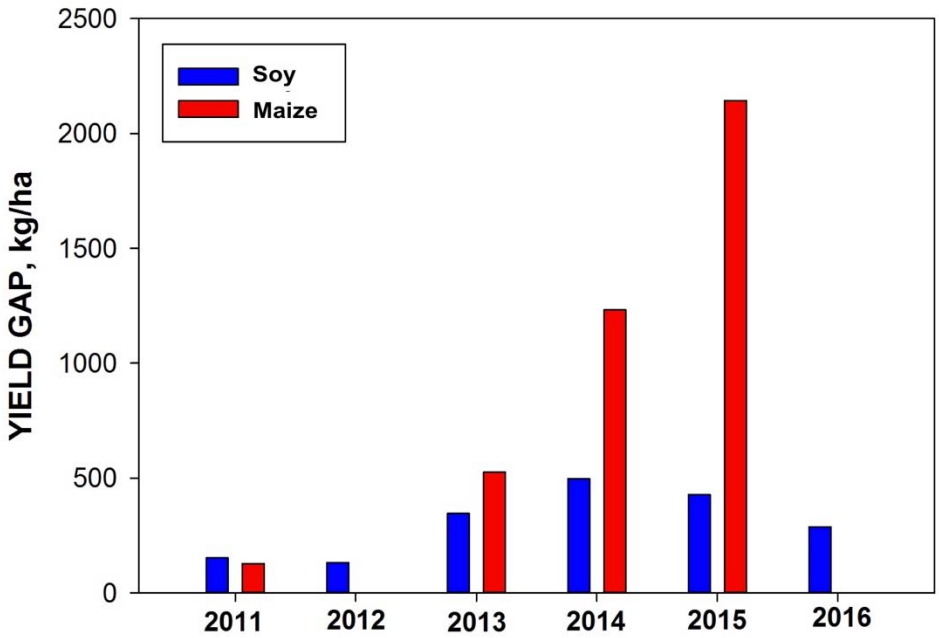

Figure 1. Yield gap (difference between 90 kg K_2O/ha application and control) for soybean and maize 2nd crop along the six years of the project.

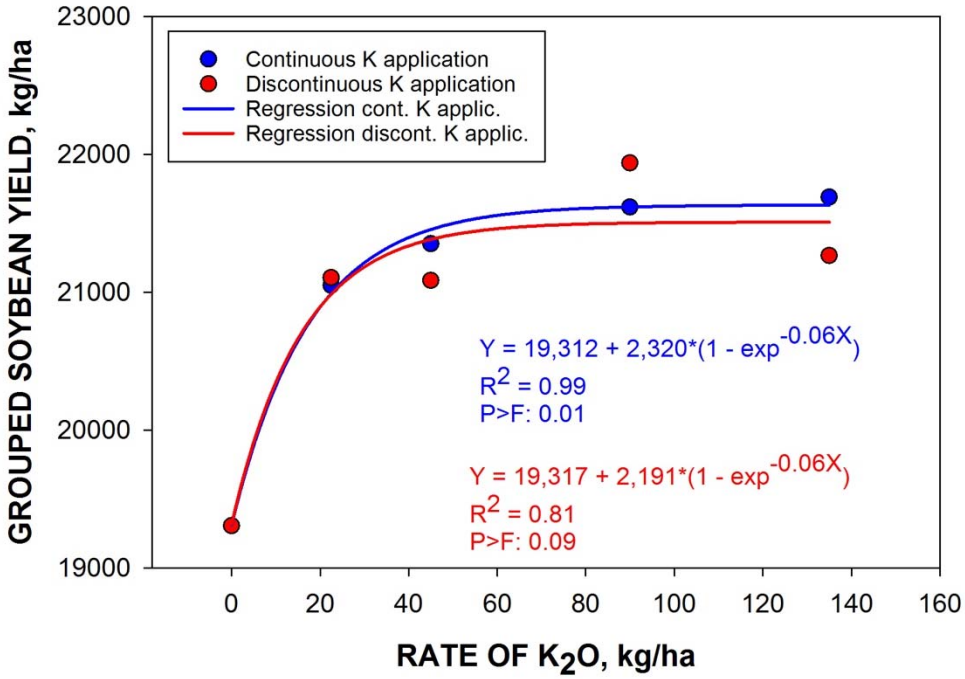

Figure 2. Grouped soybean yield response curves to K_2O rates with continuous and discontinuous K application (comparisons 1 and 2, Table 5). Crop seasons 2010-2016.

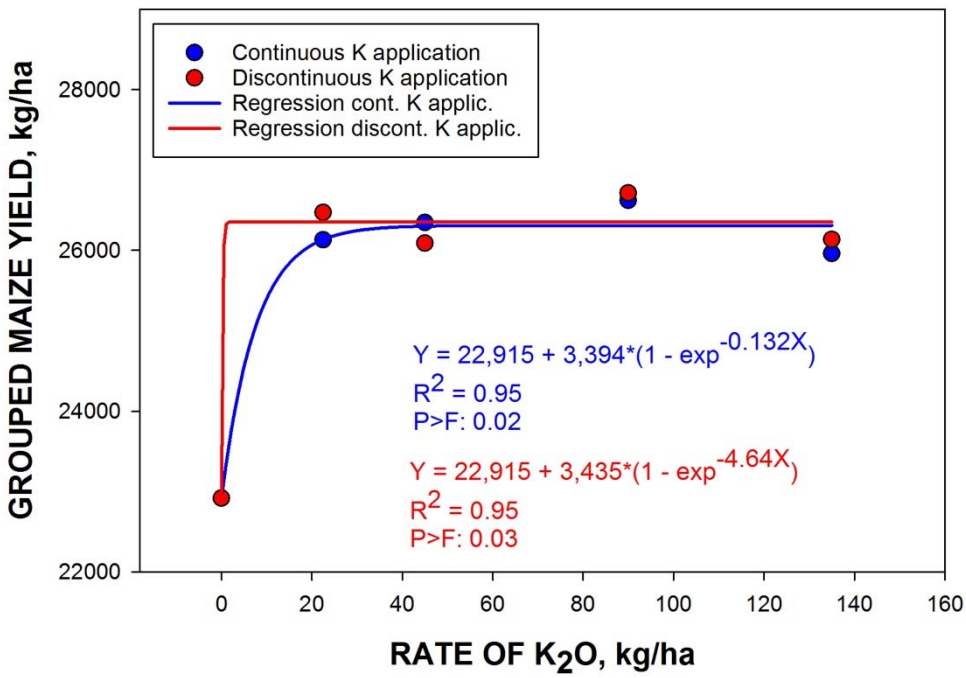

Figure 3. Grouped maize yield response curves to K_2O rates with continuous and discontinuous K application (comparisons 1 and 2, Table 5). Crop seasons 2010-2016.

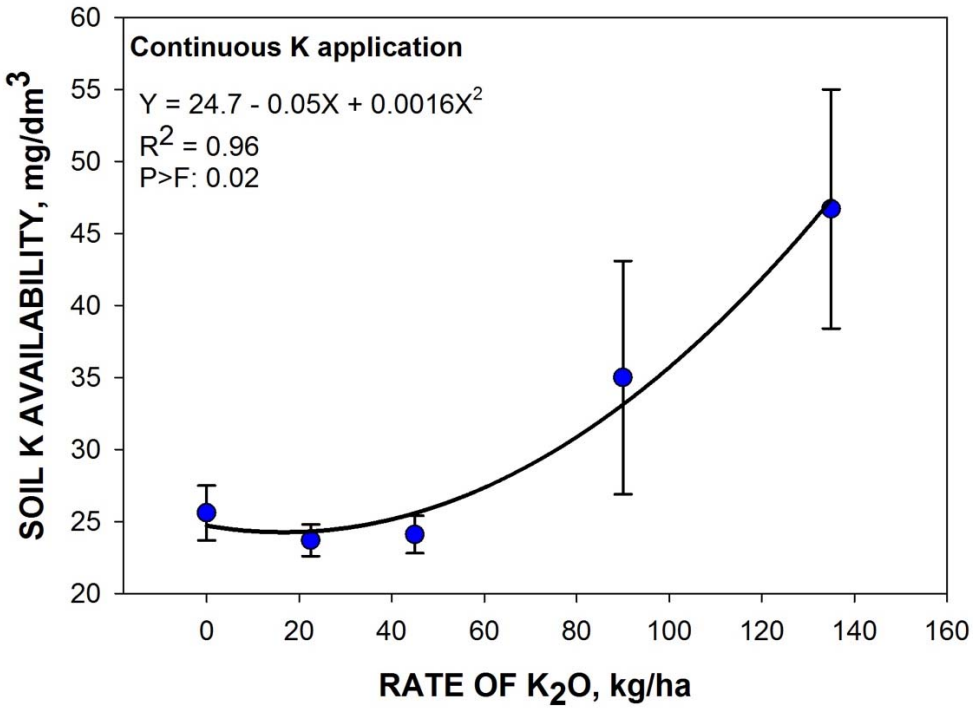

Figure 4. Soil K availability in response to K_2O rates with continuous K application (comparison 1). Crop season 2015-2016. Vertical bars represent standard deviation.

Can Cycling of Potassium from Crops and other Organic Residues be Integrated into Potassium Rate Recommendations?

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Abstract

Potassium is found in plants as a free cation or forming weak complexes, and is prone to leach from live or dead plant tissues disregard of plant residue mineralization. This is an important K pool in agricultural systems that should be considered in fertilization programs. Several factors must be considered in K cycling: soil and fertilizer K, K amounts in different plant parts and residues, exports, leaching rate from crops or residues, reactions in the soil, rainfall, and time. Crops take up K ions mainly from the soil solution and the exchangeable K pool. Potassium recycled to the soil can be leached, remain as exchangeable K, which can be estimated by soil testing, or in part become non-exchangeable, which is seldom measured, but may be available with time. Crop rotations including vigorous, deep rooted cover crops able to explore soil non-exchangeable K is an effective tool at recycling K, and can prevent leaching below the rooting zone in light-textured soils and strong K retention in other soils. The amounts of K released by cover crops vary greatly depending mainly on the dry matter yield at termination time. Potassium recycled with non-harvested parts of cash crops also varies greatly. Research with corn, soybean, wheat and other grain crops showed that up to 50-60 % of the K accumulated in vegetative plant tissue is leached to the soil within 40-45 days, and within 130-140 days over 70 % of the nutrient will return to the soil. Although it is easy to account for the amount of K potentially recycled into the soil over time, it is not easy to accurately predict the amount that will be available by the time the following crop is planted. However, better consideration of K recycling would greatly improve the efficacy of K management for crop production.

INTRODUCTION

After N, K is the nutrient required in largest amounts by plants. Its concentration in plants has been reported from 0.4 to 4.3% (Askegaard et al. 2004), and is affected mainly by plant species, site, year, tissue age, and fertilizer input. Most K uptake in annual species is observed as shoot undergoes rapid growth (Gregory et al. 1979). For cereals, more than 70% of K remains in the straw after grain harvest, andthe concentration is increased by fertilization. Therefore, this is an important source of K for the next crop, and should somehow be considered and integrated in fertilizer recommendations.

Mobility of K in plants is high at all levels – within individual cells, tissues, and in long-distance transport via xylem and phloem. It is the most abundant cation in the cytoplasm, and except for cytosol and vacuole, its subcellular distribution is largely uncharacterized. The concentration of K in the cytoplasm is kept relatively constant from 50 to 150 mM, while the concentration in the vacuole varies depending on supply status (Zörb et al. 2014). Potassium mineral salts are highly soluble, and it is not metabolized, forming weak complexes with organic molecules from which it is readily exchangeable (Marschner 1995). Therefore, K is prone to be easily leached from live or dead plant tissues irrespective of plant residue decomposition or mineralization.

Figure 1 shows how various pools of K, soil physical and chemical processes and plant processes are related. When studying K cycling in agricultural systems, it is important to consider the following processes:

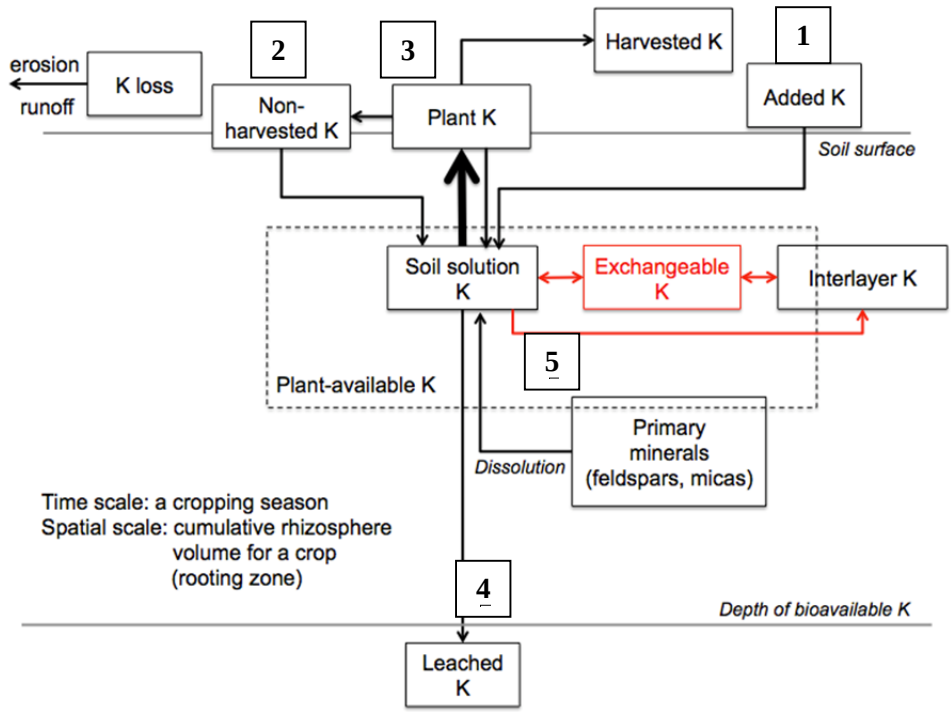

Figure 1. K cycle in cropping systems.

1. K added as fertilizers or organic amendments
2. K not taken from the system, cycled and used by crops. This may be a cash or cover crop residue.
3. In cereal cash-crops and grazed pastures most of the absorbed K is recycled to the soil, but with grain legumes and biomass or hay harvest systems a large proportion is removed and exported
4. In light textured soils K leaching may be high, accounting for more than 50 % of the fertilizer applied, depending on the rate applied.
5. Exchangeable and non-exchangeable K pools will act as a temporary source or sink for K depending on many soil, crop growth, and environment factors.

Many tropical and subtropical soils have been depleted of available and slowly available K by decades or even centuries of continuous farming with crop removal exceeding inputs. It is generally accepted that food production in these regions depends to a large extent on the efficient use of high rates of fertilizers (especially N, P and K) and liming materials. On the other hand, the non-harvested K and the K added via organic residues must be considered in the production system. In this chapter the role of crops, cover crops and organic residues on K dynamics in the cropping system, and hence, its cycling and availability, will be explored seeking a better understanding of how this could be integrated into K fertilizer recommendations.

POTENTIAL OF K CYCLING BY CROPS AND COVER CROPS

The potential of plants in cycling K in cropping systems is defined by the capacity in acquiring soil K derived from soil minerals or added with fertilizers or organic amendments, which depends on the capacity to accumulate K, the size and depth of the root system, and capacity to take up less available soil K forms. Plant species differ as to the capacity to absorb K from the poorly defined soil non-exchangeable pool, which will be later returned by leaching from plant residues. Therefore, in K-limited areas, the

choice of species or varieties efficient in utilizing nonexchangeable or sparingly soluble forms has a great potential to increase K cycling and use efficiency in the system (Zörb et al. 2014).

A variable amount of the K taken up by crops harvested for grain, grazed pastures, and cover crops will be recycled to the soil as an ion, highly soluble mineral forms, or weakly complexed in organic compounds. The cycled K will enrich the soil solution, be available to the next crop, lost with runoff or leached through the soil profile, or be transformed into less available pools in the soil. While large K uptake is important in supplying K to plants, uptake of K beyond plant needs will compromise sustainability (Rosolem & Steiner 2016). Grimes & Hanway (1967a) and Oltmans and Mallarino (2015) showed that the soil K increase after harvesting corn in the fall to the following spring was directly related to the amount of K in the residue.

Cash grain crops play an important role in K cycling in agricultural cropping systems. At maturity, approximately 25 to 45% of the total aboveground plant K is found in the corn grain but more than 50% is in soybean grain, furthermore, there is a large variation across growing conditions, species and cultivars (Bender et al. 2013; Ciampitti et al. 2013; Oltmans and Mallarino, 2015). In soybean, K fertilization results in very little additional K accumulation in grain but markedly increases K accumulation in the mature stems, pods, leaves, and petioles (Hanway & Weber 1971; Rosolem & Nakagawa 1985; Farmaha et al. 2012). In Iowa, average K accumulation in soybean grain or residue at harvest was 68 and 34 kg ha^{-1} in a 14 site-year experiment. Corn averaged, in a 33 site-year experiment 29 and 52 kg ha^{-1} in grains and residue, respectively (Oltmans and Mallarino 2015). In corn, K accumulated in vegetative tissue at plant maturity remaining in the straw after two months was 50%, and in soybean it was 19%, decreasing to 31% and 12% in six months. The amount of K remaining in the crop residue decreased as precipitation increased, and soil test K increased from fall to spring. Due to different plant structure, mainly the cornstalks containing most of the K, much more rain was necessary to leach out a similar amount of K from corn than from soybean (Oltmans & Mallarino 2015).

Crop and cover crop residues may have a high amount of K potentially available for the next crop, enough to supply K for the new crop early growth, depending on the amount release synchrony. The K quantity depends on the species or even the cultivar, as shown in Table 1. For example, forages of the genus *Brachiaria***,** one of the main genus used as cover crop in Brazil, can accumulate over 400 kg ha^{-1} of K. *Panicum* species accumulate up to 800 kg ha^{-1} of K in an entire cycle. Cover crops increase exchangeable K in the top soil layers by bringing it up from deeper soil layers (Eckert, 1991). However, when these species or others are used as cover crops in crop-livestock integrated systems or when the growing season between two main crops is short, K amounts are not so high, as shown in research with cover crops in the northern areas of the Corn Belt of the United States, where corn-soybean rotation system predominates. Cover crops reduce soil and nutrient loss, but because of a long period with very cold or frozen soils, in some regions cover crops have little effective time to grow and absorb nutrients between two cash crops. Unpublished research with cereal rye (*Secalecereale*, L) across 12 site-years (A.P. Mallarino, Iowa State University personal communication), which is the most widely used cover crop in these conditions and is commonly terminated when it is 20 to 30 cm tall, shows that the aboveground K recycled at the spring termination time ranged from 7 to 84 kg K ha^{-1}, being greatly affected by soil-test K level, the active growth period, and dry matter yield.

K AVAILABILITY SYNCHRONY IN CROPPING SYSTEMS

Losses of K from plant residues are affected by several factors such as the species, rainfall and time after desiccation. Initial K loss ranges from 4.4 to 29.3 g K kg^{-1} d^{-1} depending on the species and precipitation, and across crops, 150 mm of precipitation removed 500 g kg^{-1} of K from plant residues (Schomberg & Steiner 1999). The maximum rate of K released from several plant species by rain soon after desiccation ranges from 200 to 650 g ha^{-1} mm^{-1} of rain and is strongly correlated with the amount of nutrient accumulated in the crop remains (Rosolem et al., 2003), probably because a large proportion of this

nutrient is present in the vacuole and not bound to organic compounds (Marschner 1995). Rosolem et al. (2005) found that K fertilization increased K accumulation in pearl millet straw and K leached from the residue under simulated rainfall, and it was estimated that residue leaching could provide 24 to 64 kg ha^{-1} of K to the next crop. Oltmans and Mallarino (2015) also reported that K fertilization increases the amount of K leached by natural rainfall from corn and soybean residue compared with non-fertilized treatments with or without grain yield response.

After cover crop desiccation, some K is remobilized to roots as tissues die. Then, rainfall is the main driver of K release from plant residues. Potassium leaching rates, or the amount of K washed per mm rain, is very low with rains up to 5 mm, because this is barely enough to wet plant residues, but it is high with rains up to 20 mm, then decreasing, tending to a constant with rains over 75-80 mm (Rosolem et al. 2003; Rosolem et al. 2005). This occurs because, at first, plant residues have all K available to be washed, and additional rain will saturate the residues. From this point, additional rain can only wash out K present at the superficial layers of the residue, with little exchange with deeper layers. As a result, to be leached, K has to diffuse to the straw surface. Therefore, heavier rains would have little effect on the process, and a greater nutrient release will be observed with successive drying-wetting cycles, which occurs in many agricultural areas.

Up to 50-60 % of the K accumulated in the straw is washed within 40-45 days from plant desiccation in several species under field conditions (Giacomini et al. 2003; Calonego et al. 2012; Oltmans and Mallarino 2015), and within 130-140 days over 70 % of the nutrient will return to the soil (Spain & Salinas 1985;Calonego et al. 2012). For grasses like palisade grass, pear millet and *Pannicum,* most of the K in the straw is washed back to the soil in less than 50 days (Crusciol et al. 2011). The K release from straw left on the soil surface is not related to straw mineralization rate, since K loss is faster than dry matter loss (Rosolem et al., 2003; Calonego et al. 2012). However, leaching is increased as the plant residues age, probably as a result of cellular disruption (Calonego et al. 2005).

The differential K release from different plant species in a cropping system defines its role in supplying K to the next crop. For instance, sunn hemp, corn, and sorghum release K slowly for a long time while triticale, black oats, soybean, and cover crops terminated during early vegetative growth stages can release considerable amounts of the nutrient very fast (Rosolem et al., 2003; Oltmans and Mallarino 2015). Therefore, to estimate the value of recycled K for a following crop, it is essential to consider the type of crop from which the K is recycled, the time between desiccation and planting of the next crop, the rainfall amount and pattern within this period, and soil properties that influence the fate of recycled K.Tropical grasses used as cover crops in Brazil can release from 1.5 to 6.5 kg ha^{-1} day^{-1} of K. Considering that Palisade grass and *Pannicum* have from 90 to 100 and pearl millet 200kg ha^{-1} of K accumulated in the residues, this is more than enough to supply the nutrient for crops as soybean, corn or cotton. In the US Corn Belt, from 50 to over 70 kg ha^{-1} were washed back to the soil from soybean residues up to the time of planting the next crop, depending on K fertilization, while in corn washed K ranged from 25 to 50 kg ha^{-1} (Oltmans & Mallarino 2015). In Brazil, in a soybean-pearl millet rotation, around 70 kg ha^{-1} of K was released from plant residues from soybean planting up to 50 days after emergence. By this time soybean had taken up around 90 kg ha^{-1} of K (Foloni & Rosolem 2004). These results show the importance of the nutrient accumulated in plant residues in supplying the next crop.

K LOSSES FROM THE SYSTEM

Pal et al. (1999) showed that soluble K is negatively related to the proportion of coarse sand and positively related to the amounts of clay and silt. Thus, greater K leaching losses might be expected from sandy soils than from clayey soils (Malavolta 1985). Potassium leaching below the arable layer increases with K application rates, although the effect is less noticeable in the clay soil.
Potassium leaching in a sandy clay loam soil is related to soil K contents from prior fertilization. With no excess water, in the presence of soybean roots, K distribution in the profile was significant in a light

textured soil but was not observed on a heavy textured soil (Rosolem et al. 2012). Furthermore, in sandy soils K leaching is proportional to applied rates (Rosolem et al. 2012) and it strongly increases with annual applications over 65 kg ha^{-1} of K. The increase of fertilizer-K rates intensifies K losses by leaching below 1.0 m in sandy clay loam soils, which represents 16 to 52% of the applied K added as fertilizer (Rosolem & Steiner 2016). Therefore, due to the high potential of K leaching, splitting of K fertilizer and conserving the nutrient in the straw are important management strategies to minimize K losses by leaching and improve K use efficiency in tropical low clay soils.

K FROM AGROINDUSTRIAL RESIDUES

The application of agricultural waste to the soil to complement or substitute for K fertilization is an important alternative adopted in the agricultural sector. Such practice, besides decreasing production costs, is an appropriate way of disposal of these materials, preventing environmental degradation. Several residues can be used as K sources in agricultural systems. However, the decision to apply a residue to the soil is related not only to the waste K concentration, but also to its availability and ease of acquiring by farmers.

In sugar mills, filter cake is obtained from impurities removed during the flocculation process, decanting and filtering the sugarcane in a device called rotary filter. It is estimated that 30-40 kg of filter cake are produced for each ton of cane processed (Santos et al. 2011). This residue has a considerable amount of organic matter and nutrients (Almeida Junior et al. 2011). Filter cake can be applied to infertile soils increasing K and other nutrients availability, as well as decreasing exchangeable-Al (Korndörfer & Anderson, 1997).

Vinasse, a byproduct of biomass distillation, is the biggest source of pollution in the ethanol industry (Santos et al. 2013). Disposal of vinasse has become a problem in sugarcane-growing countries. Considering that each liter of ethanol generates around 9-14 L of vinasse, it has been forecast that about 6 trillion liters of this material will need to be managed in 2023 (Carrilho et al., 2016). On the other hand, application of vinasse and sugar industry effluents are gaining more importance due to the presence of high quantities of mineral nutrients essential for plant growth and organic matter content, which not only improves crop yields but also solves the problem of effluent disposal (Jiang et al. 2012). Vinasse has high levels of K, Ca and organic matter in its chemical composition as well as moderate amounts of N and other nutrients (Abreu-Junior et al. 2008). This residue can be profitably recycled to improve soil chemical and physical properties and is an alternative to supply nutrients for crop production.

It is estimated that on an average 30 t ha^{-1} of filter cake and 150 m^3 ha^{-1} of vinasse, are equivalent to 60 and 690 kg ha^{-1} of potassium chloride respectively. Thus, vinasseis applied to provide 100% of the K required by sugarcane (Battaglia et al. 1886). Generally, it is applied in amounts from 60 to 350 m^3 ha^{-1}. Filter cake (wet) can be applied to the total area (80-100 t ha^{-1}), preplant, at planting (15-30 t ha^{-1}) or between cane lines (40-50 t ha^{-1}). The amount of K added by such wastes is fully deducted from the mineral fertilizer recommendation (Raij et al. 1997).

According to literature, 50 % of the coffee fruit are beans and another 50 % are husk (by weight). The large amount of coffee husk from coffee processing has caused environmental concerns, therefore, alternative uses for these residues must be found. Depending on processing, various wastes are generated, such as husk, pulp, parchment, mucilage and wastewater. Coffee processing residues are rich in several nutrients, the dominant of which is K, which concentration depends on the type of coffee husk. Although coffee processing residues are considered a good source of organic fertilizer (Matiello et al. 2005), little is known about the release and mineralization of the nutrients from these residues.

K CYCLING AND FERTILIZER RECOMMENDATION

According to Mallarino et al. (2013), the Iowa State University guidelines suggest considering the amount of residue removed and average K concentrations of 7.50 and 9.58 g K kg^{-1} for corn and soybean residue, respectively (150 and 100 g kg^{-1} basis). These are average concentrations for a variety of management conditions during the 1990s and 2000s. High STK values and high-K fertilization rates would lead to more K being removed in residues than the published numbers, because of the large K increase in the vegetative tissues in response to high-K supply (Rosolem et al. 2010; Oltmans and Mallarino, 2015).

Vitko et al. (2009) evaluated K fertilization for corn harvested for grain or silage and soil sampling time effects on STK at five Wisconsin sites during 3 years, and reported that spring STK was consistently greater than fall STK (20 to 45% greater) only at one site for both harvest systems and only in 1 year the STK increase was lower with silage harvest than with grain harvest. Grimes & Hanway (1967b) showed, in a greenhouse study, that corn and alfalfa (*Medicago sativa*) residues added to soil did not differ in availability and was equal to K added with KC1 fertilizer after 72 d of ryegrass growth (*Loliummultiflorum*). Soil test K levels were usually higher in spring than in the previous fall. The STK difference was correlated with the amount of K lost for both crops, although there was greater unexplained variability in corn (r^2 = 0.16) than in soybean (r^2 = 0.54). Oltmans and Mallarino (2015) also reported that soil-test K increased from fall to spring, that the increase was correlated to the K lost from corn and soybean residue, and that both crop type and precipitation strongly influenced the K recycled and the effect on soil-test K temporal change. Unmeasured changes among soil K pools in these studies could further explain soil-test K differences between fall and spring. Furthermore, K supply to ruzigrass was more dependent on the recently added fertilizer than on the residual effect of previous fertilizations in a light texture cerrado soil from Brazil (Rosolem et al. 2012).

Summing up, it is not difficult to measure or even estimate the amount of K to be released from crop or cover crops residues. However, there is uncertainty in estimating exactly how much will actually be available in time for the next crop. One approach would be to use soil testing as a monitoring tool, and estimate K rates to be applied considering the harvested K. This would not only guarantee an adequate K supply but also system sustainability.

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Potassium Losses and Transfers in Agricultural and Livestock Systems

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Abstract

Potassium (K) is one of the main nutrients applied as fertilizer in intensive cropping and grassland systems in the world. Thus, the consumption for potash for the 2014-2018 period is expected to grow at 2.6% annual rate, reaching up to 3,400,000 t between 2014 and 2018.

Because no specific environmental issues arise from K transfers to the wider environment, K balances in agricultural and livestock systems, as well as K losses to water bodies by runoff and leaching have received little attention. Nevertheless, because K is not bound to organic materials, it can be washed directly from the soil by rainfall, representing a potential economic loss to farmers, as well as resulting in an unbalanced soil nutritional status for plant growth.

These losses can be related to the general characteristics of the agricultural ecosystem (tropical or temperate regions, cropping or grazing, tillage management, interactions with other nutrients such as nitrogen), and specifics characteristics such as soil mineralogy, texture, initial soil K status, sources of K applied (organic, inorganic), and rates and timing of fertilizer applications. This text will provide an overview of the main factors affecting K transfers and losses by surface runoff and leaching, as well as an understanding of the key factors controlling these with the aim of improving K management globally.

INTRODUCTION

Potassium (K) is one of the main nutrients applied as fertilizer in intensive cropping and grasslands systems in the world. The demand for potash for the 2014-2018 period is expected to grow at 2.6% annual rate, reaching up to 3,400,000 t between 2014 and 2018. Of this, 56% would be demanded by Asia (23% in China alone), 27% in the Americas (18% in Brazil alone), 11% in Europe (6% in East Europe and Central Asia of which Russia accounts for 3%), 6% in Africa and 0.4% in Oceania (Figure 1; Food and Agriculture Organization of the United Nations 2015).

There are no gaseous losses of K, only losses to waters by leaching and surface runoff. However, little attention has been paid to such losses because K does not result directly in eutrophication. Nevertheless, K losses represent a potential economic loss to farmers, as well as an unbalanced soil nutritional status for plant growth, so that a better understanding of the main pathways and key factors controlling losses would allow the generation of practical recommendations to ensure productivity and economic return.

POTASSIUM LEACHING LOSSES

Potassium is a mobile ion in soils and so significant amounts can be lost by leaching (Quemener 1986), affecting the efficiency of the fertilizers applied. Leaching losses can be expected when K inputs exceed the soil retention capacity and plant demand, in the presence of drainage (Johnston 2003).

Potassium can be lost in surface runoff or by leaching. Losses in surface runoff are generally low, and dependent on rainfall intensity and K inputs (Alfaro, Jarvis & Gregory 2004; Alfaro et al. 2008). In temperate systems, favorable conditions for the development of surface runoff are mainly found during winter when no mineral fertilizers are applied. Nevertheless, substantial amounts of organic fertilizers (manure, slurries) may be applied then because there is more labor capacity available and the management does not interfere with grazing and cropping. Also, spreading in winter helps to reduce

storage requirements for manure or slurry. Although some countries ban the spreading of manures and slurries in winter to reduce losses of nitrate and phosphate to waters, this practice and fertilizer applications in early spring, increase the risk of K losses in runoff (Alfaro, Gregory & Jarvis 2004). The effect is likely to be greater in grazing areas because of the potential excessive trampling-poaching caused by animals, which modifies soil structure puddling the soil surface and reducing soil porosity (Heathwaite, Johnes & Peters 1996). In this case, the control of stocking rates at critical points during the grazing season is a key factor to reduce K losses from grazed paddocks (Alfaro, Gregory & Jarvis 2004; Alfaro, Jarvis & Gregory 2004).

Rain reduces the porosity of the soil over time as raindrop impact may increase the thickness of the compacted surface layer (Rousseva, Torri & Pagliai 2002), especially at high rainfall intensities, such as those from tropical regions (e.g. Acharya et al. 2007). This risk increases in soils with poor drainage, leading to an increase of K losses in runoff. Under no-till, K fertilizer is never mixed with the soil and so K concentration in runoff increased. However, as the raindrop impact is lower, K concentration in sediments is reduced, leading to a decrease in total loss in this pathway (Bertol et al. 2004).

It has been proposed that K leaching losses follow a two phase pattern. The first (fast) phase is dependent on soil K concentration at the end of the growing season and K inputs at the beginning of the drainage season (Alfaro, Jarvis & Gregory 2004; Askegaard, Eriksen & Olesen 2003), and K transport via macropore flow. The second (slow) phase is dependent on the amount and intensity of rainfall and associated with the development of matrix flow later in the drainage season (Alfaro, Jarvis & Gregory 2004). Leaching losses can be as low as 0.2 kg K ha^{-1} yr^{-1} in the prairies of northern America (Brye & Norman 2004) and as high as 185 kg K ha^{-1} yr^{-1} under urine patches in a silt loam soil in New Zealand (Di & Cameron 2004). These losses are influenced by the rate of K applied and the timing of fertilizer application, soil type and land use, and the amount and pathways of drainage.

Potassium Fertilizer Application

High K application rates generate high K losses, especially when drainage exceeds 500 mm (Bolton, Clylesworth & Hore 1970; Thomas & Hipp 1968), so that split fertilizer applications are preferable in these situations. Rainfall distribution is often more important than the total amount (Quemener 1986) because of its impacts on surface runoff development, relative to the amount of matrix flow (Heathwaite, Johnes & Peters 1996). In tropical light textured soils managed under no-till, K leaching is high when fertilizer application exceeds plant demand (Rosolem & Steiner 2007). Fertilizer placement as well as new fertilizer alternatives could play a significant role in reducing K losses (see later).

Soil Texture

Higher leaching losses are expected in soils with a low K holding capacity such as sandy soils, in relation to clay soils (Johnston 2003), especially those in which organic matter makes up much of the cation exchange capacity (CEC), where heavy rains can seriously deplete the amounts of soil available K in a matter of days (Thomas & Hipp 1968). In these soils, K leaching losses are related to soil K concentrations due to previous fertilizer applications (Rosolem et al. 2010). Alfaro, Jarvis & Gregory (2004) showed that K losses from a clay soil can be higher than those from a sandy soil as a result of a conjunction of K input and macropore flow. This would also be the case for K leaching losses under urine patches in grazing areas (Williams, Gregg & Hedley 1990b).

Macropore flow has been shown to occur immediately after a cattle urination event, because these are large and are deposited to relatively small volumes of soil. The K supply is often in excess of the short-term requirements of the plants growing in the urine patch, and consequently K penetrates to depth in the profile (Williams & Haynes 1992). This process occurs too quickly for any significant sorption reactions between the soil and solutes in the urine (Williams & Haynes 1992). In dairy systems, cows are responsible for 74 to 92% of total K losses (Williams, Gregg & Hedley 1990a), accounting for 3-29 kg ha^{-}

^{1} yr^{-1} in grazing areas of Chile and New Zealand (Alfaro, Salazar & Teuber 2006; Williams, Gregg & Hedley 1990a), and up to 185 kg ha^{-1} yr^{-1} under urine patches in New Zealand soils (Di & Cameron 2004).

Additionally, in highly weathered tropical soils, high K mobility, and thus leaching, can be expected (e.g. Rosolem & Calonego 2013), while tillage does not affect K leaching losses (Stinner et al. 1984).

Source of Fertilizer

Most K sources (manures, composts, crop residues, and waste waters) contain K in a simple cationic form (Arienzo et al. 2009; Stockdale et al. 2002), and inorganic fertilizers and organic manures are interchangeable sources of K (Johnston & Goulding 1990). Thus adjusting K inputs in relation to estimated outputs, avoiding a surplus, becomes a key factor for reducing K leaching losses. Particular attention should be paid to K saturation in soils due to not accounting for K when using organic sources (Askegaard & Eriksen 2002; Bernal, Roig & García 1993) or waste water (Arienzo et al. 2009).

Irrigation and Drainage

Irrigation increases K losses, depending on water quality and on soil conditions (Kolahchi & Jalali 2007; Sekhon 1982). Potassium leaching increases with high cation concentrations in irrigation waters (e.g. Ca^{2+}), through ion exchange, such as those used in saline areas.

Because of an increase in crops and grasses yield in drained areas (in comparison with the undrained areas) a decrease could be expected in soil K, which might reduce the amount of K susceptible to leaching. This effect is enhanced by the fact that in areas of poor drainage, temperature is lower and oxygen availability is poorer than in well drained soils. These reduce root development and the diffusion of K into the rhizosphere and plant roots (Barber 1985), resulting in lower dry matter production and a higher availability of K in soil solution, at risk of loss in undrained areas. In contrast, K leaching losses may significantly increase in drained soils because of preferential flow when K fertilizer is applied, as discussed previously. In these cases, a key aspect to reduce K losses is the time interval between K application and the rainfall event: the longer this interval the lower the losses (Alfaro, Jarvis & Gregory 2004).

Potassium and Nitrogen use

An alternative to reduce K leaching losses would be to use nitrogen (N) management as a tool to increase the utilization of K by plants and, thereby, reduce the amount of K available for leaching at the end of the growing season. In south west England, soil K balances were strongly affected by pasture yield and losses were apparently related to the amount of available soil K, which in turn, was related to plant uptake associated to N input (Alfaro, Jarvis & Gregory 2003). Nevertheless, in intensively managed agricultural systems with nutrient surpluses, greater N leaching losses are usually linked to greater K leaching losses (Brye & Norman 2004). Potassium leaching is related to N fertilizer rates even when N is not applied in excess. Also, because liming in acidic soils increases nitrate concentration in uppermost soil layers, this can result in higher K leaching losses (Crusciol et al. 2011). Additionally, losses of N and K from permanent pastures are much less than when other crops are grown (Greenland 2000).

There should be no fundamental difference when using organic or inorganic N fertilizers on exchangeable K forms, so any N source should have similar effects on K leaching losses, although ammonium N fertilizers could increase K losses as this ion can replace K from exchangeable sites. Addiscott and Johnston (1975) showed that the use of organic sources as fertilizers increased the organic matter content of the soil and, depending on the composition of the material, it could protect soluble K. Potassium inputs in excess to plants requirements would result in greater K losses, as discussed previously.

THE WAY FORWARD

The development and implementation of fertilizer best management practices with a focus in the 4Rs (right source, right rate, right time and right place) is necessary in the short-term for productivity and economic reasons, and in the long-term because they provide more efficient ways of using non-renewable resources upon which food and feed production depend (Fixen & Johnston 2012).

Enhanced efficiency fertilizers (e.g. Di & Cameron 2004; Gillman & Noble 2005; Yang et al. 2016) provide an alternative way to increase K use efficiency. The main advantage of these is that K supply matches plant requirements, protecting K from leaching. The use of nitrification inhibitors such as Dicyandiamide in grassland soils has been found to reduce K leaching losses by up to 65%, probably as indirect effect of its addition on increasing yield and reducing nitrate leaching losses and thus, the loss of a balancing cation such as K^+ (Di & Cameron 2004). The rate of adoption of these technologies is limited because of the cost of the materials in comparison to traditional sources, the existence of regulatory policies (Gillman & Noble 2005), health and safety issues associated with their application (Timilsena et al. 2015), and sometimes reduced information available on its impacts on productivity at the farm level.

The use of Information Technology (IT) tools for nutrient management has become more common and, although originally they focused on N and phosphorus because of their environmental implications, they have been expanded to include other nutrients. Some examples of farm nutrient management tools that account for K management in crops and grasslands are MANNER-NPK and OVERSEER®. MANNER (the **MAN**ure **N**utrient **E**valuation **R**outine) is a decision support tool for quantifying the crop available nutrients in manures and other organic materials (N, P, K, S and Mg), contributing to reduced over-fertilizer application, and with it, leaching losses (Nicholson et al. 2013). The OVERSEER® nutrient budget model is a farm-scale nutrient (N, P, S, K, Ca, Mg, Na, acidity) reporting tool used by farmers and consultants throughout New Zealand (Wheeler et al. 2003). The model can be used to optimize nutrient input (both inorganic and organic) to maximize production while minimizing nutrients losses to water (Wheeler, Ledgard & DeKlein 2008). More recently, the validation of the modified Soil and Water Assessment Tool (SWAT) model to simulate stream K load and K budget at the scale of a dairy farming watershed in Japan (Wang et al. 2016) is an example of a more integrative K management approach.

Potassium plays a significant role on plant tolerance to drought (Egilla, Davis & Boutton 2005), so that its availability can play a significant role in the adaptation of crops to future scenarios of water limitation in already dry areas (Sardans & Peñuelas 2015). Recent investigations have shown that organic exudates of some bacteria and plant roots play a key role in releasing otherwise unavailable K from K-bearing minerals. Plant breeding for such key attributes can contribute towards a more sustainable agriculture, particularly in cropping systems with no access to fertilizer K (Zörb, Senbayram & Peiter 2014). Genetic improvements to increase K uptake efficiency and cope with reduced rainfall would in turn reduce K leaching losses. The risk of more frequent extreme flooding events happening every two to eight years rather than every 100 years in certain areas (Department for Environment Food and Rural Affairs 2002), remains as high risk in the future for K, and other nutrients, losses in overland flow.

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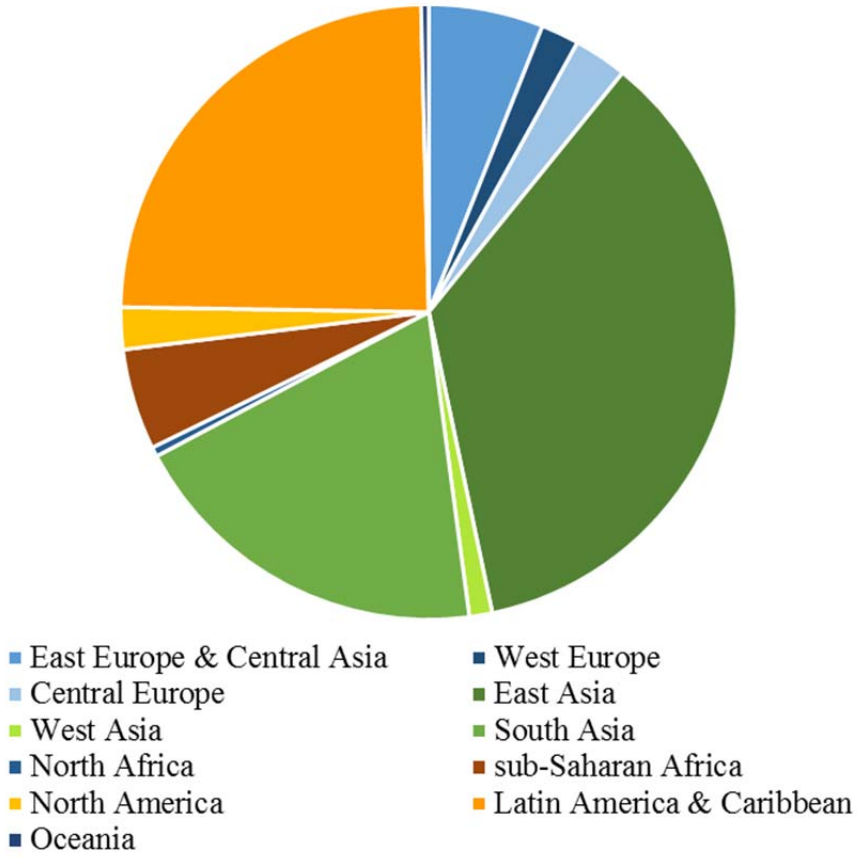
Figure 1. Regional and subregional share of world increase in potash fertilizer consumption, 2014-2018 (FAO 2015).



How Closely is Potassium Mass Balance Related to Soil Test Changes?

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Abstract
The traditional view of plant available soil test potassium (K)has been that the exchangeable fraction of soil K is the most important source of K for plants, and that other sources may play a small role in crop production, but do not influence the predictive value of the test at least for the next crop. One would then expect that as K mass balance changes, the soil test would correspondingly change and the changes would be associated with greater or reduced plant availability. However, soil test changes and the availability of K to plants are influenced by other factors: soil clay content, clay type, return of K from residue to soil, soil moisture, previous crop and cropping system, K-bearing mineral type, and whether the net K content of the soil is increasing or decreasing. This chapter reviews the literature and recent research on soil test K changes and the relation to crop uptake and yield. A mass-balance relationship of exchangeable K is only rarely achieved because of the rapid equilibrium between soil solution K, exchangeable K, K-bearing primary minerals, and clay interlayer K. In addition, soil moisture, temporal differences in exchangeable K levels with K uptake by crops, K leaching from residues, clay type, organic matter contribution to the soil CEC, and type of K amendment confound any attempt to relate K additions and losses with K soil test. Subsequent research is needed to create regionally specific K soil test procedures that can predict crop response within a subset of clays and K-bearing minerals within specific cropping systems.

Introduction
If potassium (K) nutrition of crops were a simple system, with additions of K held by the soil and released as needed, then the K supply and relative availability could be accurately predicted by a simple soil extraction. However, the reality is that the prediction of K availability is as difficult to understand as N availability. While N availability prediction is confounded by temperature, rainfall, soil moisture condition and biology, K nutrition is affected by all of those same factors with the addition of the physical and chemistry properties of the soil and its mineralogy, mainly of the K-bearing minerals.

The dynamics of sources of K and interactions between sources has been summarized and described in many diagrams, most lately by the flow chart in Figure 1 developed during the 2014 Frontiers in Potassium Science Workshop 2014 in Hawaii. It is difficult to portray the dynamics of K additions and the magnitude of K flow between different pools in a diagram because soil minerals, especially clays and clay mineralogy, organic matter content, cropping system, and environmental conditions of temperature and soil moisture vary greatly around the globe. We will attempt to capture the difficulty of using a mass-balance approach to crop K nutrition from the biological, temporal, clay mineral and primary mineral components depicted in Figure 1.

The mass-balance approach-
The basic premise of a mass-balance approach is that when K is added to the soil, most often as soluble K fertilizers, such as potassium chloride (0-0-60 to 0-0-62) or potassium sulfate (0-0-52), the K ions are retained at the soil cation exchange sites with the potential to be released later into the soil solution and taken up by the crop. The extraction used when this process is assumed is a cation-replacement solution, such as 1M- ammonium acetate. In the USA, the mass-balance approach is a common strategy for K

fertilization, particularly in states that recommend a buildup and maintenance approach to crop fertilization but also to maintain desirable soil-test values when response-based information is used to decide fertilization rates for low-testing soils. In the strict buildup-maintenance approach, the fertilizers, usually P and/or K, are applied at rates intended to replace crop grain or forage removal and, if necessary, the soil test is increased through the addition of extra fertilizer to attain a certain soil test level regarded as critical or optimum for K supply. In Illinois, for example, it is assumed that the rate of K recommended to increase the K soil test by 1 mg kg^{-1} in the medium to higher CEC (cation exchange capacity) soils of central and northern Illinois is about 10 kg ha^{-1} K (Fernandez and Hoeft, 2015), but this is a broad average.

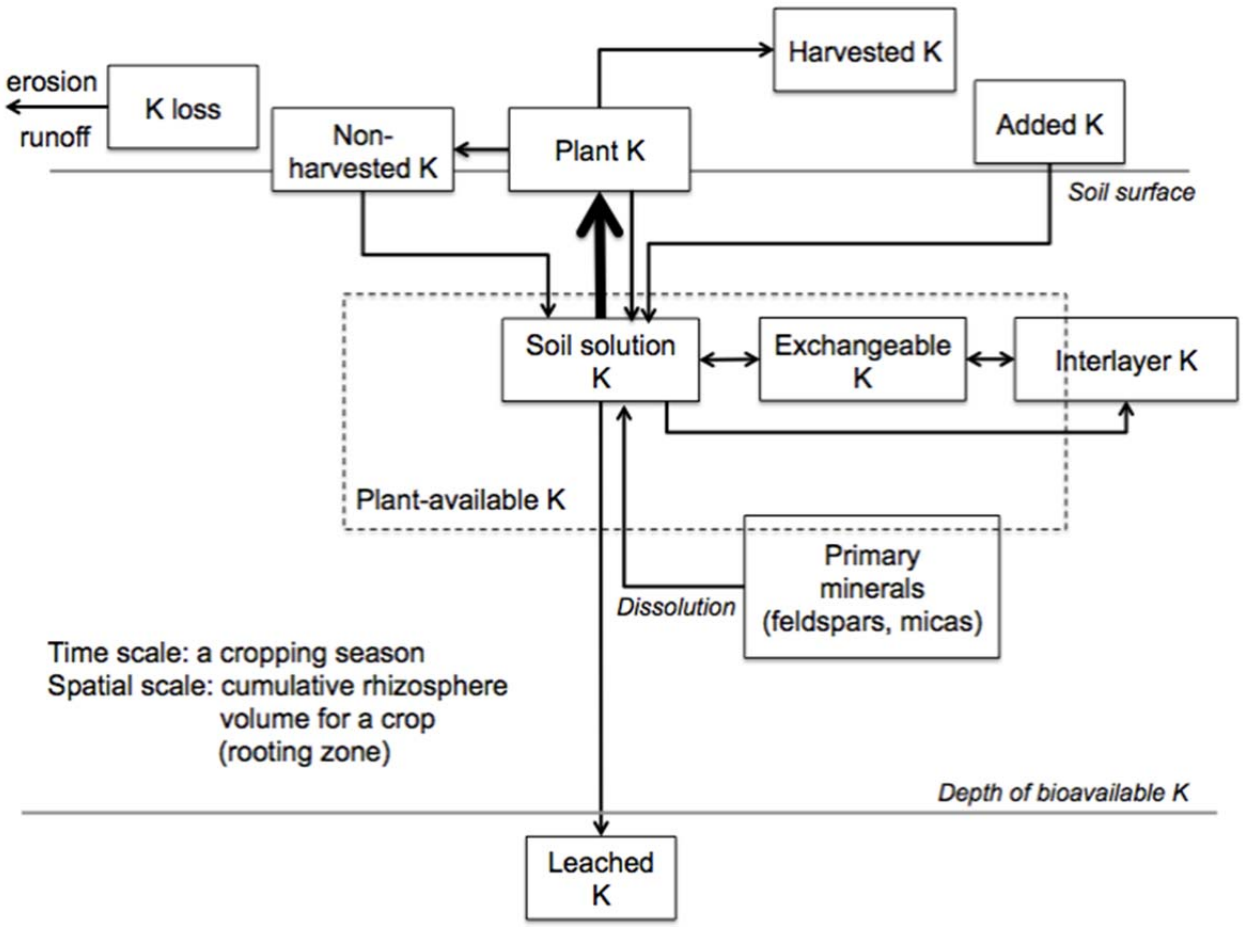


Figure 1. Sources of soil K and interactions between sources (IPNI, 2015).

In Illinois, the mean fertilizer K rates and mean yields in two 12.5 ha fields were documented for 40 years starting in 1960 (Franzen, 1993). The rates applied were greater than crop removal until 1982, which resulted in increased soil test K levels. From 1982 until 1992 no additional fertilizer K was added and K removal by corn and soybean harvests were estimated for all years. The results are shown in Figure 2. The rate at which the K test increased with K addition was different from the rate of decline with crop removal. The results show an 'hysteresis' effect. At Thomasboro, the rate of soil test K increase was 1 mg kg^{-1} for 6.6 kg K ha^{-1} added as fertilizer over crop removal. After K fertilization ceased, the rate of soil test K decline was 1 mg kg^{-1} for 2.4 kg K ha^{-1} in crop removal. At Mansfield, the rate of soil test K increase was 1 mg kg^{-1} for 5.8 kg ha^{-1} added as fertilizer over crop removal. After K fertilization ceased, the rate of soil test K decline at Mansfield was 1 mg kg^{-1} for 2.2 kg K ha^{-1} in crop removal.

In the Parana state of Brazil (Steiner et al, 2015), a K application experiment on 12 tropical soils with basalt, shale, sandstones and alluvial parent materials resulted in reductions in exchangeable K after the initial two-year soybean/pearl millet cropping sequence with comparably small reductions in exchangeable K during the following four years. In K fertilized treatments of the same soils, exchangeable K increased in all soils and reached a plateau of values after the first two crops. The subsequent K exchange values were similar through the following four crop years despite continued K fertilization. Thus the mass-balance approach appeared to be operating during the first two years, but not in subsequent four years. What was not considered by the researchers, but has been observed in Australia (Bell et al., 2009) is that K can be leached to deeper soil depths and retained at these depths. Thus, the Parana soils may have reach a 'saturation' with respect to K, and subsequent K fertilization may have increased subsoil K, but not surface K. Bell et al. (2009) support K determination in their soils at deeper depths than those usually considered.

In Alabama, USA, Cope (1981) summarized fifty years of K fertilization in four sandy low CEC (< 5 meq 100 g^{-1}) soils and one silt loam soil with CEC about 10 meq 100 g^{-1}. He found that, in the unfertilized plots, the soil test K initially decreased, but reached an equilibrium after 28 years at most; the second sampling being in 1957, 28 years following study initiation. A K rate of 18 kg ha^{-1} K resulted in no soil test change, while K rates greater than 18 kg ha^{-1} K resulted in soil test K increases in all soils. The soil test K levels during and at the termination of the experiment were related to the CEC of the soils. So, in this experiment with kaolinitic and quartz-based soil parent material soils, the mass-balance approach to K fertilization was effective.

In a summary of a series of five 16-year K rate experiments in Iowa (Villavicencio, 2011), researchers found that when K was not applied, the rate of decrease in soil test K (15-cm depth) did not match the K removal rate from the grain in the short term (Figure 3). There was very high temporal soil test K variability from year to year that the yearly K removal seldom explained. The soil test and K removal trends approximately matched over several years, however, except when decreasing soil-test K reached a minimum plateau at around 120 mg kg^{-1} when in spite of continuous K removal the soil test decrease may have been buffered by soil release from other pools in the topsoil or subsoil, or supplemented by deeper profile soil K. The soil clays at the experimental sites were dominantly smectitic. In addition, as K soil test decreased, corn and soybean yield was not always increased by K additions. Yield increases were frequent and common only at three sites where soil test K was initially < 170 mg kg^{-1}, which placed them in Iowa State University recommendation categories of 'optimal' and lower.

Thirty-year experiments in the UK, Germany, and Poland compared K balances with or without K fertilizer or farm yard manure (Blake et al., 1999). The recovery rate of K from mineral fertilizers was less than 62% and determined by the CECs and, at the UK site at Rothamsted, by the fixation capacity of the clays. In Germany and Poland, utilization of K from mineral fertilizers was reduced when farm yard manure was applied because K from the manure resulted in greatest crop uptake. A Canadian study of the kinetics of K adsorption by organic matter showed that organic matter adsorbed K is much more accessible by plants and adsorption of K onto organic matter exchange sites is more rapid (Wang and Huang, 2001). These experiments again showed that a mass-balance approach is not entirely useful because the source of K, the characteristics of the CEC sites, and the soils interact to confound any 'check-book' balance that may be attempted. An approach to making the soil to more effectively conform to a mass-balance approach was suggested by Addiscott and Johnston (1971). They proposed that, by increasing the soil organic matter content through application of farm yard manure, along with regulating the soil moisture supply to minimize K leaching, more K would be retained on the organic matter exchange sites and less would be moved into non-exchangeable forms.

A variation on the mass-balance approach is the 'Ideal Soil' CEC balance ratios championed by Bear in New Jersey (1951) and later by Albrecht at the University of Missouri (Albrecht, 1975). The premise of

this approach is that the amount of K in the soil is not as important as the ratio of K to that of the other major cations, Ca and Mg. A commonly used ratio of K in an 'ideal' soil is somewhere between 2-5% of the base exchange capacity (Graham, 1959). Although this approach is still used in parts of the USA by fertilizer and amendment sales organizations, its scientific validity has been refuted. A review of the use of this Base Cation Saturation Ratio approach was authored by Kopittke and Menzies (2007). The review concludes that the data do not support the existence of an ideal ratio and that its use would result in inefficient use of resources.

Temporal nature of K soil test values

The previous studies have demonstrated that a purely mass-balanced approach does not always account for soil test differences in exchangeable K values, and that the use of some ideal ratio of cations in directing K application is not effective. The deficiency of a mass-balance approach is also reinforced by the temporal nature of K soil test values based on a measure of exchangeable K. A 20-year study using twice-monthly soil sampling at the 0-15 cm depth for exchangeable K (1M-ammonium acetate) was conducted at Urbana, IL and Brownstown, IL, USA. Most of this data was lost and never published, but 9 years of the Urbana work was published in 2005 (Peck and Sullivan, 1995). Using tabular values, Franzen (2011) imposed a seasonal repeated analysis using the statistical package SAS (PROC UCM time series analysis using 24 data points per cycle) to the data and found that the relative K values were related to soil moisture at the time of sampling. Starting on April 1, 1986, in each year (Figure 4), the extractable K is highest in winter when soil moisture is greatest, and lowest in late summer when the soil is driest and K supply was decreased by corn uptake. The soils in this study were smectite clay dominant.

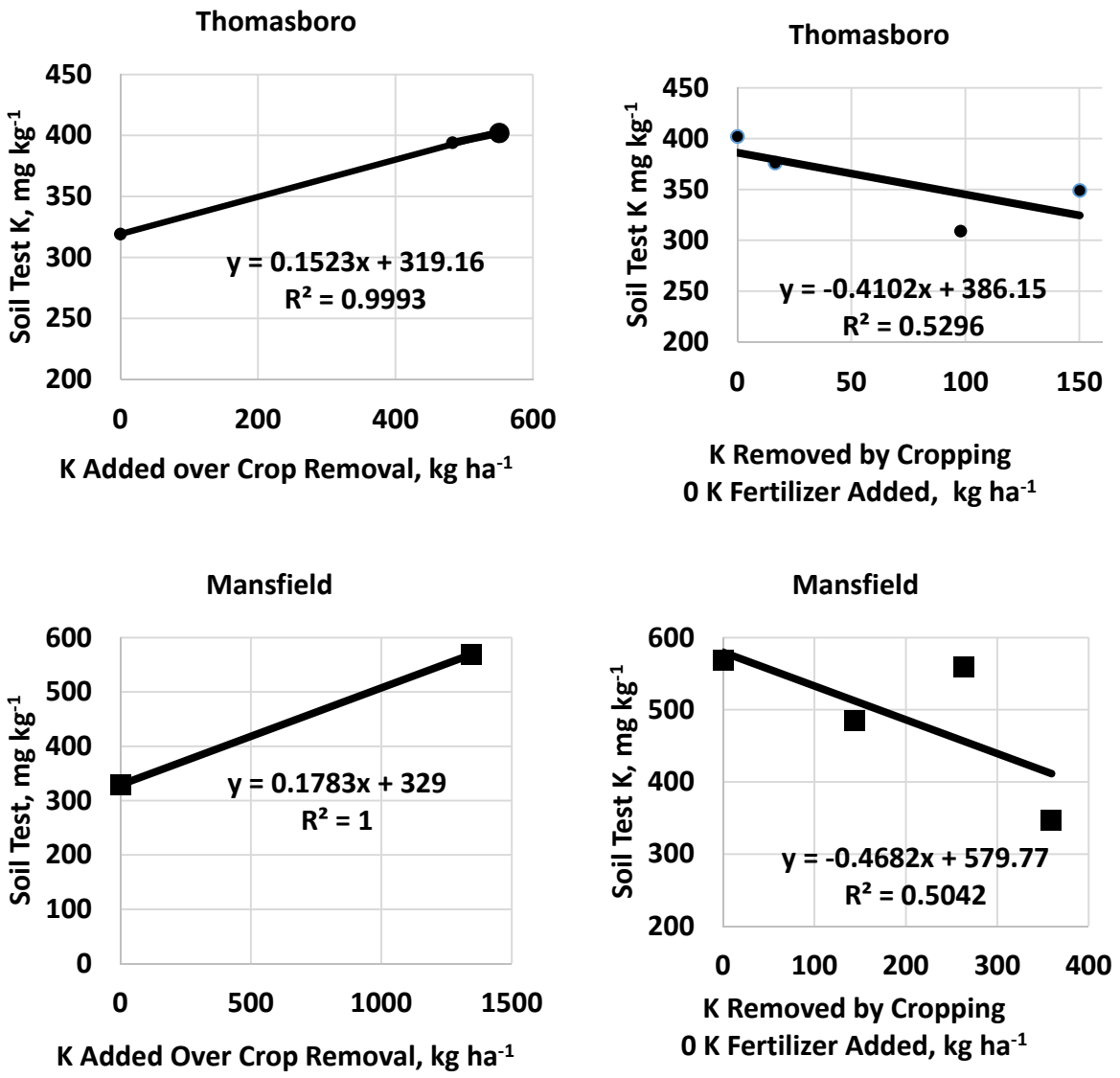


Figure 2. Cumulative net K added per hectare to Thomasboro (upper left) and Mansfield (lower left) Illinois 12.5 ha fields over a period of years, compared to K removed by crop removal at Thomasboro (upper right) and Mansfield (lower right) after K fertilization ceased in 1982 at both sites.

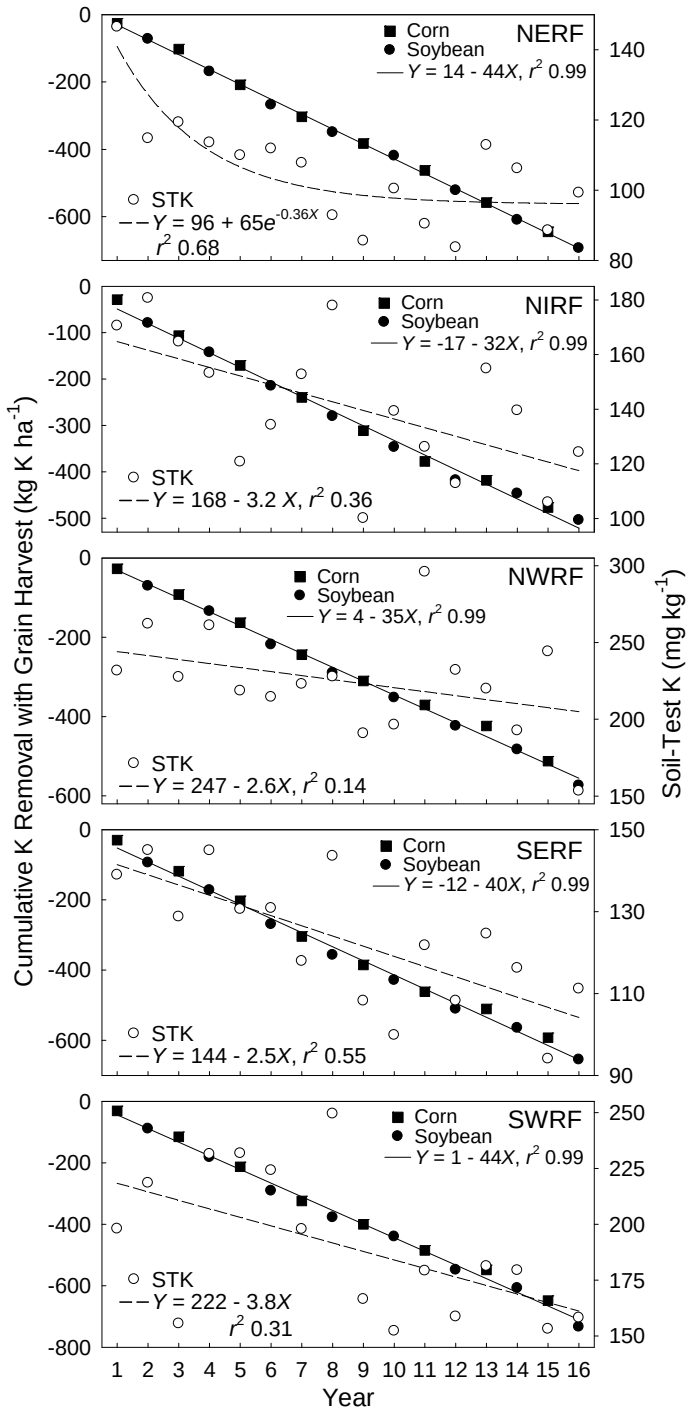
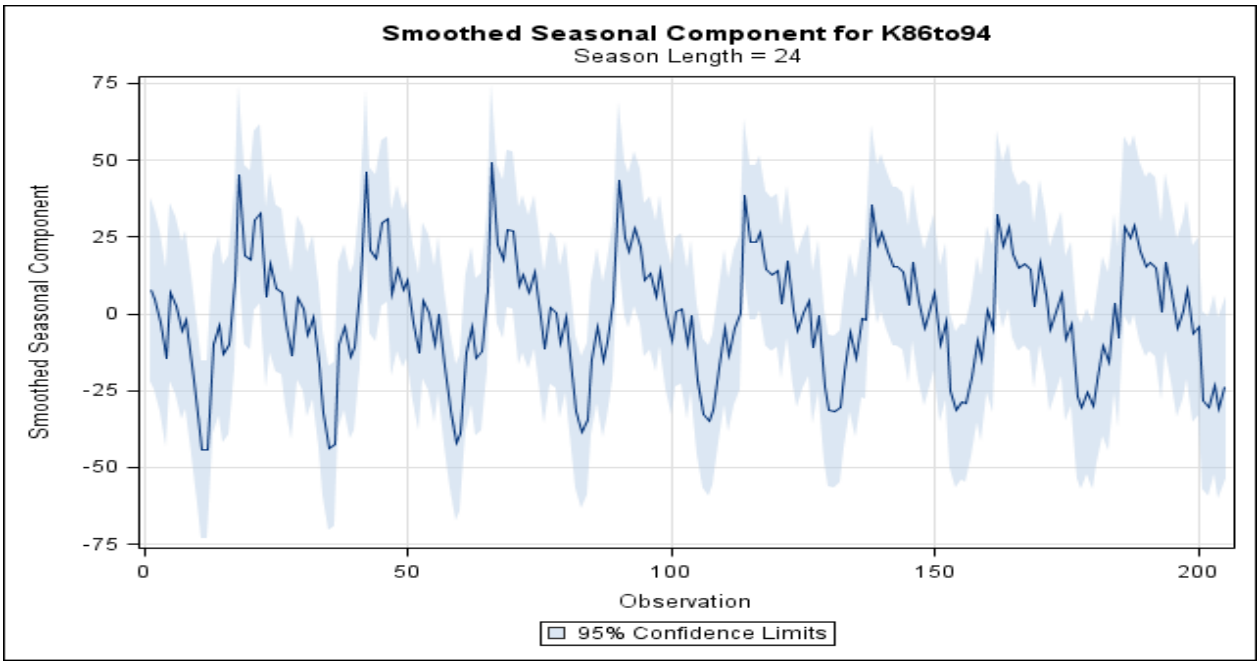


Figure 3. Trends over time for cumulative K removal with grain harvest and soil-test K for samples collected each year from the non-fertilized plots in long-term Iowa K fertilization experiments. NERF, NIRF, NWRF, SERF, and SWRF are different experiment sites throughout Iowa (From Villavicencio, 2011.



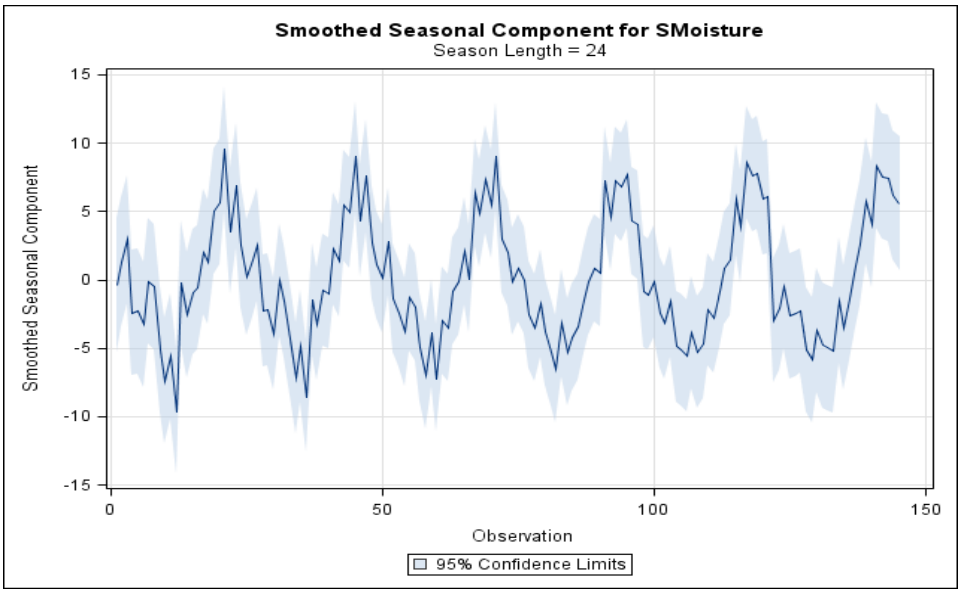


Figure 4. Seasonality of soil K (top image) over 9 years, compared with soil moisture (bottom image over 6 years. Soil samples 0-15 cm obtained twice monthly from April 1, 1986 through 1994. Soil moisture was available for the first 6 years only. From Franzen, 2011.

Recent K studies in North Dakota using illite dominant and smectite dominant clays have indicated that the seasonality of the K soil tests is slight on the illitic clay dominated sites have slight seasonality, but relatively high on the smectitic clay dominated sites. The North Dakota climate is not favorable for winter soil sampling; however, the North Dakota data shows greatest K extraction by 1M-ammonium acetate in early spring, with values decreasing as the season progresses to drier months. These data are not as clearly related to soil moisture as those from Illinois,. To determine whether the seasonality was related to crop uptake, both fallow and cropped (corn) check plots were sampled twice each month from planting to harvest. The seasonality of the K test and its decrease through the growing season was present at both the

smectitic and illitic sites when the soils were cropped (Figure 5). When the soils sampled were dominantly illitic (Figure 5), the K test tended to remain relatively constant, while in a smectitic soil, the K test levels tended to decrease in the drier part of the summer (between week 12 and 17) and increase when soils were moist (week 10, 18,19). This is consistent with fixation during dry conditions, and release when the soils are moist. The fixation in these soils is temporary, and release and fixation of K is relatively rapid and reversible based on these data.

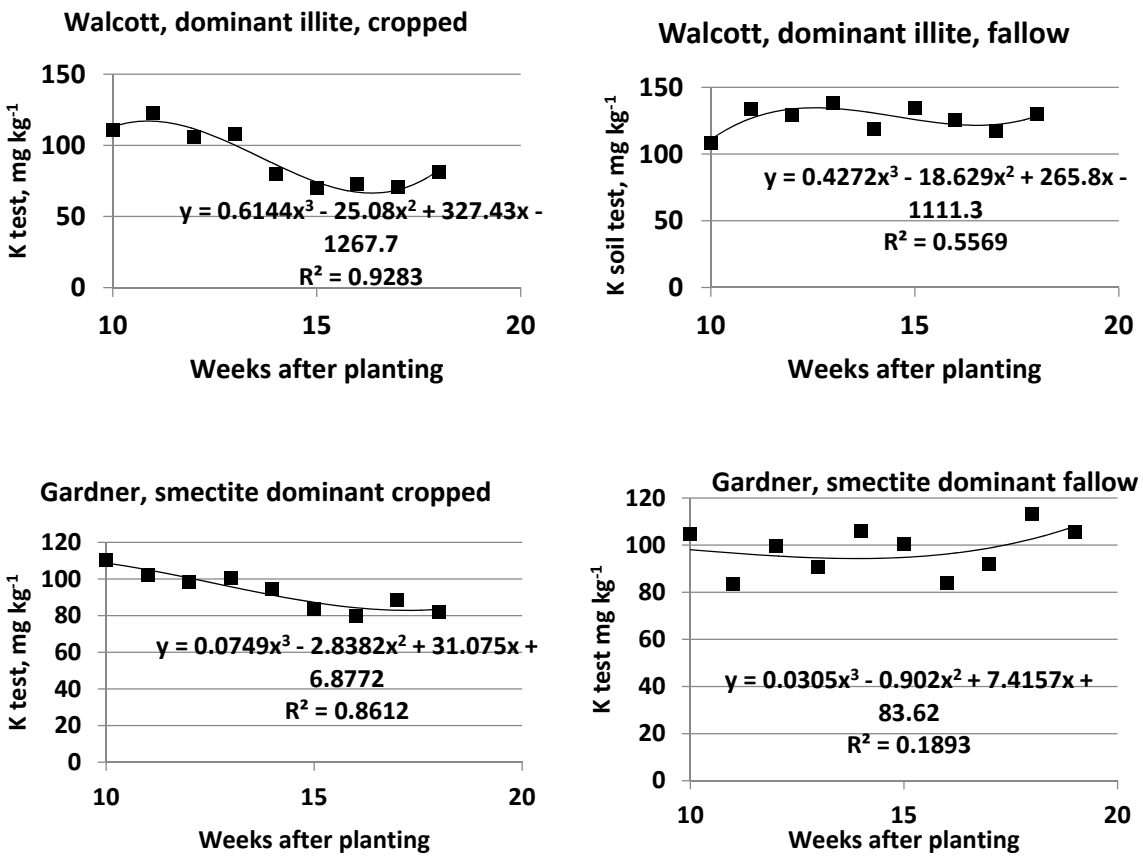


Figure 5. Change in dry soil test K levels from 10 weeks after planting to 20 weeks after planting, North Dakota in a dominant illite soil and a dominant smectitic soil under corn and fallow (Breker and Franzen, unpublished).

Crop residue recycling in K mass-balance considerations

The reason for seasonality in the K test is partially due to uptake by the crop and its release back into the soil after physiological maturity. Mean corn vegetative K content at physiological maturity in a series of Iowa K rate experiments (Oltmans and Mallarino, 2015) was 93 kg ha^{-1} for sites with a K yield response and 101 kg ha^{-1} for sites with no K response. For soybean, mean K accumulated in vegetative parts at physiological maturity was 95 kg ha^{-1} for all sites. From physiological maturity, K is lost from the vegetative portion of the plants, with mean K in vegetative tissues in corn at harvest at sites with a K yield response of 66 kg ha^{-1}, and 67 kg ha^{-1} at sites with no K response. In soybean, mean residue content of K declined to 41 kg ha^{-1} at harvest. These data indicate that soil sampling at physiological maturity, which is a practice utilized by some crop consultants, may result in lower soil test K values than if the samples were taken at harvest or later in the fall. Residue K content of corn and soybean was about 25 kg ha^{-1} and 54 kg ha^{-1} less, respectively, at harvest compared to physiological maturity. Losses from crop residues also contribute. The soybean residue in the Oltmans and Mallarino (2015) study continued to lose K throughout the fall until late January when the K content reached about 10 kg ha^{-1}. Loss of K from corn

residue steadily declined to about 30 kg ha^{-1} in early December, then decreased again during the spring thaw. Precipitation following physiological maturity explained much of the residue K decline. Across all sites, the soil test K level (15-cm depth) was higher in spring than in the fall, and the magnitude of difference was linearly related with the K loss from residue, although the relationship was much better in soybean residue (r^2 0.56) than in corn residue (r^2 0.16). These data indicate that soil sampling at physiological maturity, which is a practice utilized by some crop consultants, may result in lower soil test K values than if the samples were taken at harvest or later in the fall.

The cycling of K from residue back to soil is a noted component of many plant ecosystems (Jobbagy and Jackson, 2004). Plants mobilize K from deeper in the soil in natural systems, and their leaves and other vegetative parts are returned to the soil, resulting in an accumulation of K near the surface. Corn and soybean and other crops also return K to the soil surface; corn returning a much larger percentage than soybean (Oltmans and Mallarino, 2015). Most crop grains at harvest, including wheat and corn, do not contain high K levels in the seed that is removed, with soybean being an exception.

Although there is often a relationship between exchangeable K and crop yield response to K addition, the relationship is even less frequent with absolute crop yield. The relationship is also seldom mass-balance based, as the previous discussion would indicate. In soils with a sandy texture (Mendes et al., 2016; Alfaro et al., 2004) and in clay soils with deep cracks followed by high rainfall (Alfaro et al., 2004), K losses from the soil system by leaching is common resulting in much apparently available exchangeable K being unavailable to the crop early in the growing season; this can result in a yield penalty. In most soils, the K leached from the 0-15 cm normal K sampling depth would be retained at deeper soil depths; therefore, a multi-depth approach in soils with surface layer K leaching potential may be important to explaining mass-balance and response to K at lower soil test values. However, the main reasons used to explain why a mass-balance does not explain crop response or soil test K levels are the composition of soil minerals and clay content. Although students are often taught that the exchangeable K 'pool' in the soil is the major source of available plant K and the reservoir for most fertilizer K applied, the reality is that the equilibrium reactions between the soil solution K, exchangeable K, 'fixed' K, clay mineral interlayer K, and 'non-exchangeable' K in soil minerals such as potassium feldspar can be rapid and have a significant influence on the soil test and crop production. Discussion of the dynamics depicted in Figure 1 suggest that equilibria between exchangeable K, solution K and K additions as fertilizer are always rapid, with each being measured in hours or days, not weeks, months and years (Krauss and Johnston, 2002).

Clay chemistry and K response

According to research by Sharpley (1989) in his study of 102 soils from the continental US and Puerto Rico, water soluble K was closely related to exchangeable K within soils of similar clay-type, but not between clay-types. The release of K from exchangeable sources into solution increased from smectitic to 'mixed' clays to kaolinitic clays. Sharpley recommended that an analysis of exchangeable K and K reserves (as nitric acid-extractable K) would provide a better indication of K supply for crops.

An Australian study reported K fertilization policies in Red Ferrosol, low CEC soils, and Black and Grey Vertisols, which are moderate to high clay content soils. Analyses of exchangeable K, soil solution K and the activity of K in soil solution varied 6-7 fold between soil types (Bell et al., 2009). The management of K for optimal crop production varied with soil. The Vertisols were highly K buffered, and applications of K were not as effective as those in the low CEC Red Ferrosols. A better K fertilization approach for the Vertisols was to apply a near-row concentrated band of K fertilizer rather than a broadcast application that resulted in lower concentration of K within the soil volume. In the high clay Vertisols with high CEC (50-60 meq $100g^{-1}$), a deep band of K with N and P was also effective in relieving K deficiency.

In a study of 23 K rate experiments in North Dakota in 2014 and 2015, the response of corn to an exchangeable K critical level of 150 mg kg^{-1} K was not predicted at 10 sites (Table 1). The relative yield of the check in relation to soil test K of these sites is shown in Figure 6. The relationship of exchangeable K to relative yield was very weak. A multiple regression analysis (Table 2) of relative yield with the potassium feldspar concentration of the mineral fraction of the 23 sites and the relative clay mineral percentage of the clay fraction is shown in Table 1. The greatest relationships with yield were illite > K soil test > Smectite >>> K-feldspar. Therefore, to maximize the prediction of yield response to K in these North Dakota soils, the clay mineralogy should be included, along with the K soil test.

Table 1. A series of 23 K rate studies in corn in North Dakota, with clay mineralogy of the clay fraction and potassium feldspar content of the mineral portion of the soil are indicated. Beginning preplant soil test K (1N-ammonium acetate on dry soil) is also indicated along with expected yield increase compared to the yield increase experienced.

Site, Year	K test, mg kg^{-1}	Expected Yield Increase	Actual Yield Increase	Potassium feldspar-%	Smectite%-Illite %
Buffalo, 2014	100	**Y**	**N†**	7.1	85-11
Walcott E, 2014	100	Y	Y	5.8	84-13
Wyndmere, 2014	100	**Y**	**N**	6.1	72-22
Milnor, 2014	100	**Y**	**N**	11.7	35-57
Gardner, 2014	115	Y	Y	5.3	76-20
Fairmount, 2014	140	**Y**	**N**	8.0	80-14
Walcott W, 2014	80	**Y**	**N**	7.3	52-40
Arthur, 2014	170	**N**	**Y**	1.7	85-11
Valley City, 2014	485	N	N	9.0	70-23
Page, 2014	200	N	N	5.7	74-20
Absaraka, 2015	113	**Y**	**N**	9.9	84-14
Arthur, 2015	125	Y	Y	9.5	85-12
Barney, 2015	170	N	N	6.3	79-16
Casino, 2015	120	Y	Y	6.4	85-12
Dwight, 2015	110	Y	N	6	82-15
Fairmount1, 2015	188	**N**	**Y**	5.6	87-10
Fairmount2, 2015	118	**N**	**Y**	7.4	79-12
Leonard N, 2015	380	N	N	6.9	70-25
Leonard S, 2015	190	N	N	5.5	52-41
Milnor, 2015	118	Y	Y	8.6	74-20
Prosper, 2015	205	N	N	9.2	83-14
Valley City, 2015	200	N	N	5.6	65-30
Walcott, 2015	109	Y	Y	6.2	47-48

† Bold font denotes site where expected yield response or non-response was not recorded.

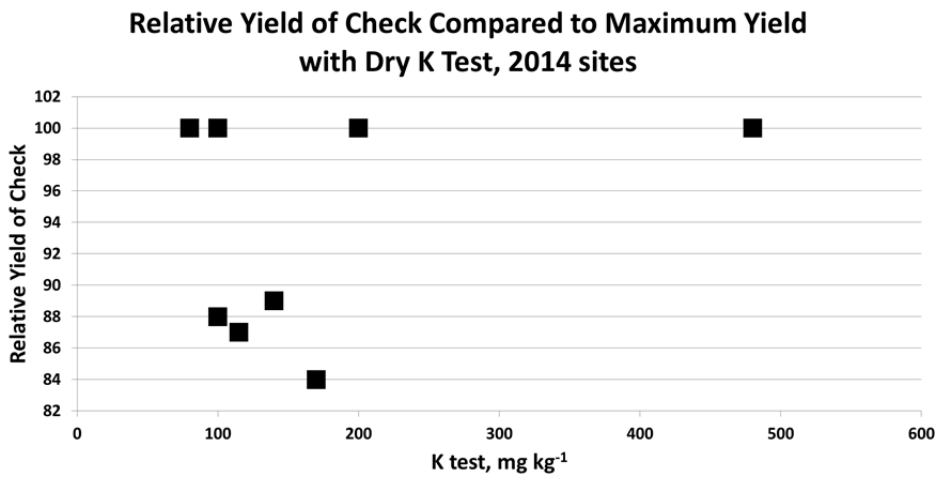


Figure 6. Relative yield of check in North Dakota K rate studies in 2014 and the relationship to soil test K.

Table 2. Multiple linear regression of possible factors relating to relative yield of 2014 and 2015 K rate trials in North Dakota from Table 1.

Factor	K test	K-feldspar	Illite	Smectite
K test	1.0			
K-feldspar	0.17	1.0		
Illite	-0.03	-0.32	1.0	
Smectite	0.05	0.33	-0.99	1.0
Relative yield	0.29	-0.0002	0.32	-0.25

A different article in these proceedings focuses directly in the importance of different soil K pools in relation to soil-test K and plant-availability of soil K, but it is relevant to mention here some concepts and findings. Potassium application and its interaction with clays, particularly a change in clay type with K addition or loss has been documented. Barre et al. (2007) hypothesized that the illite-dominance of prairie soils in temperate regions was due to the production and stabilization of illite from K redistributed from deeper soil strata to surface strata through root uptake and residue deposition to the surface. Barre et al. (2009) provided a brief review of studies supporting the hypothesis of illite construction and deconstruction under prairie vegetation, and offered a model that might predict clay stability under K addition or loss through intensive cropping without adequate K replenishment. A study from China in a loess-derived soil containing illite and chlorite focused on topsoil total K compared to a reduction in exchangeable K during 15 years of continuous alfalfa cropping. The topsoil exchangeable K decreased due to alfalfa forage uptake and removal; however, the total K in the topsoil increased due to K additions from deep soil K taken up by the alfalfa roots and deposited in the upper strata of the soil, producing a highly crystalline illitic clay (De-Cheng et al., 2011).

Evidence for changes in illite with K additions and losses through cropping also come from examination of long-term treatments in the Morrow Plots at the University of Illinois Experiment Station at Urbana, Illinois, USA. Soil samples from the plots were archived from 1913. The differences in clay mineralogy between 1913 and 1996 indicate changes in clay mineralogy with cropping. These changes were small in the corn-oats-hay rotations; however, there was a significant loss of illitic clay from the continuous corn rotation with no amendments. The authors considered that the stability of illite/smectite under the corn-oats-hay rotations was the result of K inputs from non-clay K-containing minerals restoring the K lost from the clay minerals under this less intense cropping system. Use of NPK fertilizer was adopted in 1955, and this restored the illite content of the clay mineralogy in the continuous corn plots to what was measured in 1913. The authors speculated that the addition of K replenished the clay mineral K, stabilizing and restoring illite/smectite integrity. The illites/smectites serve as a reservoir of K in prairie soils, but the clays can be degraded under continuous cropping. Briefly summarized previous work in Iowa (Clover and Mallarino, 2009) and ongoing unpublished work has shown that in Iowa smectite-dominant soil series (but with smaller contents of illite and vermiculite) the measurement of both soil-test K and non-exchangeable K explain the effects of K additions and removal by corn and soybean on post-harvest soil K levels. Also, more rapid than expected relative changes between soil-test K and non-exchangeable K explained part of the soil K variation between one crop and the next.

An important review of K chemistry was presented by Sparks and Huang (1985). One of the main points of the review was to highlight experiments in which the K replacement in the soil solution from non-exchangeable K in clays and potassium feldspars was measured in hours and days, i.e. was fast enough to meet crop needs. They also noted that wetting and drying affects the movement of K in and out of clay interlayers. Soil wetness increases the content of reduced iron within the clay interlayers, which has a large hydrated radius. The larger radius facilitates the movement of K^+ out of the clay interlayers. Dry soil increases the concentration of oxidized iron within the clay interlayers, blocking the outflow of K^+ from the clays.

Some soils retain K^+ on drying, including smectitic soils in temperate regions (e.g. Barbagelata and Mallarino, 2015, due to increased soil solution K concentration pushing the equilibrium between the soil solution and the soil clay in the direction of interlayer K^+ (Dowdy and Hutcheson, 1962).

Relative unresponsiveness in removal of K in harvested grain/fodder, despite wide variability in crop K status and responsiveness to K fertilizer application.

The following data is from the long term K field experiment on an Oxisol soil at Kingaroy, Australia (Bell et al., 2009). Variation in grain/peanut kernel/cotton seed concentration was analyzed as a function of crop yield, with yield variation in response to differences in K supply. Despite large yield responses to increasing soil K availability in most crops (3-5 fold range in yields of cotton and peanuts, and nearly 2-fold ranges in yields of wheat and sorghum), and a large number of plots that have luxury K supply at the high yielding ends of the distribution, there is effectively no variation in K concentration in the harvested product. The lack of corn grain K concentration despite variation in soil K availability was also observed by Oltmans and Mallarino (2015) There is, however, large species variation in the rate of K removal (removal of K in soybean grain is about 5 times the rate of removal in sorghum grain). This means that growers can reasonably, accurately budget to replace K removal in a crop rotation – something that is harder to do in other nutrients where both yield and grain concentration vary in response to differences in soil supply.

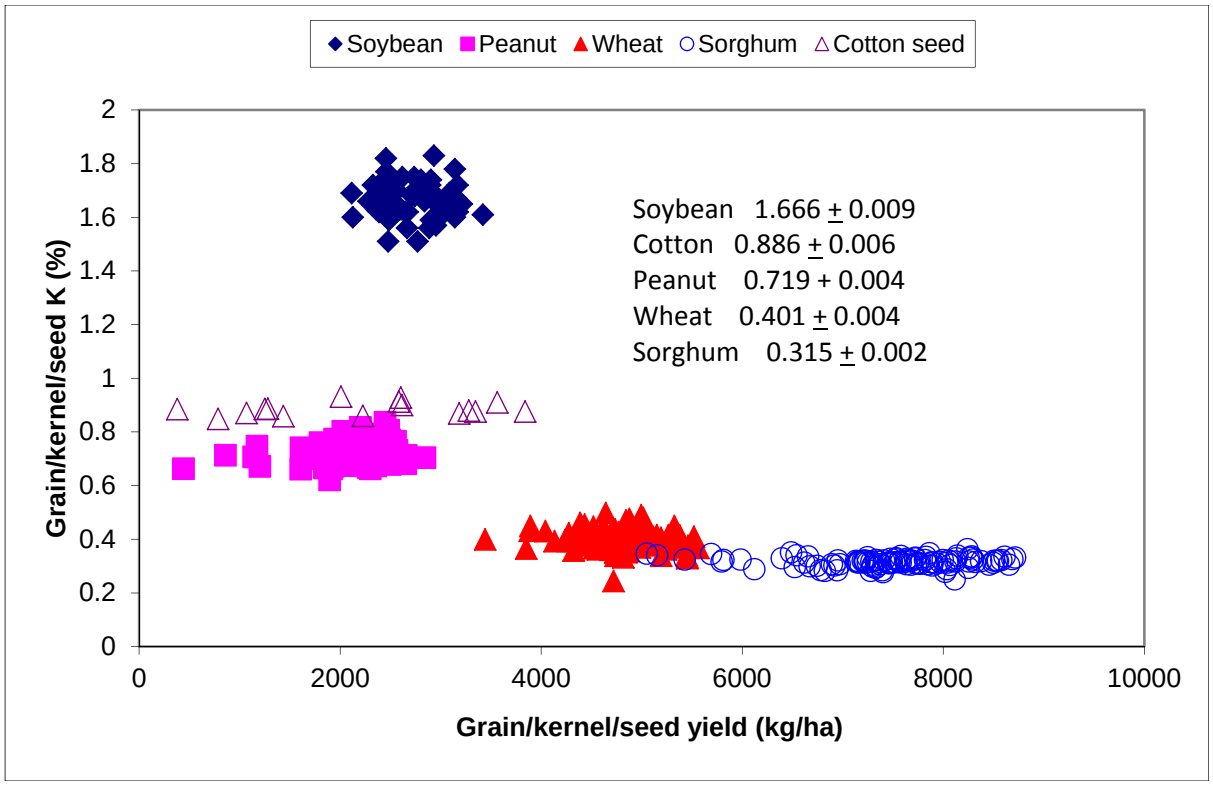


Figure 7. Relationship between crop yield (as effected by variation in soil K status) and the concentration of K in harvested grains for 5 crop species grown on an Oxisol soil at Kingaroy, in SE Queensland, Australia. Each species typically represents data from 2-3 growing seasons (MJ Bell – unpublished data).

Potassium losses due to erosion from wind and water

A seldom considered source of K loss is from loss of topsoil due to wind and water erosion. An analysis of nutrient losses in North Dakota from the time of plowing (1880 through 1920, depending on the location within the state) is underway, and complete for phosphate (P). Total P loss from wind erosion in North Dakota since the time of plowing is estimated to be 17 M tonnes of P. (Franzen, 2016). This is equivalent to over 200 years of P application by North Dakota farmers to the 10M ha of available state cropland at rates commonly used in 2016. Total K loss since plowing is estimated to be much higher. Analysis of dust sampled from North Dakota origin topsoil loss in eastern US cities in the 1930's contained 19 times more P and 45 times more K than samples obtained in regions of origin after the storms (Hansen and Libecap, 2004). Topsoil loss in large portions of the state not under no-till or modified no-till systems is still on-going. A site northwest of Grand Forks, ND characterized in 1958 and re-characterized in 2014 revealed 48 cm of topsoil loss due to wind erosion over the 56 years (Montgomery, 2015).

SUMMARY

The mass-balance of K in the surface soil is a function of (i) K added in fertilizers and manures, (ii) plant redistribution of subsoil K to the surface, (iii) K losses due to leaching in low CEC soils, and sampling to deeper depths than the 0-15 cm depth to determine subsoil contribution, (iv) K removal with grain, forage and crop residues, and (v) K lost in soil erosion from wind/water. A mass-balance relationship of exchangeable K is only rarely achieved because of the rapid equilibrium between soil solution K,

exchangeable K, K-bearing primary minerals, and clay interlayer K. In addition, soil moisture, temporal differences in exchangeable K levels with K uptake by crops, K leaching from residues, clay type, organic matter contribution to the soil CEC, and type of K amendment confound any attempt to relate K additions and losses with K soil test. Subsequent research is needed to create regionally specific K soil test procedures that can predict crop response within a subset of clays and K-bearing minerals within specific cropping systems.

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How Do Mineralogy and Soil Chemistry Impact How Closely Potassium Soil Test Changes Are Related To Mass Balance?

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Abstract

Potassium is the seventh most abundant element in the earth's crust. During weathering, K is enriched in the soil compared to other base cations, which are more readily leached. While most base cations exist in solution, exchangeable, and mineral forms, soil K also exists in a fixed form, where it may be less available for plant uptake. Rapid soil tests to assess bioavailable K levels are usually based on exchange reactions with ammonium or calcium. Such soil-test K values can fluctuate unpredictably throughout the year and from year to year. To understand these fluctuations in soil-test K, many studies have focused on relationships between extractable K, moisture conditions at the time of sampling, drying conditions during sample storage, drying temperatures, and soil mineralogy. The inability to understand and predict these fluctuations remains a critical issue in nutrient management. The mineralogical literature presents strong evidence that K fixation can be related to the presence and mineralogy of 2:1 layer silicates, to the presence of hydroxy Al interlayers, and to the oxidation state of Fe in those layer silicates. Our objectives here are to review both the effects of clay mineralogy on K fixation and the role of the oxidation state of structural Fe on K fixation. We will present a coherent model of K fixation that has the potential to account for soil test results and determinations of mass balance of soil K. Variations in K fixation are caused by both temporal and spatial variations in layer charge in 2:1 layer silicates. Greater negative layer charge results in greater K fixation due to electrostatic interactions as well as the size and low hydration energy of K ions. Charge originating in tetrahedral sheets is associated with greater K fixation than is octahedrally derived charge. Because layer charge is partly a function of the oxidation state of structural Fe, the redox environment also affects potassium fixation and may be responsible for both rapid and long-term fluctuations in soil-test K values.

INTRODUCTION

Soil test K values do not necessarily reflect net changes of K in the soil system. Workers in the field of soil K noticed early that (1) K could be added to the soil with no increase in soil extractable K and (2) no K could be added to the soil and yet soil extractable K values would increase (Dyer 1894; Page and Williams 1925). This suggested to the workers a process by which the K was going from an extractable form to a non-extractable form in the fertilized soils and perhaps vice versa in the unfertilized soils. Since those early observations, we have learned that while most basic cations exist in solution, exchangeable, and mineral form, potassium additionally exists in a fixed form which is less readily extracted than solution and exchangeable forms (Fig. 1).

Soil test K values have been shown to fluctuate over time. Generally, soil test K values decrease during the growing season as K is being taken up by crops, reaching a minimum around harvest time. Afterward, during the winter, soil test K levels slowly rebound being replenished from non-extractable K sources and organic matter, sometimes to their original springtime high and sometimes to a lower level (Bell and Thornton 1937; Childs and Jencks 1967). Within this general pattern, however, there are other oscillations in soil test K values, the causes of which are less clear.

Soil test K values can be increased by release of K from both mineral and organic sources. Soil test K values can be decreased by fixation, plant uptake, and leaching from the soil profile. The additions and losses from organic source release, plant uptake, and profile leaching are relatively easy to quantify, model, and predict. The additions and losses to soil extractable potassium from potassium release and fixation by soil minerals are comparatively much more difficult to quantify, model, and predict. Consequently, unexplained fluctuations in soil test K are often attributed to soil fixation and release phenomena because the more easily understood potassium movement pathways fail to explain these fluctuations.

The mineralogical literature presents strong evidence that K fixation can be related to the presence and mineralogy of 2:1 layer silicates and to the oxidation state of Fe in those layer silicates. The objectives of this paper are to (1) review the effects of clay mineralogy on K fixation, (2) discuss the role of the oxidation state of structural Fe on K fixation, and (3) present a coherent model of K fixation that has the potential to account for soil test results and determinations of mass balance of soil K.

WHAT IS POTASSIUM FIXATION?

K fixation is the process by which exchangeable or water soluble K is trapped in the contracted interlayer space of layer silicates. In some ways, K fixation can be conceptualized as the reversal of mica weathering (Fig. 2). Micas are 2:1 layer silicates with K^+ ions occupying the ditrigonal cavities of adjacent layers. When micaceous minerals weather, their interlayers expand, K is released, and there is an equivalent increase in CEC. When K is fixed between the layers of expanded 2:1 layer silicates, the interlayers contract, trapping K^+ ions in the ditrigonal voids, and we observe equivalent decreases in CEC. While these processes have been largely studied in laboratory settings (Barshad 1948; 1951; 1954; Jackson 1963; Reichenbach and Rich 1975; Wear and White 1951), their effects can be observed at the field level. Continuous cropping without K fertilization leads to decreases in the amounts of micaceous minerals observed in the soil and increases in the content of expandable 2:1 layer silicates. Conversely, long-term fertilization with potassium has been shown to increase the apparent mica content of soils, even though minerals with layer charges high enough to classify as micas are not being formed (Meunier & Velde 2004; Scheffer, Welte & Reichenbach 1960).

WHY IS POTASSIUM FIXED?

Monovalent cations such as potassium, ammonium, rubidium, and cesium ions are all fixed in a similar manner (e.g., Barshad 1954; Meunier & Velde 2004; Sucha & Siranova 1991) whereas divalent cations such as sodium, calcium, magnesium, barium, and strontium are not fixed to any appreciable extent. This is because the monovalent cations have relatively weak energies of hydration compared to the divalent cations which have relatively strong energies of hydration. In order for cation fixation to occur, the electrostatic attraction between the cation and interlayer surface must exceed the attraction between the cation and its hydration shell so that the interlayer space will dehydrate and collapse (Hurst & Jordine 1964; Kittrick 1966). Furthermore, monovalent cations have been supposed to be better able to match the local negative charge of the ditrigonal cavities in the tetrahedral sheet than divalent cations, which, due to their larger hydration energies and hydration shells, are more likely to be positioned between ditrigonal holes rather than in them (Reichenbach & Rich 1975). Soil samples dried and/or heated with added K tend to fix more K than samples allowed to stay continuously moist, presumably because the drying and/or heating process encourages the dehydration of the interlayer space (Alexiades & Jackson 1965; Bouabid, Badraoui & Bloom 1991; Stanford 1947; van Olphen 1966).

SOIL MINERALOGICAL FACTORS AFFECTING POTASSIUM FIXATION

K has been documented to be fixed by micas, vermiculites, and smectites (Barshad 1951; 1954; Ranjha, Jabbar & Qureshi 1990; Rich 1968; Martin and Sparks, 1985). Where these types of minerals predominate in the clay-sized fraction of the soil, K fixation is often related to the clay content of a soil

(e.g., Shaviv et al., 1985). However, K fixation has been documented in silt-sized and even very fine sand-sized vermiculite and hydrobiotite as well (Murashkina, Southard & Pettygrove 2007a; 2007b).

Not all 2:1 layer silicates fix K to the same extent. The degree to which 2:1 layer silicates fix K is largely a function of interlayer charge and the distribution of that charge over the octahedral and tetrahedral sheets. Interlayer charge affects the electrostatic attraction of the interlayer for K^+ ions (Rich 1968). Other factors being equal, greater layer charge is often correlated with greater fixation (Barshad 1954; Bouabid, Badraoui & Bloom 1991). Murashkina, Southard & Pettygrove (2007a; 2007b) speculated that K fixation in some soils dominated by smectite may be due to high-charge smectites that are transitional to vermiculite. Charge location, however, also influences K fixation. K fixation capacity has also been found to be well correlated with tetrahedral CEC but poorly correlated with octahedral CEC (Bouabid, Badraoui & Bloom 1991). This is likely because negative charge originating from the tetrahedral sheet retains K^+ ions more strongly than equivalent negative charge originating from the octahedral sheet due to the proximity of the charges to the interlayer surface (Reid-Soukup & Ulery 2002).

In acid soils, the presence of hydroxy Al and/or Fe interlayers in vermiculite and smectite affects K fixation (Saha & Inoue 1998). The hydroxy Al and Fe interlayers act as obstructions between 2:1 layers that restrict the collapse of the interlayer space about the K^+ ions. This results in a decrease in cation exchange capacity and causes K to become more exchangeable and less fixed (Saha & Inoue 1998).

Due to the impact of layer charge on K fixation, the redox state of structural Fe in 2:1 layer silicates can also influence K fixation. Reductions of structural Fe in both smectites and vermiculites have been shown to lead to increases in negative layer charge and K fixation. Furthermore, reductions of tetrahedral Fe appear to have a greater impact on K fixation than reductions of octahedral Fe (Chen, Low & Roth 1987; Dong, Kostka & Kim 2003; Favre, Stucki & Boivin 2002; Florence, Ransom & Mengel, 2016; Stucki, Golden & Roth 1984; Stucki et al. 2000). This is likely due to increased coulombic attraction between interlayer surfaces and K^+ ions facilitating interlayer dehydration and collapse.

The oxidation of structural Fe in micas can lead to interlayer expansion and K release. Conversely, the reduction of structural Fe in expanded 2:1 layer silicates can lead to interlayer collapse and K fixation (Scott and Amonette 1988). Note, however, that the oxidation of structural Fe in micas can either stabilize or destabilize interlayer K, depending on both the pH of the environment and on whether the oxidation of structural Fe leads to the ejection of the Fe atoms from the octahedral sheet (Thompson and Ukraniczyk 2002). When the oxidation of octahedral Fe in micas leads to Fe ejection, nearby hydroxyl ions tend to orient toward the empty octahedral site, allowing interlayer K ions to nest closer into the ditrigonal cavity and subsequently to be held more tenaciously (Barshad and Kishk 1970).

RELEVANCE TO POTASSIUM SOIL TEST VALUES

We typically do not think of soil mineralogical characteristics as being dynamic on the time scale of a growing season. It is unlikely that the actual amount or identity of K-fixing minerals in the soil will change appreciably over a growing season. However, soil redox conditions can be rather dynamic over short time periods, which can in turn affect the oxidation state of structural Fe in K-fixing minerals in the soil. Thus, it is possible that temporal fluctuations of soil test K values observed in field settings are related to the oxidation-reduction of structural Fe. That is, it is possible that when conditions are reducing, we see a fixation of K and when conditions are oxidizing, we see a release of K.

K FIXATION MODEL

The rate and magnitude of potassium fixation and release has been documented to be related to a wide array of factors, including but not limited to: soil mineralogy, soil type, soil horizon, particle size distribution, particle size, grinding, soil weathering, cropping intensity, soil K fertilization, previous K saturation, moisture conditions, temperature conditions, hydroxyl interlayering, the presence of organic

cations and molecules, soil pH, liming, and redox conditions (Goulding 1987; Martin and Sparks 1985; Sawhney 1970; Stanford 1947). This long list of environmental, mineralogical, cultural, and biological factors affecting K fixation makes predicting and understanding the mass balance of K seem daunting.

However, if we look at this list of factors in terms of K fixation simply being the result of the forces of contraction exceeding the forces of contraction in 2:1 layer silicates in the presence of interlayer K, then the list becomes conceptually more manageable. Soil mineralogy matters because only 2:1 layer silicates fix K. Soil type and soil horizon have an apparent effect on K fixation because the amounts and types of 2:1 layer silicates will vary between soil types and soil horizons. Particle size distribution, particle size, and grinding matter because they affect the accessibility of interlayer spaces. Smaller particles generally mean easier access to interlayer spaces. Soil weathering and cropping intensity affect soil K fixation capacity because as we remove more K from the system, there are more sites made available for K fixation. Soil K fertilization and previous saturation of soil samples with K matter because the more we saturate K fixation sites, the fewer we have left available. Moisture and temperature conditions affect K fixation by affecting the availability of water molecules with which to expand the interlayer space. The presence of hydroxyl interlaying, organic cations, and organic molecules affect K fixation by propping open the interlayer space and preventing layer collapse. Redox conditions can have an effect on K fixation because it can affect layer charge, which in turn affects the attraction of K^+ ions to interlayer surfaces.

Clay layers can collapse either from the lack of expansion forces (i.e., water, hydroxyl interlayering, organic cations and molecules) or when van der Waals forces of attraction exceed the forces of expansion. The strength of van der Waals forces lies in the proximity of clay layers to each other, and the proximity is controlled by the coulombic force of attraction of interlayer cations for interlayer surfaces. The greater the attraction, the closer the cation is held to the interlayer surface. The closer the cation is held, the closer an adjacent clay layer can approach. The closer adjacent clay layers become, the stronger van der Waals forces become. If van der Waals forces can exceed the forces of expansion, then the clay layers will collapse. Hence, cations with high energies of hydration and large hydrated ionic radii are not appreciably fixed because it is difficult to overcome the distance that these large hydrated cations place between clay layers and the energy with which they hold onto their surrounding water molecules.

The coulombic force of attraction of interlayer cations for interlayer surfaces is in turn a function of layer charge, charge location, and bond geometries in the layer silicate. Increased layer charge equates with increased attraction between interlayer cations and interlayer surfaces. Tetrahedrally derived negative charge is more effective than octahedrally derived negative charge at attracting interlayer cations as a result of its proximity to the basal layer surface. Similarly, bond geometries—particularly the hydroxyl group orientations of the octahedral sheet, which are largely a function of cationic occupancies in the octahedral sheet—affect the attraction of interlayer cations for interlayer surfaces by controlling the nearness with which interlayer cations can approach negative layer charge sites.

At the molecular scale, most K fixation can be thought of most simply as the forces of lattice contraction exceeding the forces of lattice expansion with K ions in the interlayer space (Fig. 3). In other words, the contraction is a result of the attraction of the positively charged cation for negatively charged sites on the silicate surface. Expansion occurs when the layer charge is insufficient to overcome the energies of hydration of the cations in the interlayer. One could also attribute “expansion forces” to the repulsion of the strong dipoles of the oxygen ions that are fixed in place on the basal planes of the minerals. Most of the documented factors affecting K fixation and release can be understood entirely through their effect on those three aspects: (1) contraction force, (2) expansion force, and (3) K presence. In this paper, we have argued that K fixation and release phenomena at the molecular scale can explain fluctuations in soil exchangeable K. Although redox-driven changes in K fixation might explain some temporal fluctuations in soil exchangeable K, more work needs to be done to further test the role of Fe redox processes on K

fixation. It is clear that some soils are less susceptible to fluctuations in measurements of exchangeable K than others, perhaps due to their high K buffering capacity.

An ability to correlate soil test measurements with the mass balance of specific pools of K in the soil is important for maintaining maximum K efficiency in soil fertility. However, the determination of such a mass balance of K is difficult for soils exhibiting K fixation because the extent of the fixation is affected by the mineralogy of the layer silicates as well as the oxidation state of Fe in those layer silicates. Variations of K fixation caused by these factors are responsible for the spatial and temporal variations of soil test K levels in unpredictable ways. In the context of soil test determinations, forms of soil K are often described as being unavailable, difficultly available, slowly available, moderately available, and readily available—all relative classes of availability. However, the relative availability of K is better characterized by a continuum instead of classes where recognizable stopping points occur along the continuum. In addition to the recognition of K fixation and release, the agronomic value of fixed K must be considered. For soils subject to K fixation, traditional soil test measurements that are based on ammonium-exchangeable K clearly do not represent the great seasonal and spatial variations occurring in field conditions. There is still much to learn about the factors governing not only the plant availability of different pools of K but also K fixation and release.

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TABLES AND FIGURES

Figure 1. Relationships between different pools of soil potassium.

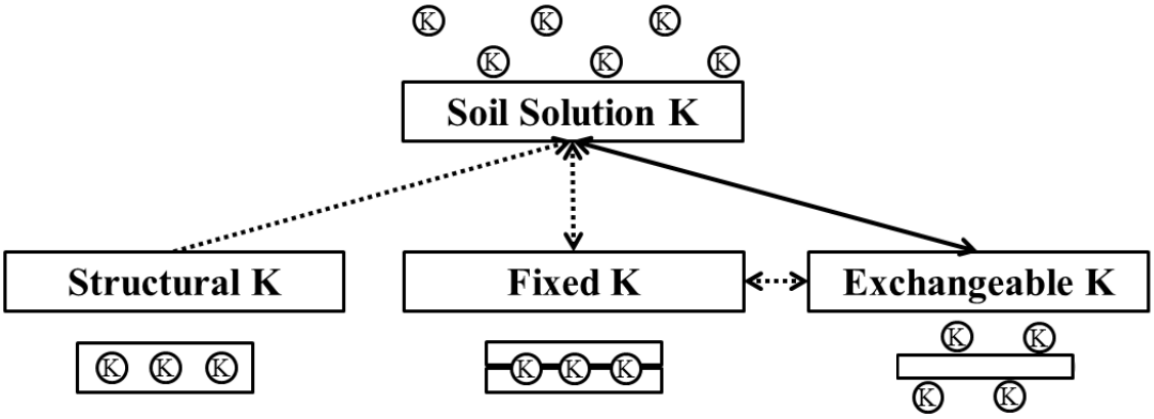


Figure 2. Conceptualization of potassium fixation that can be visualized as the reversal of mica weathering.

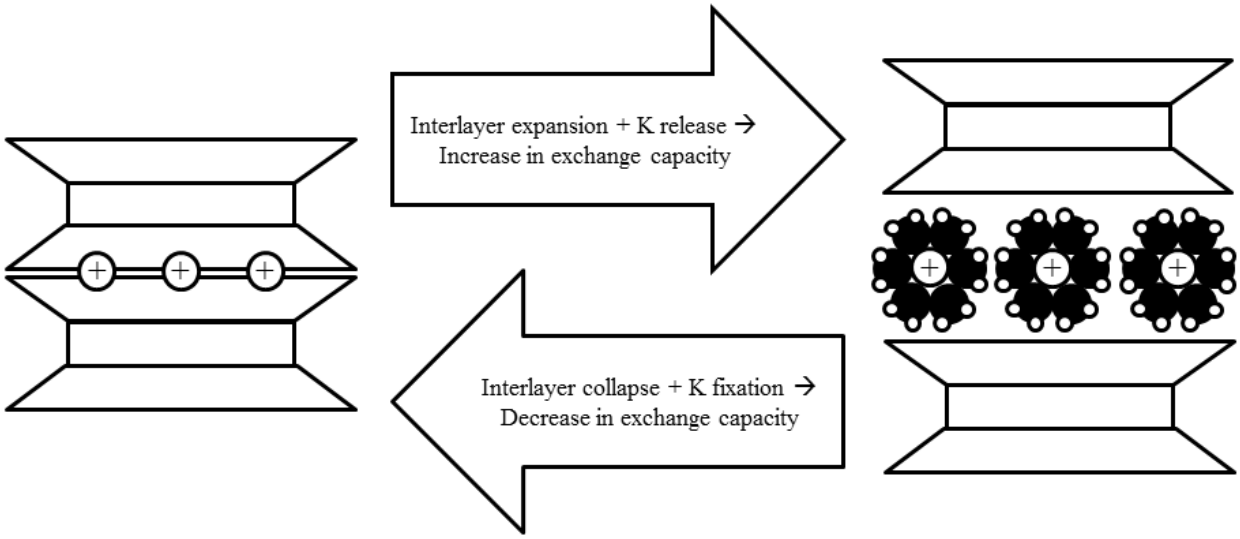
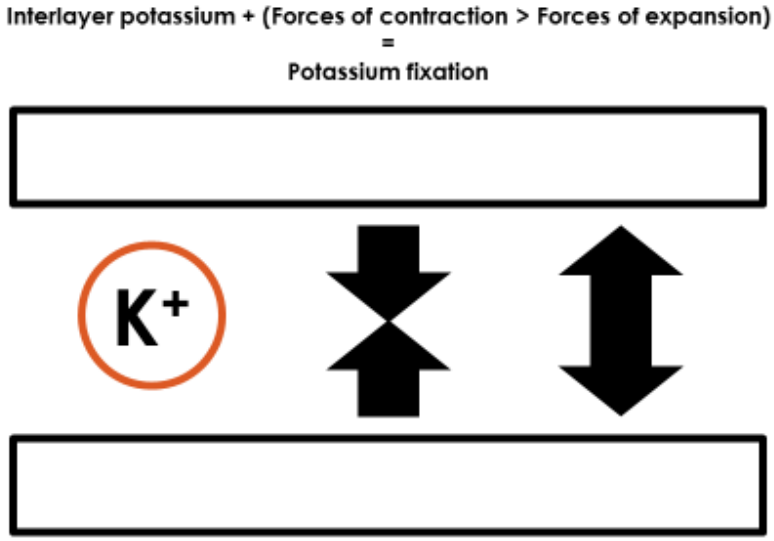


Fig. 3. Potassium fixation model.



Does Potassium Balance Explain the Change in Mehlich-3 Extractable Potassium in Arkansas Soils?

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Abstract

The 'build and maintain' philosophy is the basis of many K fertilization recommendations and is based on several assumptions that have not been appropriately tested. The objective of this summary was to assess whether Mehlich-3 extractable K from the 0-10 cm soil depth can be explained by the balance between fertilizer-K inputs and crop removal. Data from multiyear trials conducted on Calhoun (81 mg K kg^{-1}), Captina (115 mg K kg^{-1}), and Dewitt (145 mg K kg^{-1}) silt loams were used to characterize soil-test K response to cumulative-K balance and the rate of soil-test K change. The three trials had durations of 5 to 16 years. The soil-test K depletion rate (mg K kg^{-1} yr^{-1}) for soil that received no fertilizer-K was -3.1 for the Calhoun soil [rice (*Oyza sativa*) - soybean (*Glycine max*) rotation], -7.6 for the Dewitt soil (rice-soybean rotation), and -11.3 for the Captina soil [bermudagrass hay (*Cynodon dactylon,* L.) Pers.] with time explaining 55-75% of the soil-test K variability. The average annual-K removal rate (kg K ha^{-1} yr^{-1}) usually increased as yield and K rate increased with mean ranges among annual-K rates of 39-51 for the Calhoun, 47-50 for the Dewitt, and 70-360 for the Captina. The quadratic relationship between cumulative soil-test K change and estimated cumulative-K balance across time was significant for each soil but the relationship strength varied. A net-K balance of 0 was predicted when soil-test changes of +34 mg K kg^{-1} for the Captina soil, -12 mg K kg^{-1} for the Dewitt soil, and +1 mg K kg^{-1} for the Calhoun soil. The 'crop replacement' K management approach failed to accurately maintain soil-test K at its initial value on the three soils used in this assessment. More robust tools to increase awareness and track soil-test K responses to K fertilization should be developed.

INTRODUCTION

The correlation and calibration research process is fundamental to ensure that soil nutrient availability indices provide information that is meaningful in regards to sound agronomic, economic, and environmental measures of sustainability. Research has tended to focus on the correlation step of soil-test-based nutrient management and shows that the correlation between soil nutrient availability indices and crop response to fertilization varies among soils and crops. The use of statistical analysis to calibrate research-based nutrient addition rates for soils has seemingly been ignored or avoided by the selection of alternative methods and philosophies of establishing nutrient addition rates (Dahnke and Olson, 1990). Two main philosophies are described in the early literature and include the 'Sufficiency Approach' and the 'Build and Maintain Approach' (Olson et al., 1987). The Sufficiency approach requires that multiple nutrient rates be used in research to identify the minimum nutrient rate that maximizes yield usually by regression analysis or multiple means comparison statistics.

The literature is lacking specific information confirming that soil-test K can be maintained using the 'check-book' approach of replacing the amount of K removed using an appropriate and realistic yield goal. Madaras et al. (2014) reported on this topic and showed that a zero K balance resulted in a net decline in ammonium acetate extractable K. One problem with the check-book approach and calculation is that it assumes no K loss or reduction in availability from run-off, leaching, and/or physical fixation in the soil or contribution and deposition of subsoil K to the sample depth. Research and soil-test methods that can accurately quantify K availability losses are warranted but difficult to fund since K is considered

an environmentally passive element and, for the most part, soil-test-based, fertilizer-K recommendations appear to be accepted as agronomically accurate by most end-users. The understanding or perception among end-users (e.g., farmer or consultant) about replacement fertilization is also poorly understood.

Multiyear trials show exchangeable K has multiple outcomes including no net change across time when no fertilizer-K is applied and soil-K is removed by annual cropping (McCallister et al., 1987; Mallarino et al., 1991b), decreases when crop removal exceeds K fertilization rate (Mallarino et al., 1991a); and increases in some soils (McCallister et al., 1987). The act of oven drying soil in preparation for analysis has been cited as a reason for variability in extractable soil-K across time (Luebs et al., 1956), but temporal variability appears to occur regardless of whether soil is extracted in the field-moist or oven-dried state (Mallarino et al., 1991a,b).

The objectives of this research were to examine i) the change rate of soil-test K from three long-term field trials in Arkansas and ii) whether fertilizer-K rates based on K-balance consistently deplete, maintain, or build soil-test K across time. Our hypothesis was that soil-test K change rate would vary among soils and, and that soil-test K would decline across time when the fertilizer-K rate was based on crop-K removal since K may be lost via other pathways in addition to crop removal.

RESEARCH METHODS

Soil test data were collected annually from three multiyear K fertilization trials. The first trial was conducted from 2006-2010 in a field mapped as a Captina silt loam at the Main Agricultural Experiment Station located in Fayetteville, AR with an established stand of common bermudagrass that had been used for hay production and grazing. Individual plots were 6.1-m long and 1.8-m wide and the trial included six fertilizer-K rates and four replications in a randomized complete block design. The treatments included cumulative season-total rates equaling 0, 93, 186, 279, 372, and 465 kg K ha^{-1} as muriate of potash (600 g K_2O kg^{-1}) and ample P and N following each harvest (3 or 4 harvests yr^{-1}) to ensure maximal yield production. A subsample of harvested biomass from each plot and harvest was collected, processed and analyzed for K concentration to calculate K removal in harvested biomass. Composite soil samples, consisting of eight 2.5 cm i.d. cores, were collected to a depth of 10 cm from each plot before treatments were initiated and then annually when bermudagrass was dormant between January and March of each year. The Mehlich-3 extractable K concentrations were statistically uniform within each research site and averaged 115 mg K kg^{-1}.

The second and third trials were established on soils mapped as a Calhoun and Dewitt silt loam, respectively. Upon trial initiation the Mehlich-3 extractable K concentrations were statistically uniform within each research site and averaged 81 mg K kg^{-1} for the Calhoun soil and 145 mg K kg^{-1} for the Dewitt soil. Both trials are ongoing, cropped to a rice-soybean rotation and managed with no-tillage. The Calhoun soil trial was established in 2000 with eight replicates of five initial annual-K rates ranging from 0 to 140 kg K ha^{-1} in 28 kg K ha^{-1} increments. In 2006, the increment was changed to 37 kg K ha^{-1} resulting in a range of 0 to 149 kg K ha^{-1}. The 16-yr mean K rates are listed in Table 1. The Dewitt soil trial was established in 2007 and includes two concurrent areas that alternate between rice and soybean with each having six replicates of five annual K rate increments of 37 kg K ha^{-1}. The individual plot size is 4.9 by 7.3 m for the Calhoun soil and 4.6 by 7.7 m for the Dewitt soil. Composite soil samples (0- to 10-cm depth) are collected each winter during the months from January thru March with each composite consisting of five, 2.5 cm diameter soil cores. Rice and soybean yields were measured each year by harvest with a small plot combine and yields were adjusted to uniform moisture contents of 120 g kg^{-1} rice and 130 g kg^{-1} for soybean. Crop residues were not removed from the fields, but rice straw is occasionally burned.

Soil samples from each site were oven dried for 48 to 72 h at 65°C (APHIS requirement), crushed to pass a 2-mm diameter sieve, analyzed for water pH (1:2 soil weight:water volume ratio), extracted for plant-

available nutrients using the Mehlich-3 method, and nutrient concentrations determined with an inductively coupled plasma atomic emission spectrophotometer.

The mean grain yields for rice and soybean, aboveground biomass yield for bermudagrass, and Mehlich-3 extractable soil-test K values were calculated for each year and treatment. Since rough rice and soybean grain-K concentrations were not measured, grain-K concentration was assumed to be uniform across annual-K rates and to average 3.68 g K kg^{-1} for rice (0.2 lb K_2O bu^{-1}) and 16.6 g K kg^{-1} for soybean (1.2 lb K_2O bu^{-1}) using values from the International Plant Nutrition Institute Nutrient Removal Calculator (https://www.ipni.net/app/calculator/home). The mean, cumulative K added and removed was calculated for each treatment and year.

Statistical analysis of the data involved using linear regression models to define the change in Mehlich-3 extractable K of soil receiving each annual-K rate across time. A second analysis was performed for each soil to regress the absolute change in Mehlich-3 extractable K across soil sample time (year) against the cumulative K balance in with a model that initially included the linear and quadratic terms. If needed, non-significant (P>0.15) model terms were removed sequentially and the model was refit until the final model with significant terms was obtained. All statistical analyses were performed using the REG or GLM procedures using SAS v9.4 (SAS Institute Inc., Cary, NC).

RESULTS

The mean annual crop-K removal was 39 to 51 kg K ha^{-1} yr^{-1} for the Calhoun soil and 47 to 50 kg K ha^{-1} yr^{-1} for the Dewitt soil (Table 1). Significant rice and soybean yield differences among annual-K rates occur annually on the Calhoun soil (unpublished data) but have occurred only sporadically on the Dewitt soil, which explains the difference in the range of K removal between the two soils. The relatively large standard deviation of the mean annual-K removal is due to a considerable difference in K removal between rice (low removal) and soybean (higher removal) and crop yield differences among years. The mean annual-K balance (annual-K input – annual-K removal) for both soils cropped to rice and soybean was positive for every annual-K rate except the no fertilizer-K control and the lowest rate of fertilizer-K (Table 1). In contrast to the rice-soybean rotation, the mean K removal by harvested bermudagrass hay ranged from 70 to 360 kg K ha^{-1} yr^{-1} (Table 1). Despite the greater overall annual-K rates applied to bermudagrass on the Captina soil, the K removal was negative for the three lowest annual-K rates, near 0 for soil fertilized with 279 kg K ha^{-1} yr^{-1}, and positive for soil receiving the two highest annual-K rates. The net annual balance would suggest that Mehlich-3 extractable K for the Calhoun and Dewitt soils that receive ≥68 kg K ha^{-1} yr^{-1} should increase. Likewise, the results suggest soil-test K on the Captina soil should be maintained when 279 kg K ha^{-1} yr^{-1} was applied and increase with the two greater annual-K rates.

Mehlich-3 extractable K in the 0-to 10-cm soil depth decreased by -3.1, -7.6, and -11.3 mg K kg^{-1} yr^{-1} for the Calhoun, Dewitt, and Captina soil, respectively, when no fertilizer-K was added (Table 1; Figs. 1-3). Time explained 55 to 74% of the variability in soil-test K for soil receiving no fertilizer-K. As the annual fertilizer-K rate increased, the strength of the linear model declined to the point that neither the linear or a quadratic model was significant. Despite some of the annual-K rates being greater than the rate of crop-K removal, soil-test K failed to increase significantly (e.g., slope not different than 0).

The regression analyses performed for each soil included the initial Mehlich-3 extractable K values (i.e., year 0, before annual fertilization and cropping), but the predicted intercept terms were often numerically different (Table 1). No model (linear, quadratic, or cubic) accurately described the starting Mehlich-3 extractable K at time 0. The numerical differences in intercept values among annual-K rates simply indicate that soil-test K was affected by fertilizer-K rate with extractable K increasing as K rate increased. The slope values for each annual-K rate were also numerically different and showed different trends across time with the Mehlich-3 extractable K declining at greater rates for the lowest fertilizer-K rates.

When combined, the different intercept and slope coefficients predicted that the Mehlich-3 extractable K differences among annual-K rates would, as expected, become wider with time (Figs. 1-3). For the Calhoun and Dewitt soils, the most surprising aspect of the predictions was that the actual soil-test K values generally declined across time despite relatively large and positive annual-K balances for some treatments (Table 1). The equations predicted that the last measured Mehlich-3 K values would be relatively constant (108-111 kg K ha^{-1} yr^{-1}) or lower than the initial value for all treatments except the greatest annual-K rate (145-148 kg K ha^{-1} yr^{-1}). The linear regression models for the Captina soil were significant only when annual-K removal was greater than K addition. The quadratic models failed to improve the relationships for any of the three soils (not shown). Qualitatively, the relationships show that K fertilization rate influences Mehlich-3 extractable K, but in the no-till, row crop systems Mehlich-3 extractable K declined despite substantially positive annual-K balances.

The use of the cumulative K balance for each K rate and sample year to predict the net change in Mehlich-3 K (Figs. 4-6) supported the qualitative relationships between Mehlich-3 extractable K regressed across time for each annual-K rate (Table 1). For each soil, the quadratic model describing the change in Mehlich-3 K as predicted by Cumulative K balance was statistically significant, but the strength of the model varied among the three soils. The strength of the relationship was poor for the Calhoun soil ($r^2 = 0.198$), intermediate for the Dewitt soil ($r^2 = 0.460$), and strong for the Captina soil ($r^2 = 0.897$). Coincidentally, the strength of the relationship declined as with the duration of the experiment increased and the number of observations increased. Based on the defined relationship for these three soils, a K-balance of zero, where K inputs equal crop removal, would result in Mehlich-3 extractable K changes of +34 mg K kg^{-1} for the Captina soil, -12 mg K kg^{-1} for the Dewitt soil, and 0 mg K kg^{-1} for the Calhoun soil. The change in Mehlich-3 extractable K and the net annual-K balance were in closest agreement for the Captina soil cropped to bermudagrass (Table 1). The different predictions for the three soils suggest that K losses vary among sites and production systems due, but not limited, to differences in K retention (e.g., cation exchange capacity), fixation capacity, crop management, or competing ions.

The decline and variation in soil-test K across time has been shown by many researchers (McCallister et al., 1987; Mallarino et al., 1991a, 1991b; Davis et al., 1996; Madaras et al., 2014) and its unpredictability is a clear impediment to soil-test-based K management practices. McCallister et al. (1987) suggested that stronger extractants failed to recover different amounts of non-exchangeable K among soils receiving different K rates suggesting K is lost from the system. Cope (1981) showed that soil-test K was maintained or increased with relatively low annual-K rates, low cation exchange capacity soils lose K more readily than high cation exchange capacity soils making them more difficult to maintain and build, and proposed that soil test K will decline to a point where a 'quasiequilibrium' is reached with K release. The literature clearly indicates that soil-test K can be a useful, albeit an imperfect tool, for K management in cropping systems. Additional research efforts are needed to understand K retention, K loss from leaching and runoff, and to develop more meaningful soil-test methods and calibration curves for making fertilizer rate recommendations. The three soils used in our study suggest that fertilization based on the anticipated crop response to fertilization using an appropriate fertilizer rate that matches short- and long-term nutrient management needs is most appropriate for Arkansas row crops.

CONCLUSIONS

Mehlich-3 extractable K from three long-term K fertilization trials show that fertilizer-K rate influences the amount of K that is extracted from soil across time. The response of Mehlich-3 K across time in soils that received no fertilizer-K was predicted with the greatest accuracy and the strength and accuracy of the models for soils that received fertilizer-K declined as K rate increased. Cumulative K balance was positively associated with the change in Mehlich-3 extractable K, but the three soils showed different responses. The results suggest fertilization with the K rate that matches the anticipated K removal is unlikely to maintain soil-test K at its initial value. Since soil-test K is highly variable it seems that fertilization based on 'build and replacement' rates may be undesirable. A more scientifically defensible

approach for recommending K fertilization is to calibrate yield response to fertilizer-K rate in long-term trials and/or to examine response curves from multiple short-term K rate trials within specific soil-test levels.

Properly executed fertilization rate trials with the objective of correlation and calibration should allow scientists to develop curves that associate K rates with the proportion of maximum yield for each soil-test level. Crop response based fertilization strategies would also farmers to examine the economics of K fertilization, which is especially important when the farm economy is poor and for crops grown in geographic areas where soil-test K is relatively accurate in identifying K-deficient soils. A comprehensive database of soil-test K values coupled with crop yield and K removal estimates would aid in developing a more comprehensive understanding the dynamics among soil K pools, fertilizer additions, and crop removal K.

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Table 1. Mean annual-K rate, K removal in harvested portion of crop, net annual-K balance, and intercept and linear slope coefficients describing the rate of Mehlich-3 K change across time for three soils.

Soil†	Mean K rate	Mean Annual Removal	Net Annual Balance	Mehlich-3 K Change Rate			Predicted & (Actual) Mehlich-3 K ‡
	kg K ha^{-1} yr^{-1}	kg K ha^{-1} (SD)		intercept	Slope	R^2	mg K kg^{-1}
Calhoun	0	39 (±15)	-39	92 (±5)	-3.1 (±0.5)	0.55	42 (41)
(*n* = 34)§	34	46 (± 20)	-12	95 (±5)	-2.6 (±0.5)	0.42	53 (46)
	68	48 (± 21)	+20	98 (±5)	-2.3 (±0.6)	0.32	61 (53)
	102	50 (± 21)	+52	106 (±6)	-1.9 (±0.6)	0.22	76 (71)
	136	51 (± 22)	+85	107 (±6)	-1.2 (±0.6)	0.08	88 (81)
Captina	0	70 (± 44)	-70	100 (±9)	-11.3(±2.9)	0.74	43 (57)
(*n* = 6)	93	141 (± 38)	-48	118 (±12)	-13.7(±3.9)	0.70	49 (61)
	186	218 (± 53)	-32	126 (±9)	-11.6 (±3.0)	0.70	68 (80)
	279	285 (±56)	+6	144 (±25)	-4.0 (±8.4)	ns¶	124 (133)
	372	339 (± 71)	+33	155 (±32)	8.1 (±10.5)	ns	196 (200)
	465	360 (± 71)	+105	186 (±36)	15.9 (±11.9)	ns	266 (244)
Dewitt	0	47 (± 20)	-47	140 (±6)	-7.6 (±1.0)	0.73	72 (84)
(n = 20)	37	48 (± 22)	-11	147 (±5)	-5.9 (±1.0)	0.64	94 (98)
	74	49 (± 22)	+25	158 (±6)	-4.8 (±1.2)	0.45	115 (113)
	111	49 (± 23)	+62	167 (±8)	-2.9 (±1.5)	0.12	141 (126)
	148	50 (± 24)	+98	175 (±11)	0.7 (±2.0)	ns	181 (161)

† The initial Mehlich-3 extractable K averaged 81 mg K kg^{-1} for the Calhoun soil, 115 mg K kg^{-1} for the Captina soil, and 145 mg K kg^{-1} for the Dewitt soil.
‡ Column provides the predicted and (actual mean) Mehlich-3 K after cropping and fertilization for 16 years for the Calhoun, 5 years for Captina, and 9 years for the Dewitt soil.
§ Observation number indicates the number of observations per regression for each soil and K rate. For the Calhoun and Dewitt soils, two means for each year of soil samples (2 means for each of 17 or 10 soil samples years, respectively). The Captina soil represents 1 mean for each of 6 soil sample years.
¶ ns, not significant

Fig. 1. The predicted linear Mehlich-3 extractable K response across 16 years to five fertilizer-K rates applied to a Calhoun silt loam soil cropped to irrigated rice and soybean. Coefficients for linear equation are listed in Table 1. The filled circles represent the two mean Mehlich-3 extractable K concentrations of soil that received no fertilizer-K each year. The dashed horizontal line at 81 mg K kg^{-1} represents the initial soil-test K at the start of the experiment.

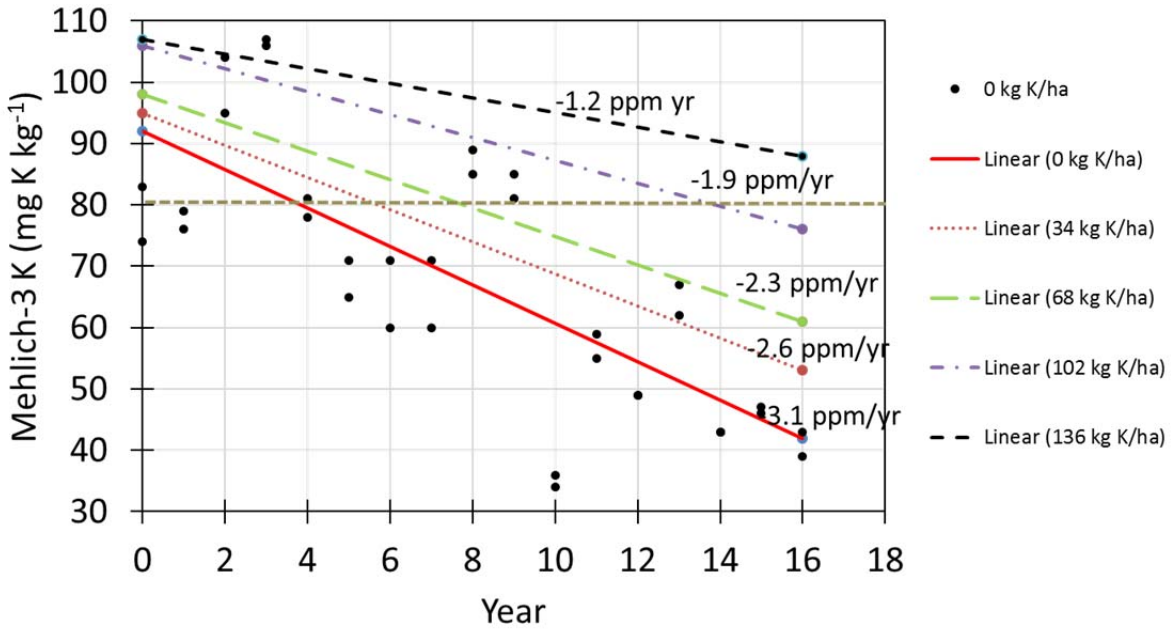


Fig. 2. The predicted linear Mehlich-3 extractable K response across 9 years to five fertilizer-K rates applied to a Dewitt silt loam soil cropped to irrigated rice and soybean. Coefficients for linear equation are listed in Table 1. The filled circles represent the two mean Mehlich-3 extractable K concentrations of soil that received no fertilizer-K each year. The dashed horizontal line at 145 mg K kg^{-1} represents the initial soil-test K at the start of the experiment.

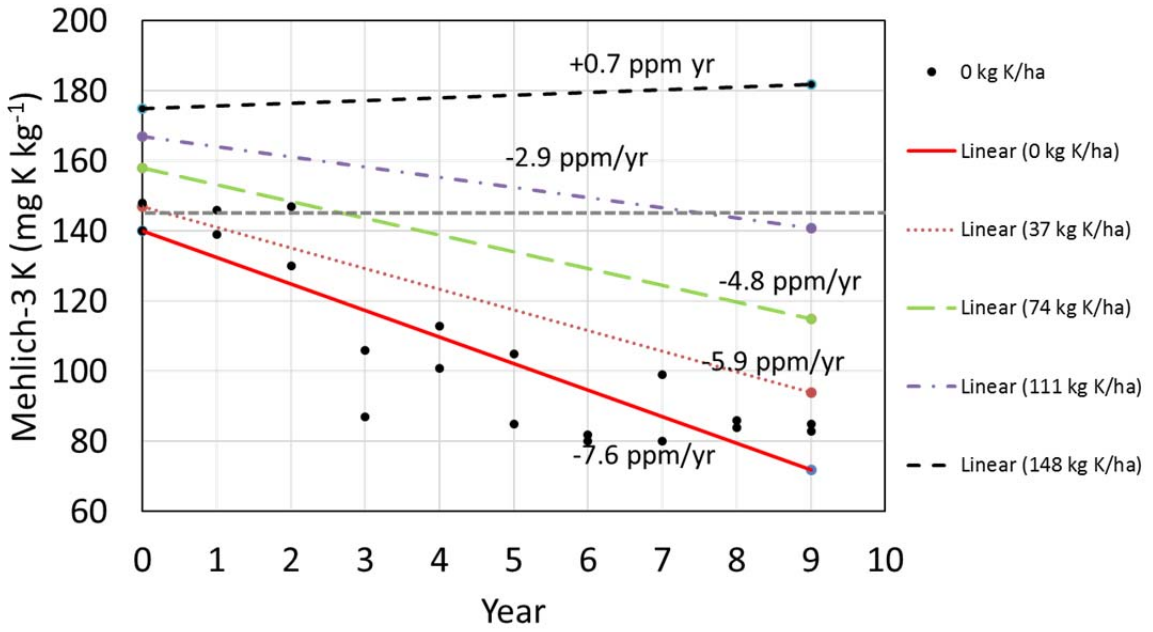


Fig. 3. The predicted linear Mehlich-3 extractable K response across 5 years to six fertilizer-K rates applied to a Captina silt loam soil cropped to bermudagrass hay. Coefficients for the linear equation are listed in Table 1. The filled circles represent the mean Mehlich-3 extractable K concentrations of soil that received no fertilizer-K each year. The dashed horizontal line at 115 mg K kg^{-1} represents the initial soil-test K at the start of the experiment.

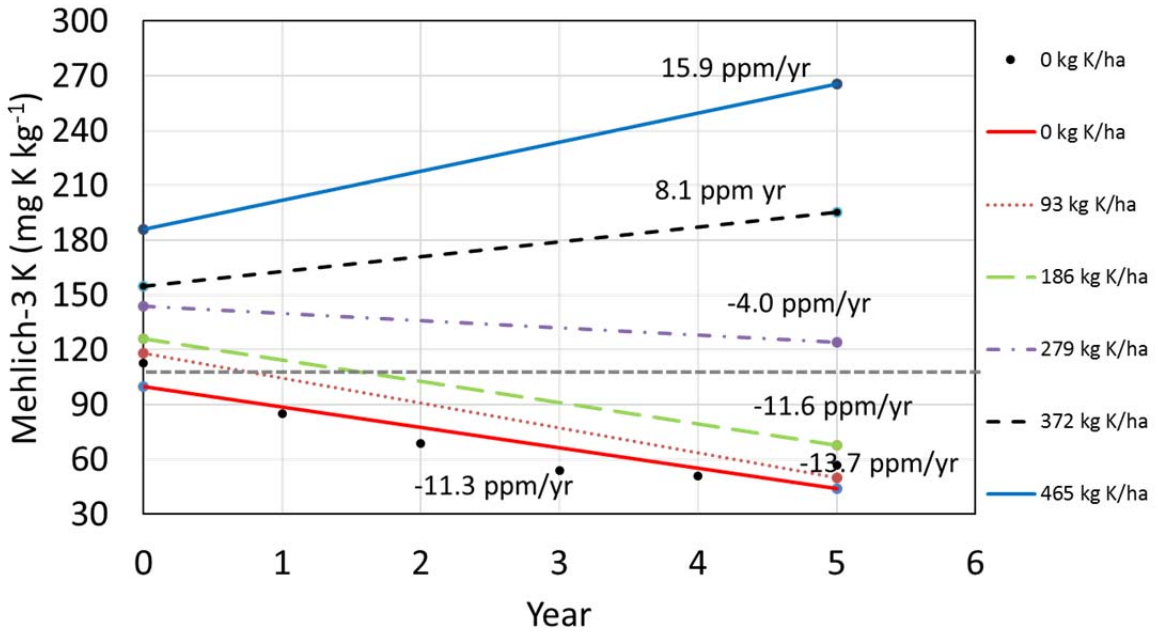


Fig. 4. Quadratic relationship between the net change (e.g., $Year_n$ – $Year_0$) in Mehlich-3 extractable K regressed against cumulative-K balance during a 16-year K fertilization experiment on a Calhoun silt loam cropped to irrigated rice and soybean.

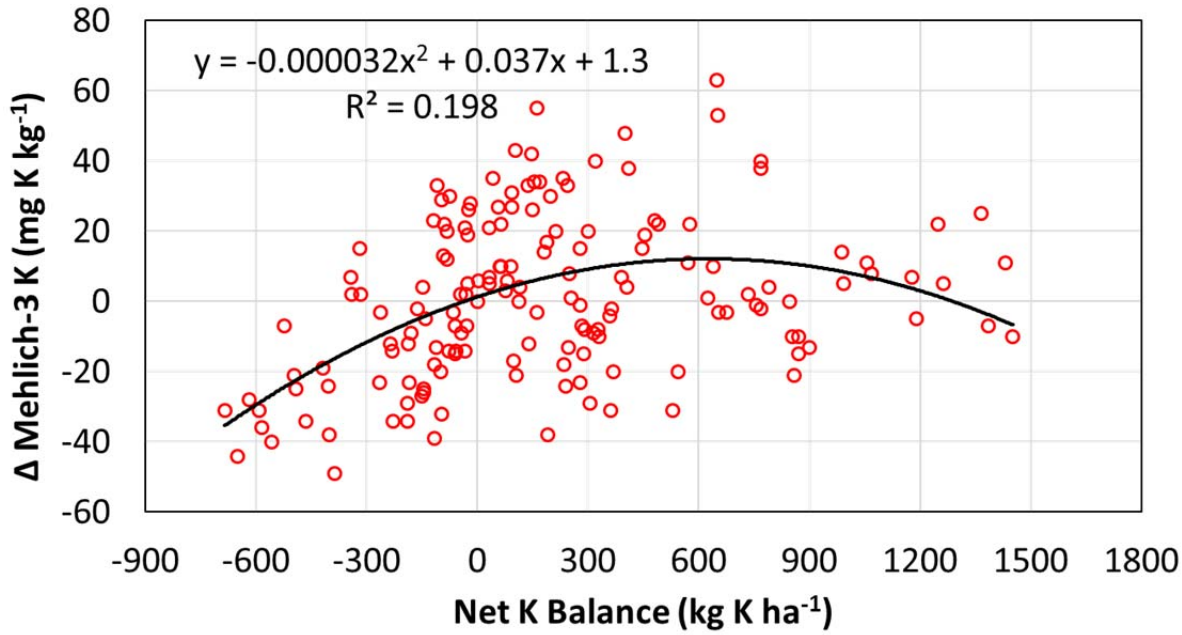


Fig. 5. Quadratic relationship between the gross annual change (e.g., $Year_n$ – $Year_0$) in Mehlich-3 extractable K regressed against cumulative-K balance during a nine-year K fertilization experiment on a Dewitt silt loam cropped to irrigated rice and soybean.

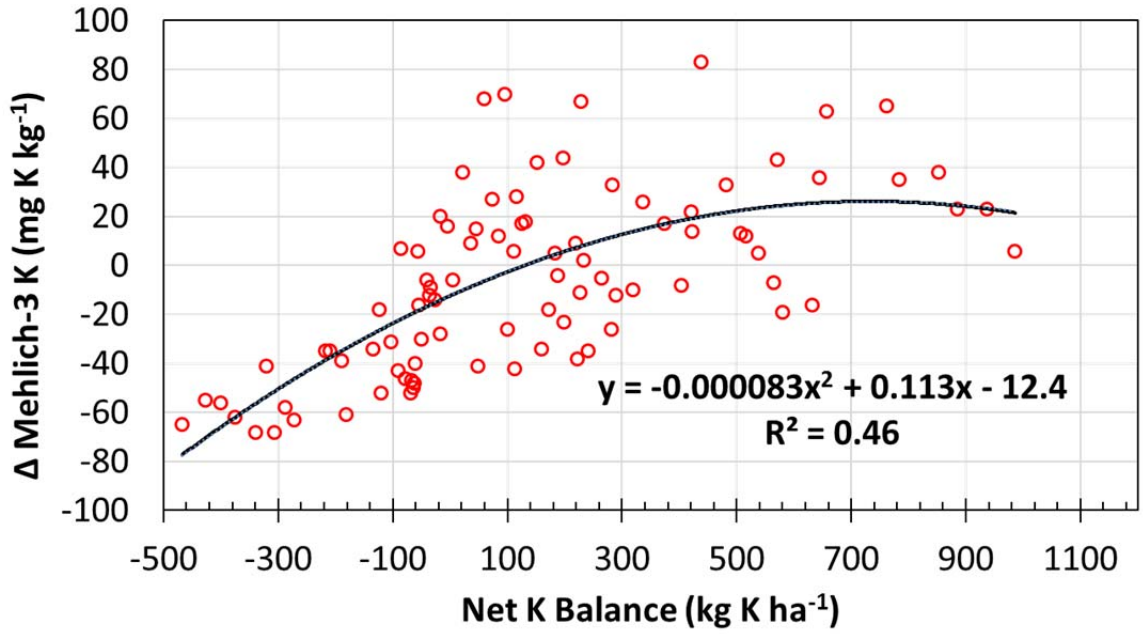
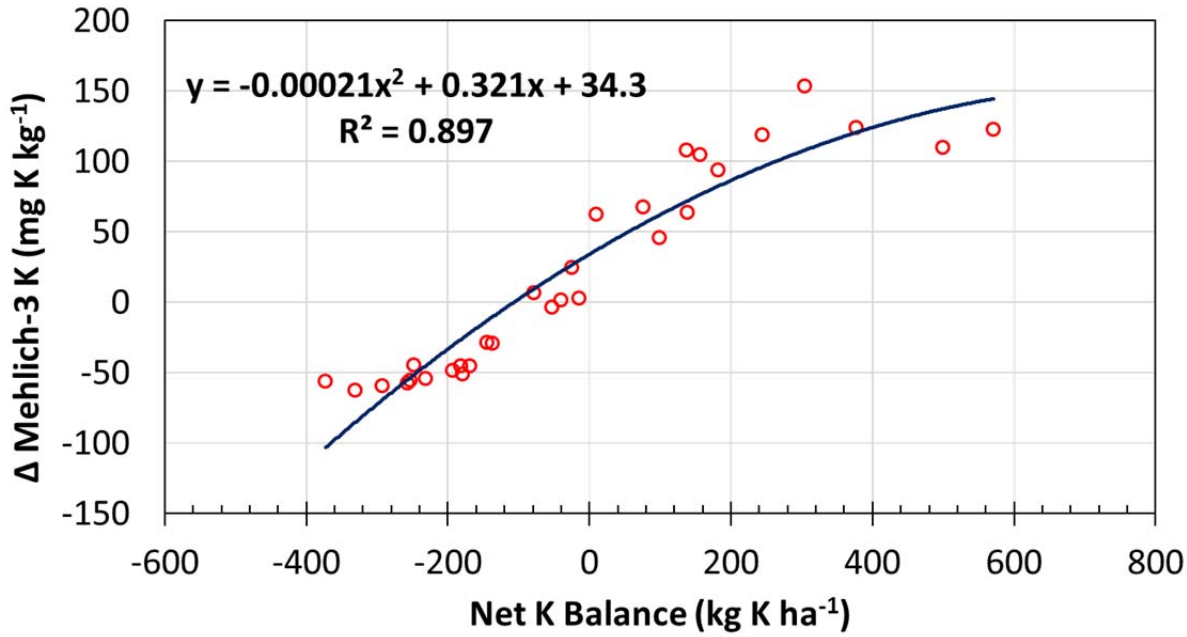


Fig. 6. Quadratic relationship between the gross annual change (e.g., $Year_n$ – $Year_0$) in Mehlich-3 extractable K regressed against cumulative-K balance during a five-year K fertilization experiment on a Captina silt loam cropped to bermudagrass hay.



4R Rate: Improving the Accuracy of Potassium Rate Recommendations

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Abstract
During the last 25 years, the application of K at low rates, mainly with organic and compound mineral fertilizers, has been a common practice in Russia on chernozems with increased and high soil potassium (K^+) supply. In a series of 3-year-long field experiments conducted in the Central Chernozemic Zone and the Northern Caucasus, the efficiency of the direct and residual effects of KCl was studied in 24 experiments by comparing with the optimal NP background fertilization and the absolute control. The aims of the work were (I) to determine optimal application rates of KCl based on crop response to K application, crop quality, K^+ balance, and economic parameters; and (II) to assess the suitability of the existing K^+ test methods with a view to predict K+ supply.

KCl application rates were 0 to 280 kg/ha for sugar beet, corn, rape, and soybean. In soil samples collected at the beginning of the experiment and during three next years, exchangeable (in 1 *M* NH_4OAc), mobile (in 0.5 *N* HAc or in 1% $(NH_4)_2CO_3$), and easily exchangeable (in 0.01 *M* $CaCl_2$) K^+ forms were determined. It was found that K^+ supply depends on the exchangeable K^+ pool. During the first season of KCl application, the positive K balance resulted in an increase in the content of exchangeable and mobile K^+. At the negative K balance, a decrease in the reserve was manifested, especially for exchangeable K^+, less likely for easily exchangeable K^+ (r was 0.77 and 0.64, respectively). The comparison of different extracts showed that the correlation between the contents of exchangeable and $CaCl_2$-extractable K+ forms was most stable; relationships between mobile and exchangeable K^+, on one hand, and plant-available K+, on the other hand, were of more local character. Optimal application rates of KCl based on the set of criteria were proposed with consideration for the partial compensation of K removal by crop.

INTRODUCTION

The most of arable land in the Central Chernozemic Zone (CCZ) of Russia are located in the forest-steppe and steppe zones. The CCZ soil cover mainly consists of chernozems. Parent rocks in the main area of the chernozemic zone have loamy-clayey texture and, with some exceptions, calcareous character. The application of low potassium rates, mainly with organic and compound fertilizers, is a common current practice for chernozems with increased and high supply of plant-available potassium. Thus, these soils utilize potassium via the extensive use of soil fertility.

The rational regulation of the soil potassium supply significantly depends on the estimation procedure. The information value of soil K test results is determined by the correctness of their interpretation and the adequacy of the used soil K interpretation classes. Agrochemical service in the CCZ and Northern Caucasus uses two main standard methods (soil K tests) for the determination of mobile potassium in soils: the Chirikov method (extraction with 0.5 *M* CH_3COOH) for soils of the forest-steppe zone and the Machigin method (extraction with 1% $(NH_4)_2CO_3$) for noncalcareous soils of the forest-steppe and steppe zones. Soil K test interpretation classes for the potassium supply are given in Table 1.

The opportunity for the simultaneous determination of mobile phosphorus in the same extract is one of the main advantage of these methods. According to literature data (Sokolova et al., 2002; Kozlova et al., 2003; Yakimenko, 2003), the use of acid and alkaline extracts causes the dissolution of soil minerals,

which can overestimate the results and thus creates an illusion of favorable potassium status in the soil. These extracts are never used for a large-scale agrochemical studies in the world (Prokoshev and Deryugin, 2000; Khristenko and Ivanova, 2002). Some authors note that the existing system of soil potassium diagnostics with the use of standard soil K test methods is not always capable of revealing critical situations in soil potassium supply and adequately estimating the effective fertility in terms of this nutrient (Prokoshev et al., 2005; Yakimenko, 2009; Nikinina et al., 2013).

In this region the input of potassium into the soil increased from 13.5–45.0 kg/ha in 1964–1979 to 43.8–88.0 kg/ha in 1986–1990 and decreased later on to minimum values of 5.3–14.8 kg K_2O/ha in 1996–2004. An increase in potassium input into arable soils has been recorded recently: to 9.2–24.7 kg/ha in 2003–2009 (Chekmarev et al., 2013). The major amount of potassium was added with mineral fertilizers. Organic fertilizers mainly ensured the potassium supply of soils (5.8–17.8 kg/ha) in the early 1990s, while mineral fertilizers are again the main sources of potassium at present (6.6–19.3 kg K_2O/ha compared to 2.6–8.3 kg K_2O/ha due to organic fertilizers).

According to the results of the last agrochemical survey in the CCZ arable soils with increased content of mobile potassium are dominant. However, a stable tendency of decrease in the content of mobile soil K in the plow soil layer has been recorded in different agricultural regions (Chekmarev et al., 2013). The suitability and efficiency of potassium fertilizers for these soils under current conditions is of immediate concern, due to the intensification of agricultural production in this region. However, during last 25 years almost no field experiments on the study of the effectiveness of potassium fertilizers have been performed in the region.

Therefore, starting from 2012 a series of 3-year-long field experiments was undertaken in the CCZ and Northern Caucasus to study the effectiveness of KCl in a crop rotation containing crops with high potassium removal. The trials were conducted on chernozems with medium and increased content of routinely extracted soil K. The project goals are as follows: 1) Determine optimal potash fertilizer rates for major crops in crop rotation 2) Evaluate the validity of currently used soil K test interpretation classes for proper assessment of plant potassium requirements, 3) Develop proposals on possible fine-tuning of current practice to develop K fertilizers recommendations.

OBJECTS AND METHODS

In Lipetsk, Voronezh, Belgorod, and Rostov oblasts, 24 on-farm experiments were undertaken for 3 consequent crops in rotation. The single application of KCl was for the first crop in rotation (sugar beet, grain maize, rapeseed or soybean). For the next two crops in rotation (cereals) the residual effect of KCl has been studied.

The effect of four increasing KCl rates was studied on the background of optimal NP rates and absolute control (without fertilizers). Each treatment was performed in triplicate.

In the experiment with sugar beet, the following fertilization treatments were used: absolute control (without fertilizers); NP (background); background + K70 (K1); background + K140 (K2); background + K210 (K3); background + K280 (K4).

In the experiment with grain maize (Rostov and Voronezh oblasts), the following fertilization treatments were used: absolute control (without fertilizers); NP (background); background + K60 (K1); background + K120 (K2); background + K180 (K3); background + K240 (K4).

In the experiments with soybean (Belgorod oblast) and spring rape (Lipetsk oblast), the following fertilization treatments were used: absolute control (without fertilizers); background (NP); background + K1; background + K2; background + K3; background + K4. The single rate of potassium fertilizers in

experiments with rape was 60 kg/ha in 2013 and 30 kg/ha in 2014 and 2015. The single rate of potassium fertilizers in experiments with soybean was 60 kg/ha in 2013 and 2014 and 30 kg/ha in 2015.

Several soil K test methods were used to estimate the contents of different potassium forms. The content of mobile potassium in the soil was determined by the standard Chirikov and Machigin methods (GOST 26204, 1991; GOST 26205, 1991); the content of exchangeable potassium was determined by the Maslova method (in 1 *M* CH_3COONH_4) (GOST 26210, 1991), and easily exchangeable potassium was determined in a 0.01 *M* $CaCl_2$ extract.

The content of soil K was determined in soil samples collected separately from each experimental plot at the beginning of the experiment and after a growing season. Determinations were performed on a flame photometer. In the calculation of potassium balance, the element input included the input of K_2O with fertilizers, and the output items included the removal of potassium by the main and side crops.

EFFECT OF POTASSIUM FERTILIZERS ON CROP YIELDS

The results of 3-year-long studies on sugar beet (Rostov, Lipetsk, and Voronezh oblasts), grain maize (Voronezh and Rostov oblasts), spring rape (Lipetsk oblast), and soybean (Belgorod oblast) showed that in the CCZ on chernozems with increased and medium soil K levels maximum yield increase due to K was for sugar beet (7.5–9.2 t/ha) followed grain maize (1.3 t/ha), spring rape (0.2 t/ha), and soybean (0.1 t/ha). On the average for three years the contribution of potassium to the yield increase was maximum for grain maize (18%) followed by sugar beet (14–15%), spring rape (13%), and soybean (6%).

In this paper we will discuss the obtained results for locations and crops demonstrated the most significant response to K fertilizers: sugar beet in Lipetsk, sugar beet and grain maize in Voronezh.

Experiments carried out with sugar beet in Lipetsk and Voronezh oblasts showed significant differences in crop response to K (Tables 2, 4). In Lipetsk oblast the increasing K rates progressively increased the yield of beets and the maximum yield increase was at the maximum K rate (280 kg/ha). This tendency was stable under the contrast weather conditions in 2013–2015 and the almost triple changes in crop yield (24–70 t/ha). In the Voronezh oblast, the maximum yield increase was at double (140 kg/ha) and triple (210 t/ha) K rates.

Analogous tendencies were revealed in Voronezh oblast in experiments with grain maize. The maximum yield increases were obtained for the double and triple potassium rates (120 and 180 kg/ha, respectively). No significant differences were observed between them. The increase in the fertilizer rate resulted in a reduction in the contribution of fertilizer potassium to the yield increase.

ECONOMIC EFFICIENCY OF POTASSIUM FERTILIZERS

The economic efficiency of potassium fertilizers for sugar beet and grain maize was estimated against the background treatment with the averaging of obtained yields for the 3 years of studies. Crop production cost was determined with account of market price for 1 t of granulated KCl for two contrasting years: 2013 and 2015. In 2013 the market price for 1 t of granulated KCl was significantly less (13 000 rubles) than in 2015 (21 500 rubles). Net income was calculated in correspondence with the market price for crops in 2013 and 2015.

In Voronezh oblast application of potassium fertilizers for sugar beet gave an additional net income in all experimental treatments. The maximum income was obtained for the double K rate (K2): in 2013 - 12 000 rubles/ha, in 2015 >20 000 rubles/ha. The further increase in the potassium rate resulted in a reduction of net income, which was more manifested in 2015 values. In Lipetsk oblast, for sugar beet the increase in net income was less significant and reached 7000 rubles/ha at 2013 values and 11 000 rubles at 2015 values (Figure 1).

In experiments with grain maize performed in the Voronezh oblast, the maximum net income was obtained at the application of the double potassium rate (140 kg of K_2O/ha): 6500 rubles/ha at 2013 values and 7400 rubles at 2013 values (Figure 2). When the triple rate was used, the income decreased by 50–80%.

Comparative estimation of potassium fertilizers profitability for beet and grain maize showed that the mean net income for sugar beet was 2–3 times higher.

RECOMMENDED RATES OF POTASSIUM FERTILIZERS BASED ON RESULTS OF FIELD EXPERIMENTS

Optimal rates of potassium fertilizers calculated using multi-criteria estimation are given in Table 5. Only for trails with grain maize in Voronezh oblast estimate of the optimal rate using a set of criteria show the same rate (120 kg/ha) for all criteria. In the other cases, differences were from 70 to 210 kg K_2O/ha. Relatively stable optimal potassium rates were obtained for sugar beet in the Voronezh and Lipetsk oblasts: 140 and 280 kg K_2O/ha, respectively. The uncertainty of the optimal rate in the Voronezh oblast experiments was related to the maximum yield reached at the application of double K rate in the favorable year and triple rate in the unfavorable year. The triple K rate was preferred for a series of unfavorable years in economic terms. However, the rate of 140 kg/ha was optimal for obtaining the maximum net income. Under the favorable conditions of increasing sugar beet biomass, positive balance was created only at the maximum K rate, while a rate of 140 kg/ha was sufficient for it at the low sugar beet yield. As a result, the data averaged for 3 years show that the triple potassium rate is necessary for reaching a positive balance.

In trails with sugar beet in Lipetsk the use of a set of criteria based on the direct effect and residual effect on the crop yield, crop quality, and the reaching the positive balance revealed advantages of the maximum potassium rate (280 kg K_2O/ha). The increase in sugar yield due to potassium application was 21–27% compared to the NP background, which was higher than the corresponding parameters for the Voronezh oblast. At lower absolute incomes in comparison with Voronezh oblast, the relationship between the income and potassium rate increased, when the rate increased to 280 kg/ha in the favorable year, and abruptly decreased, when the potassium rate exceeded 140 kg/ha in the unfavorable year. As a result, the data averaged for 3 years show uncertainty of the economic criterion for the selection of optimal potassium rate. The single potassium rate (70 kg K_2O/ha) show the maximum agronomy efficiency with account for residual effect of K in experiments performed in the Lipetsk and Voronezh oblasts. From the direct effect of K application, the double and triple rates are preferred. The choice of K rate based on this criterion is possible only for maximizing the yield of sugar beet during a series of favorable years only.

RELATIONSHIP BETWEEN SOIL POTASSIUM STATUS AND POTASSIUM BALANCE

Changes in the potassium status of soils under the effect of potassium fertilizers are closely related to the potassium balance formed in the experiments.

The results of field experiments conducted during the first year of study (fall of 2012 - fall of 2013) showed that, for potassium-demanding crops like sugar beet, a stable positive balance at the obtained yields was observed only in the treatment with the high rate of potassium fertilizer (280 kg K_2O/ha). In experiments with grain maize, positive potassium balance was reached at the application of double and triples potassium rates (120 and 180 kg K_2O/ha, respectively). The single or double potassium rate (60–120 kg K_2O /ha) was sufficient for ensuring a positive potassium balance at the growing of rape and soybean.

The dynamics of mobile (Chirikov method) and exchangeable (Maslova method) potassium in the first year of study corresponded to the forming potassium balance. The relationship between potassium balance and exchangeable potassium was significant for the combined data set of experiments in the

Belgorod, Voronezh, and Lipetsk oblasts, $r = 0.64$ (P = 0.95). When the data for the Rostov oblast were included, the coefficient of correlation remained significant, but decreased to 0.37. The relationship between potassium balance and mobile potassium was insignificant for the total data set and the results of experiments in the Belgorod, Voronezh, and Lipetsk oblasts; the coefficients of correlations were 0.27 and 0.33, respectively. Changes in the contents of mobile and exchangeable potassium occurred unidirectional; the coefficient of correlation for the total data set was 0.49 (significant at $P = 0.95$).

Analysis of relationships in Figure 3 shows than both potassium forms demonstrate an increase at the positive potassium balance and a decrease at the negative potassium balance.

In both cases, the estimate is almost unbiased, because the both trend lines pass through the origin of coordinates. However, absolute changes for exchangeable potassium are more manifested then for mobile potassium, which calls for observations of exchangeable potassium to monitor the potassium status of soils.

Exchangeable potassium showed a higher soil K level than mobile potassium, generally by one gradation (one soil K test interpretation class). Nonetheless, the exchangeable form was more susceptible to the forming potassium balance. The difference between the potassium contents found by the Chirikov and Maslova methods reached 64–124 mg/kg and increased with increasing potassium rate in the experiment with grain maize (Belgorod oblast), 159–191 mg/kg in experiments with sugar beet and spring rape (Lipetsk oblast), and 93–175 mg/kg in experiments with corn and sugar beet (Voronezh oblast).

In the Rostov oblast, the determination of potassium contents in soil samples from the experiments with sugar beet and grain maize by the Machigin and Maslova methods showed that the Machigin method extracted more potassium from the soil of the experiment with grain maize than the Maslova method, and the difference between the methods was 8–105 mg/kg. An inverse relationship was observed for the experiment with sugar beet: the Maslova method extracted more potassium by 27–118 mg/kg. The results obtained for experiments in the CCZ correspond to those observed earlier for samples collected at the establishment of the experiment plots. In the Rostov oblast, the obtained results reflect the oppositely directed dynamics of exchangeable and mobile potassium forms recorded in the experiment with sugar beet. The initial level of soil supply with potassium remained in almost all experiments, which indicates the use of unexchangeable potassium pools and an increase in potassium availability, especially in the treatments with negative potassium balance. A decrease in potassium supply by one gradation was observed for the treatments with the highest potassium deficit in the experiment with sugar beet (Lipetsk and Rostov oblasts). In most cases, the decrease or increase in potassium content observed as a trend was insignificant, with the retention of the initial supply level.

The decrease in the degree of correlation between the parameters considered, when the results for the Rostov oblast were included in the data set, is difficult to interpret unambiguously. The use of the Machigin solution for the samples from the Rostov oblast, which makes the results incomparable with those of the Chirikov method, can be an influencing factor. The higher potassium supply of soils in the Rostov oblast than on the other plots, which masked annual variations, can be another factor.

The dynamics of easily available potassium mainly reflected changes in the content of exchangeable potassium.

Correlation analysis of the results obtained by three methods for studying plant available potassium forms showed that the closest correlation is observed between the contents of potassium exchangeably extracted by the Maslova solution and that extracted by the $CaCl_2$ solution ($r = 0.73$ for the total data set), while the lowest correlation is observed between exchangeable and mobile potassium ($r = 0.62$) (Table 6). A tendency toward an increase in the degree of correlation is observed after the first year of studies, which

confirms the significance of the effect of K fertilizers on the dynamics of exchangeable and easily exchangeable potassium forms.

The increase in the contents of exchangeable and mobile forms characterizes a positive potassium balance in the first year after application of potassium fertilizer. Let us consider the results of experiments with the maximum crop yield and, hence, the maximum potassium removal.

In the 2013 experiment with sugar beet performed in the Voronezh oblast, the crop yield in the treatments with the addition of potassium fertilizers exceeded the values averaged for 3 years of studies by 26–36%. The studied soil had an increased content of mobile potassium before the establishment of the experiment; its variation among the experimental plots was 100–124 mg/kg soil. According to soil K test interpretation classes for exchangeable potassium, the studied soil generally had a high content of K_2Oexch; the variation among the experimental plots was 280–301 mg/kg soil. The initial content of easily exchangeable potassium soluble in a $CaCl_2$ solution varied among the plots in the range of 22–34 mg/kg soil. The most deficient potassium balance was formed in the control, NP, and (NP + K70) treatments. When the rate of potassium fertilizers increased, the balance deficit decreased, and the addition of the single potassium rate of 280 kg/ha ensured a positive balance (Table 7).

In the NP treatment, both methods reflected some increase in the content of available potassium, compared to the treatment without fertilizer addition, and the retention of the initial supply.

At the lower rate of potassium fertilizers (70 kg/ha annually) and the negative potassium balance, the content of K_2Oexch was similar to that in the NP treatment, while the Chirikov method showed a reliable increase in the content of mobile potassium. Thus, the Chirikov method more adequately recorded the improvement of soil potassium status in the treatment with the negative potassium balance formed at the addition of the single fertilizer rate (K70).

When the potassium application rate increased to 140–280 kg/ha, a reliable increase in exchangeable potassium by 12–20 mg was observed compared to the NP treatment. In general, the content of exchangeable potassium varied among the experimental treatments within the range 277–304 mg/kg soil, which corresponds to high potassium supply according to the gradations of exchangeable potassium.

The determination of mobile K_2O also showed a reliable increase in its content at the addition of potassium fertilizer. The increase in the content of K_2Omob compared to the NP treatment was 16–30 mg/kg soil, and the supply of the studied soil with mobile potassium remained on the initial (elevated) level (85–115 mg/kg soil).

However, the determination of the easily mobile component of exchangeable potassium in a $CaCl_2$ solution showed no reliable changes in its content compared to the NP treatment (Table 8).

In the 2013 experiment with sugar beet performed in the Lipetsk oblast, the crop yield reached in the treatments with the addition of potassium fertilizers exceeded the values averaged for 3 years of studies by 21–25%.

The estimation of the initial potassium status in the experimental soil showed that the studied soil had an increased content of mobile potassium before the establishment of the experiment according to soil K test interpretation classes for the Chirikov method; its variation among the experimental plots was 107–123 mg/kg soil, while the soil supply according to soil K test interpretation classes for exchangeable potassium was high (245 mg/kg soil). On the average for three replicates, the content of exchangeable potassium was 2.0–2.5 times higher than the content of mobile potassium. The initial content of easily exchangeable potassium in the soil was 35 mg/kg soil, or 13.5% of exchangeable K_2O.

A decrease in the contents of exchangeable and mobile potassium was observed in the NP treatment, and the Maslova method showed a relatively higher decrease than the Chirikov method; i.e., the Maslova method more adequately recorded the deterioration of soil potassium status at the higher removal of potassium under exhausting conditions (Table 9).

The application of potassium fertilizers at rates of K70–K210 caused a tendency of increase in the contents of exchangeable and mobile potassium forms with increasing rates of potassium fertilizers. In both cases, it was unreliable because of the significant spatial variation among the experimental treatments. Only at the application of fertilizer at a rate of K280, the Chirikov method reflected a reliable increase in the content of mobile K_2O. The absolute values of changes were close to those obtained in the experiment with sugar beet in the Voronezh oblast, and the increase in the content of mobile potassium at the addition of potassium fertilizers was more rapid than that of exchangeable potassium in both experiments.

Data on the effect of increasing rates of potassium fertilizers on the content of easily exchangeable potassium are given in Table 10. The analysis of data showed a relative constancy of easily exchangeable potassium, with a tendency toward a slight increase, which becomes reliable at the application of the maximum rate of potassium fertilizer (280 kg K_2O/ha).

Changes in the contents of different soil K forms during the vegetation period are largely determined by the economic balance of potassium, which characterizes the compensation of potassium removal with crop biomass by the application rates of potassium fertilizers. Generalized results of 10 experiments with grain corn and sugar beet performed in the CCZ (Voronezh, Lipetsk, and Belgorod oblasts) in 2013–2015 are shown in Figure 5. The balance coefficient of utilization of an element from fertilizers and soil (BCUFS), which was used as a balance parameter, was determined as follows:

$$BCUFS = \frac{Rf}{F} \cdot 100\%,$$

where *Rf* is the removal of potassium with the main and side crop in the treatment with fertilizer application, kg/ha; and *F* is the fertilizer rate, kg a.i./ha.

If the balance coefficient is higher than 1, depletion of potassium pool in the soil occurs. In this case, the crop yield decreases, when the content of plant available potassium is below the critical level. If the balance coefficient is lower than 1, potassium accumulation generally occurs. In this case, the content of available potassium should increase, which indicates that the fertilizer rate should be reduced to the level compensating the removal of potassium by crop.

The distribution of experimental treatments against the BCUFS = 1, which characterizes the maintenance of the initial reserves of available potassium in the soil, first comes under notice. In most treatments, the tested rates of potassium ensured its positive balance, which indicated the correct selection of the fertilizer rate range. An increase in potassium content was typical for both exchangeable and mobile forms; it became visible when the BCUFS value was below 70%, i.e., when the potassium input exceeded its removal in almost 1.5 times. On the average for the vegetation period after application of K fertilizers (direct effect), the content of mobile and exchangeable potassium forms could increase by 50 mg/kg, although a double increase was observed for some treatments. At the negative balance with the 70–80% compensation of potassium removal, the decrease in the contents of both potassium forms was 25 mg/kg on the average. On the background of relatively lower data variation, the correlation of potassium balance with changes in the content of exchangeable form was more significant than with the mobile form; in the former case, the correlation coefficient was –0.77 and was significant at P =0.95. The dynamics of easily mobile potassium showed only a slight tendency toward an increase in its content when the input exceeded the removal in three times, but it remained below 10 mg/kg on the average and was not

manifested at the negative balance. The correlation between potassium balance and changes in the content of easily mobile form was –0.64 (significant at *P* =0.95).

The increase in the content of exchangeable potassium positively affected the yields of sugar beet and grain maize. The relationship between the parameters shown in Figure 6 shows that the increase in the content of exchangeable potassium by 20% after the application of potassium fertilizer ensured an increase in crop yield by 5% against the NP background, which corresponded to 2.7 t/ha for beet and 0.3 t/ha for grain maize in the Voronezh oblast, as well as to 2.4 t/ha for sugar beet in the Lipetsk oblast (Tables 1, 2). This relationship was observed for the set of treatments with the content of exchangeable potassium corresponding to the high potassium supply of soils. The correlation coefficient was 0.53 on the average and increased from 0.35 to 0.69, when the content of exchangeable potassium increased from 200 to 300 mg/kg (significant at *P* =0.95). Thus, the application of potassium fertilizers even at the high supply of soil with exchangeable potassium is justified by an additional increase in the yields of crops with high potassium removal rates. The study of an analogous change in crop yield under increasing content of mobile potassium showed that the correlation coefficient increased from 0.39 to 0.44 for the sets with increased and high contents of mobile potassium (Table 1) and remained insignificant at *P* =0.95 on the background of higher spatial variation compared to the exchangeable form.

CONCLUSIONS

In the CCZ on-farm experiments with the application of potassium fertilizers on chernozems with increased and medium soil K level the maximum yield increase due to K was 7.5–9.2 t/ha for sugar beet, 1.3 t/ha for grain maize, 0.2 t/ha for spring rape, and 0.1 t/ha for soybean.

The calculation of optimal application rates of potassium fertilizers using multi-criteria estimations shows that the optimal rate for sugar beet on chernozems with increased and medium soil K levels is equal to 140 kg K_2O/ha, with possible increase to 210 kg/ha in favorable years for crop development, in the Voronezh and 210 to 280 kg K_2O/ha in the Lipetsk oblast. For grain maize, the optimal rates in Voronezh oblasts are 120 kg/ha.

The exchangeable and mobile potassium forms showed an increase at the positive potassium balance and a decrease at the negative balance, the absolute value being up to 100 mg/kg for the vegetation period. Absolute changes were more manifested for the exchangeable form than for the mobile form. Correlation analysis of the results of three methods for studying plant available potassium forms showed the most stable correlation between exchangeable and $CaCl_2$-extractable potassium forms; relationships between the content of mobile potassium and its exchangeably adsorbed and plant-available forms were of more local character. The degree of correlation increased from the beginning of the experiment to end of the first year of study, which indirectly indicated the effect of fertilizer potassium on the dynamics of exchangeable and easily exchangeable potassium forms.

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Table 1. Soil K test interpretation classes for soil supply with mobile potassium, mg/kg soil (Derzhavin and Bulgakov, 2003).

Soil K level	Content of K_2O by Chirikov method	Content of K_2O by Machigin method
Very low	<20	<100
Low	21–40	101–200
Medium	41–80	201–300
Increased	81–120	301–400
High	121–180	401–600
Very high	>180	>600

Table 2. Sugar beet response to K, Voronezh oblast

Treatment	Beet roots yield, t/ha				Average for 3 years yield increase due to K, t/ha	Contribution of K fertilizer to yield increase, %
	2013	2014	2015	Mean		
Control	63.77	42.67	44.05	50.16	–3.29	–
NP	66.21	44.93	49.22	53.45	0.00	–
NP + K1	73.00	47.77	**54.13**	58.30	4.85	8
NP + K2	**80.39**	**51.50**	**55.91**	62.60	9.15	15
NP + K3	74.78	**55.90**	**55.96**	62.21	8.76	14
NP + K4	**75.81**	**54.40**	48.41	59.54	6.09	10
LSD05	9.59	5.30	4.30			

Table 3. Grain maize response to K, Voronezh oblast

Treatment	Grain yield, t/ha				Average for 3 years yield increase due to K, t/ha	Contribution of K fertilizer K to yield increase, %
	2013	2014	2015	Mean		
Control	9.1	2.87	5.4	5.79	–0.21	–
NP	9.8	3.14	5.06	6	0.00	–
NP + K1	10.23	**3.44**	5.9	6.52	0.52	8
NP + K2	**11.22**	**3.61**	**7.12**	7.32	1.32	18
NP + K3	10.62	**3.48**	**7.54**	7.21	1.21	17
NP + K4	10.18	3.29	6.2	6.56	0.56	8
LSD05	0.93	0.15	1.44			

Table 4. Sugar beet response to K, Lipetsk oblast

Treatment	Beet root yield, t/ha				Average for 3 years yield increase due to K, t/ha	Contribution of K fertilizer K to yield increase, %
	2013	2014	2015	Mean		
Control	51.13	24.28	49.63	41.68	–6.24	–
NP	56.91	32.42	54.43	47.92	0.00	–
NP + K1	**61.75**	**34.21**	56.27	50.74	2.82	6
NP + K2	**65.10**	**36.08**	58.38	53.19	5.27	10
NP + K3	**67.34**	**35.48**	**59.54**	54.12	6.20	11
NP + K4	**69.31**	**36.15**	**60.77**	55.41	7.49	14
LSD05	1.16	0.15	4.59			

Table 5. Optimal rates of potassium fertilizers for grain maize and sugar beet with account for their direct effect and residual effect, average for 3 years of studies

Maximum yield increase due to K	Maximum yield increase with account for residual effect of K	Maximum yield of sugar (beet) or protein (corn)	Positive potassium balance	Maximum agronomy efficiency with account for residual effect of K	Maximum net income
Voronezh oblast, sugar beet					
140-210	140	140	210	70	140
Lipetsk oblast, sugar beet					
280	280	280	280	70	140–280
Voronezh oblast, grain maize					
120	120	120	120	120	120

Table 6. Coefficients of correlation between the contents of potassium extracted by different methods in the studied soil samples (significant at $P = 0.95$)

Correlation coefficient	Mobile potassium–exchangeable potassium	Mobile potassium–$CaCl_2$-extractable potassium	Exchangeable potassium–$CaCl_2$-extractable potassium
Voronezh oblast	0.74/0.47†	0.69/0.49	0.70/0.90
Rostov oblast‡	0.47/0.58	0.65/0.67	0.78/0.63
Lipetsk oblast	0.63	0.65	0.95
Total	0.62	0.67	0.73

† values obtained after the first year of studies and before the establishment of the experiment are given in numerator and denominator, respectively.
‡ except the plot with the maximum potassium supply.

Table 7. Effect of increasing potassium fertilizer rates on the contents of exchangeable and mobile potassium in the experiment with sugar beet, Voronezh oblast, 2013

Treatment	K rate, kg K_2O/ha	Potassium balance, kg/ha	Content of K_2Oexch	Change in K_2Oexch due to fertilizer application	Content of K_2Omob	Change in K_2Omob due to fertilizer application
			mg/kg soil			
Control	–	−160	277	–	85	–
N24P104	–	−156	284	+7	96	+11
NP + K1	70	−147	283	+1	102	+17
NP + K2	140	−94	297	+13	115	+30
NP + K3	210	−32	304	+20	109	+24
NP + K4	280	+56	296	+12	101	+16
LSD05			10.4		12.2	

Table 8. Potassium balance and the content of easily exchangeable K_2O after application of potassium fertilizers in the experiment with sugar beer, Voronezh oblast, 2013

Treatment	K rate, kg K_2O/ha	Content of easily exchangeable K_2O	Changes due to application of K fertilizer
		mg/kg soil	
Control	–	31/11†	–
N24P104	–	30/11	–
NP + K1	70	32/11	+2
NP + K2	140	34/11	**+4**
NP + K3	210	34/11	+2
NP + K4	280	33/11	+1
HCP_{05}		**3.1**	

†percentage of easily exchangeable K_2O in exchangeable K_2O.

Table 9. Effect of increasing rates of potassium fertilizers on the contents of exchangeable and mobile potassium in soil of the experiment with sugar beet, Lipetsk oblast, 2013

Treatment	K rate, kg K_2O/ha	Potassium balance, kg/ha	Content of K_2O_{exch}	Change in K_2O_{exch} due to K fertilizer application	Content of K_2O_{mob}	Change in K_2O_{mob} due to K fertilizer application
			mg/kg soil		mg/kg soil	
Control (without fertilizers)	–	–215	210	–	77	–
N170P155	–	–247	189	–21	72	–5
NP + K1	70	–175	208	+9	84	+12
NP + K2	140	–115	196	+7	80	+8
NP + K3	210	–78	202	+3	91	+19
NP + K4	280	–5	214	+25	107	**+35**
LSD_{05}			**35.8**		**26.9**	

Table 10. Changes in the content of easily exchangeable K_2O after application of potassium fertilizer in the experiment with sugar beet, Lipetsk oblast, 2013

Treatments	K rate, kg K_2O/ha	Content of easily exchangeable K_2O	Changes due to K fertilizer application
		mg/kg soil	
Control (without fertilizers)	–	34	–
N170P155	–	31	–
NP + K1	70	36	+5
NP + K2	140	33	+2
NP + K3	210	34	+3
NP + K4	280	41	**+10**
HCP_{05}		**4.9**	

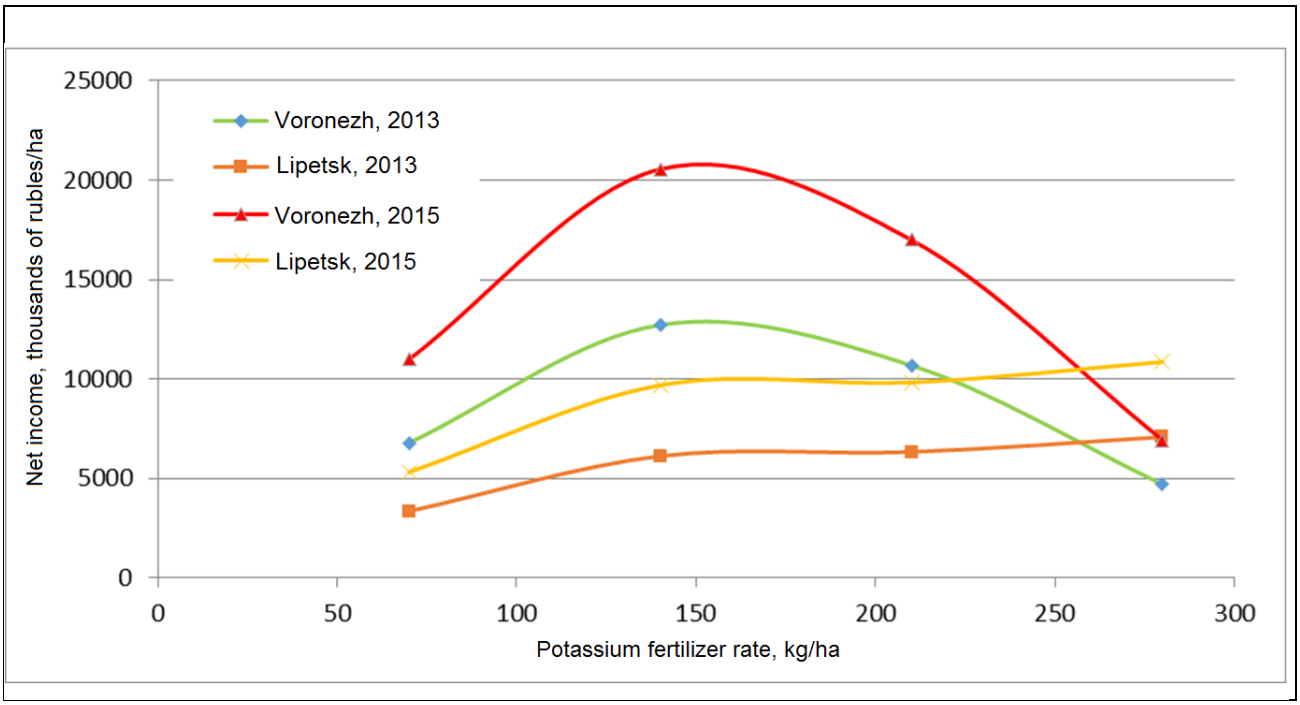

Figure 1. Profitability of potassium fertilizers applications for sugar beet in Voronezh and Lipetsk oblasts.

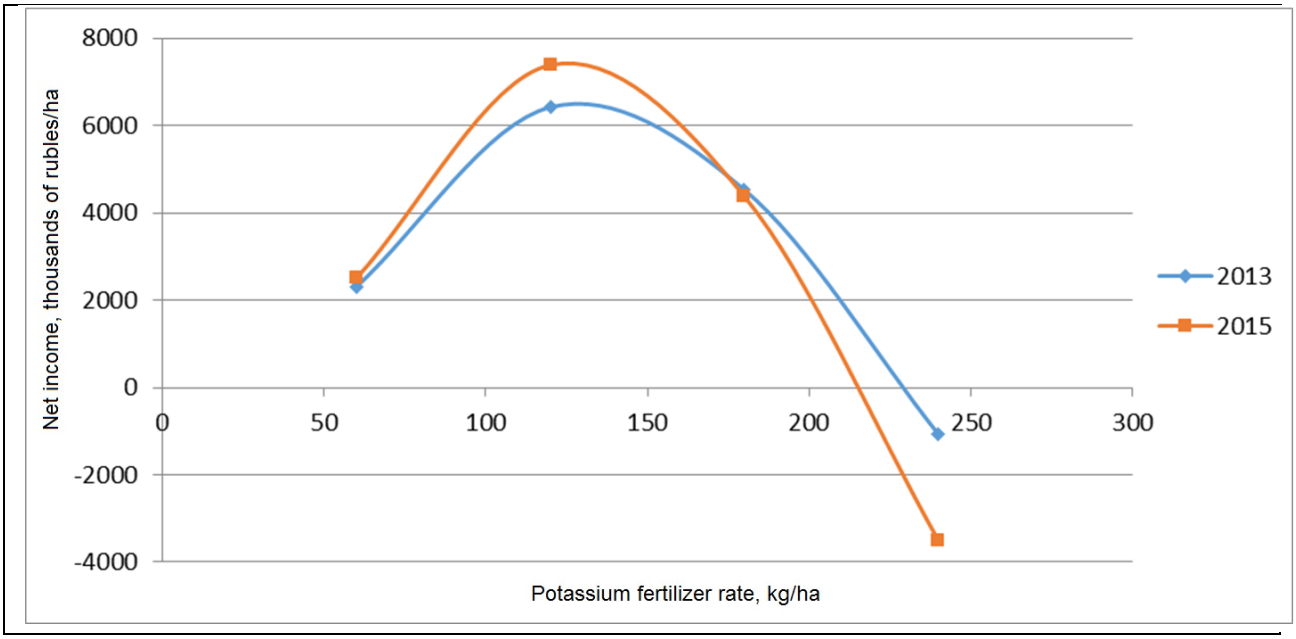

Figure 2. Profitability of potassium fertilizers applications for grain maize in Voronezh oblast.

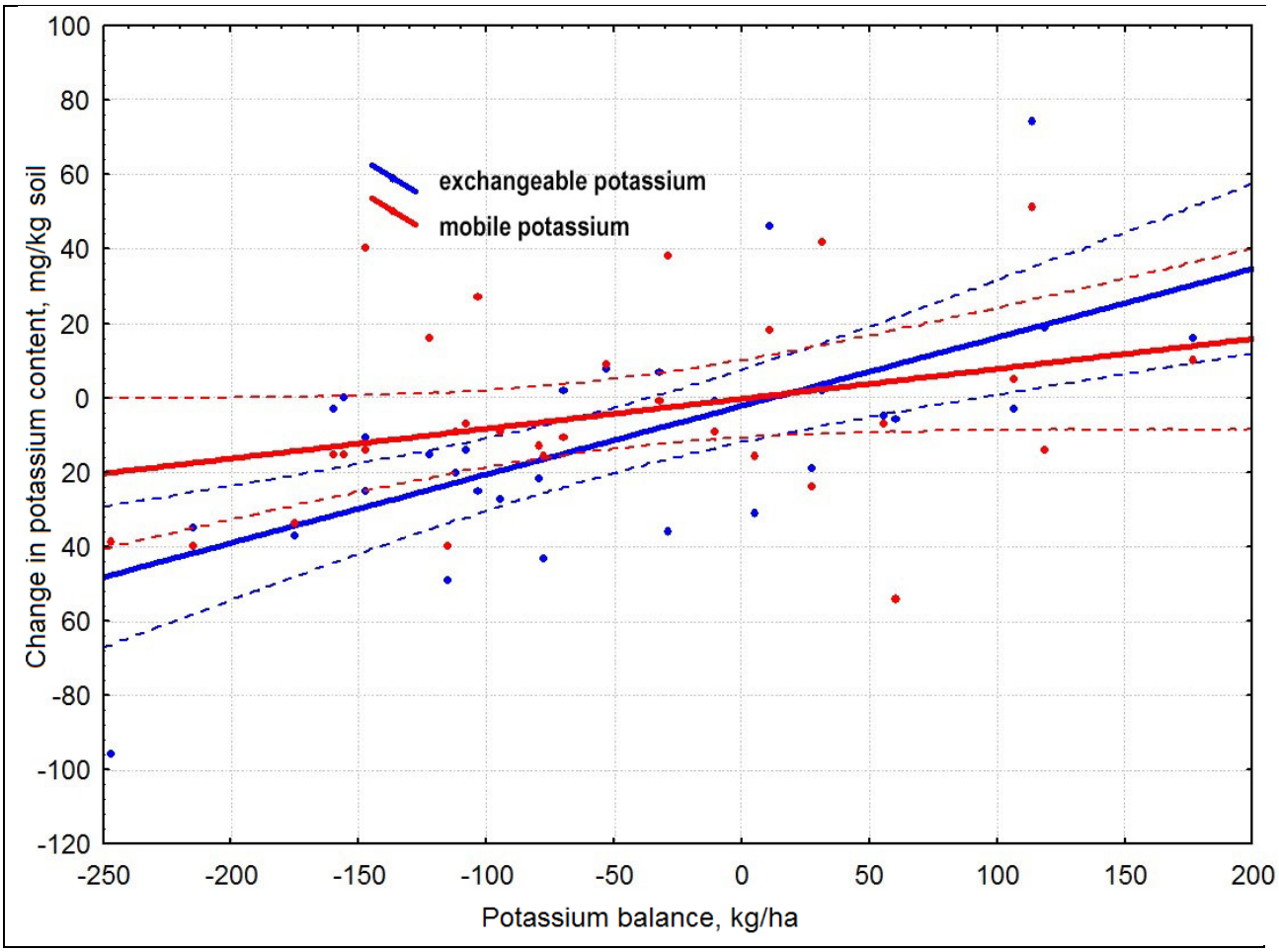

Figure 3. Relationship between changes in exchangeable and mobile soil K during the first year of study and potassium balance from the results of experiments in Belgorod, Voronezh, and Lipetsk oblasts; solid lines denote linear trends; dashed lines denote confidence intervals at $P = 0.95$.

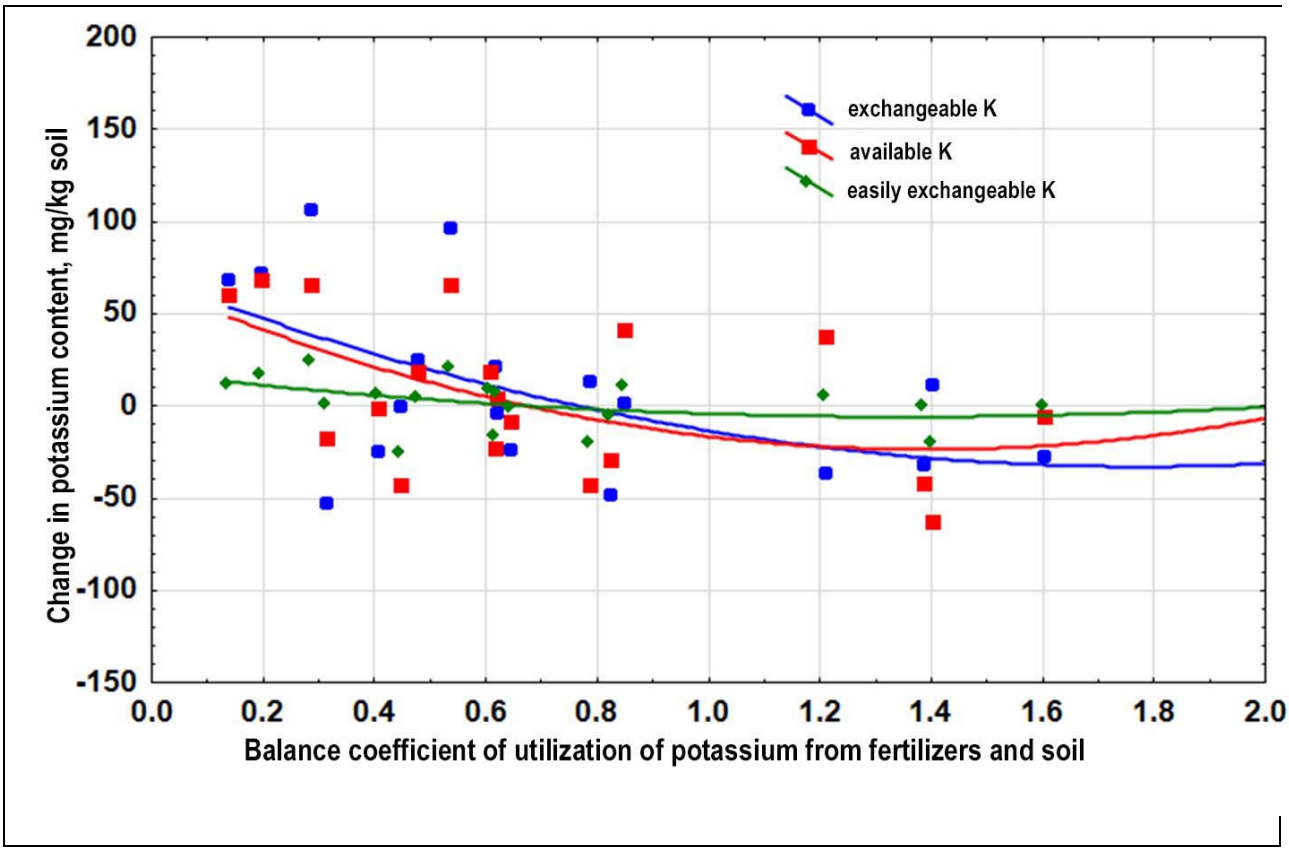

Figure 4. Changes in the contents of different soil K forms during the vegetation period versus the balance coefficient of utilization of potassium from fertilizers and soil in experiments with grain corn and sugar beet in the CCZ, 2013–2015.

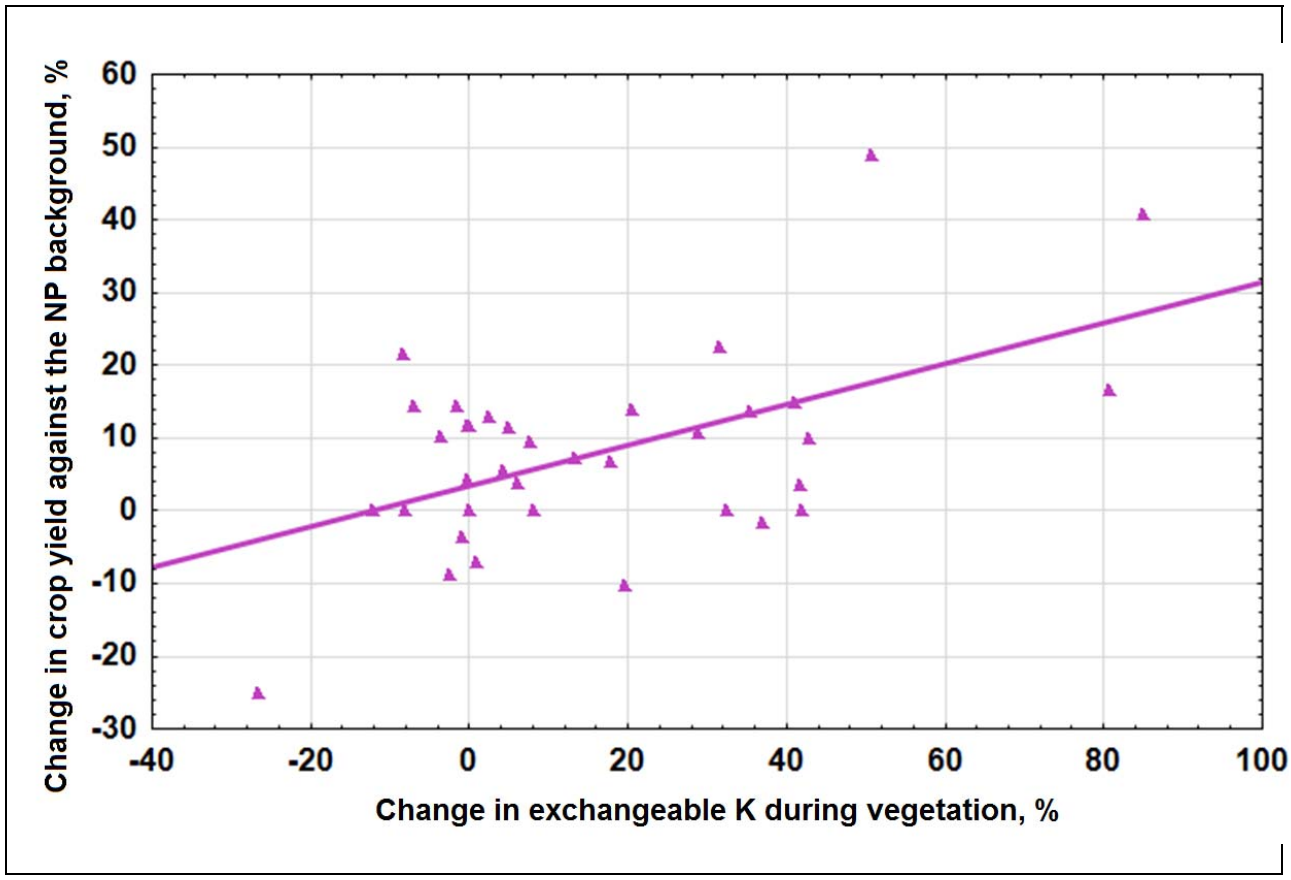

Figure 5. Effect of the increase in the content of exchangeable potassium on the change in the yield of sugar beet and grain maize for the set of treatments with the contents of exchangeable potassium higher than 250 mg/kg.

How can Factors Influencing Soil Potassium Acquisition by Crop Roots be used to Improve Potassium Rate Recommendations?

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Abstract

The amount of potassium (K) fertilizer to apply to a soil to obtain a crop yield response is most commonly based on a measurement of exchangeable K in the soil. This approach has been quite successful where calibration with crop yield is adequate. In many soils, especially those with significant 2:1-type clay minerals, however, plants are able to acquire non- or slowly-exchangeable K, for which there is no routine soil test. So, is it simply a matter of refining soil test procedures, e.g., changing chemical extractants, to better predict K fertilizer rates? Probably not, because reliance only on a soil K test ignores the numerous physical and chemical soil properties that to a large extent, determine the development, distribution, and function of roots in the soil, and thus their ability to acquire K. Roots do not grow uniformly in soil, and water and K are not distributed evenly in the soil profile. Soil compaction, drought and salinity stress, and aluminum toxicity in acid soils, are examples of soil factors that inhibit root growth, and thus hinder uptake of K and other mineral nutrients. Further, root morphology differs greatly among crop species. Root length, root radius, and the presence of root hairs play a significant role in the acquisition of K from soil. Differences in the physiological activity, i.e., K influx rate, also affect the K uptake efficiency of the plant. Research suggests that root exudates can mobilize soil K or influence release of non-exchangeable K. All of these factors must be considered if we hope to improve K fertilizer rate recommendations. As demand for food, feed, and bioenergy feedstocks increase, and climate change affects productivity, improved understanding of crop K fertilizer needs becomes more important.

INTRODUCTION

The K requirements of crops are nearly the same as those of nitrogen (N). While biological N fixation and rainfall provide significant amounts of N to terrestrial ecosystems, there are no such sources of K. Hence, the K requirements of crop plants must come from existing soil reserves, K recycled in crop residues, and inputs of K fertilizers. To meet the needs of the growing world population for food, feed, fiber, and bioenergy feedstocks, increases in both K fertilizer use and K-use efficiency of crop plants are needed.

The aim of this review is to discuss various aspects of soil K availability and soil K acquisition by crop roots as they relate to the need for supplemental K fertilizer. Potassium chloride (KCl) is the major form of K fertilizer that is used in crop production. Potassium sulfate (K_2SO_4) and potassium nitrate (KNO_3) are also commercially available, but tend to be more expensive. Organic fertilizers, such as manures, composts, and by-product materials, are also utilized extensively. Potassium in these materials occurs mostly in a soluble form similar to the K in mineral fertilizer. Therefore, the K can be substituted one-to-one.

For more information on the topics discussed, several recent, excellent reviews are available. For additional details on: i) K use in diverse cropping systems, see Öborn et al. (2005) and Römheld and Kirkby (2010); ii) efficiency of K uptake and utilization, see Rengel and Damon (2008) and White (2013); and iii) mechanisms of root K uptake and transport within the plant, see Britto and Kronzucker (2008) and Nieves-Cordones et al. (2014).

SOIL SUPPLY OF POTASSIUM

Soil Potassium

The K content of mineral soils ranges from 0.04% to 2.9% (Sparks and Huang, 1985). This translates to 10-20 g kg^{-1} total K in the surface layer (20 cm) of most agricultural soils. Soil K can be divided into solution, exchangeable, non-exchangeable, and structural K fractions. The K^+ present in soil solution is directly available to plants and microbes. In agricultural soils, K^+ concentrations generally range from 0.05 to 1 mM (Barber, 1995). Plant roots can acquire sufficient K for growth from soil solution containing micro-molar K^+ concentrations (White, 2013). Exchangeable K is electrostatically bound to the surfaces of clay minerals and humic substances. Exchangeable K is also considered readily available to plant roots. The pools of solution and exchangeable K make up only about 0.1-0.2% and 1-2%, respectively, of the total K in soil (Sparks, 1987). Non-exchangeable forms are considered slowly available, while structural forms are essentially unavailable K sources for annual plants. The interchange between solution K and exchangeable K is rapid, but the interchange between solution K and non-exchangeable K is relatively slow. The quantities of K^+ in soil solution, held on exchange sites and in non-exchangeable form, and the chemical equilibria existing among these fractions, determine the temporal availability of K to crops (Römheld and Kirkby, 2010; White, 2013).

Need for Potassium Fertilizer

The ability of soils to supply the K requirements of crops varies significantly. While some soils can supply more K than required by a crop, so that no K fertilizer is necessary, other soils have little capacity to retain or release K to plant roots and must receive sufficient K fertilizer each year to satisfy the entire requirement of the crop (White, 2013). In many regions of the world, the amount of K fertilizer applied to crops is less than the K removed in grain and biomass (Römheld and Kirkby, 2010). Accounting for losses to the environment via erosion and leaching, there has been a gradual decline in the K content of agricultural soils. As a consequence, K has become a limiting nutrient in intensive agricultural production systems worldwide (Zörb et al., 2014).

The amount of K fertilizer to apply to a soil to obtain a crop yield response is most commonly based on a measurement of exchangeable K in the soil (McLean and Watson, 1985). Exchangeable K is determined by extracting dried soil samples with neutral ammonium acetate, Mehlich-3 solution (ammonium fluoride), ammonium chloride, or calcium chloride. This approach has been quite successful where calibration with crop yield is adequate. In many soils, especially those with significant 2:1-type clay minerals, however, plants are able to acquire significant amounts of non- or slowly-exchangeable K (Rengel and Damon, 2008). Research suggests that it is quite difficult to measure plant-available soil K that is released from non-exchangeable K pools, since the dynamic equilibrium among the various forms of soil K during crop growth is quite complex (Zörb et al., 2014). Thus, there are no routine methods available to adequately measure this fraction. Nevertheless, it is crucial to understand the factors that regulate K release from the soil non-exchangeable pool for optimum K fertilizer management.

In addition to releasing K, soil minerals can also preferentially adsorb ("fix") K, significantly affecting K availability (Sparks and Huang, 1985). The degree of K adsorption depends on the type of clay mineral and its charge density, soil water content, competing ions, and soil pH. Soil wetting and drying also significantly affect preferential adsorption of K. Montmorillonite, vermiculite, and weathered micas are the major clay minerals that tend to fix K (Sparks, 1987). The adsorption process of K is relatively fast, whereas the release of adsorbed K is very slow due to the strong binding force between K and clay minerals (Zörb et al., 2014). The K^+ concentration in soil solution is thought to control whether a soil adsorbs or releases K (Sparks, 1987). The H+ concentration in soil solution (i.e., soil pH) also plays a key role in K release from clay minerals. Therefore, optimization of soil pH may be a means of enhancing K availability.

K Fertilizer and Soil K Supply

When K fertilizer is added to soil to increase K supply to plant roots, a fraction of the added K will increase K^+ concentration in soil solution, a fraction will be adsorbed onto exchange sites, and a fraction may be preferentially adsorbed into nonexchangeable forms that will not rapidly equilibrate with solution K (Bertsch and Thomas, 1985). The distribution of added K among these fractions will vary not only with soil type, but also with the rate of K applied. Kovar and Barber (1990) evaluated the changes in soil K supply following addition of seven rates of K fertilizer ranging from 0 to 1245 mg K per kg of soil for 33 diverse soils. The relation between soil solution K and K added was slightly curvilinear (Fig. 1), indicating that the proportion of added K that remained in solution was, to a limited extent, concentration dependent. The relation between exchangeable K and K added was linear for all soils, indicating that the proportion of added K adsorbed by the exchange sites was independent of the K fertilizer rate (Fig. 2). In all 33 soils, some of the added K was fixed into non-exchangeable forms. The changes in soil solution K and exchangeable K with K addition were not correlated with any commonly measured soil physical or chemical property, such as clay content or cation exchange capacity, which makes it difficult to generalize how soils may respond to K fertilizer. In addition, applications of other nutrients, e.g., ammonium (NH_4^+), together with K may also affect the distribution of added K among the solution, exchangeable, and nonexchangeable fractions.

As discussed by Zörb et al. (2014), there is also a need to better understand the effect of K fertilization on soil physical properties and soil water holding capacity. Holthusen et al. (2010) found that application of mineral K fertilizers enhanced soil water-holding capacity and improved aggregate stability of sandy soils in particular. The authors speculated that higher K+ concentration in soil solution may cause an increase in micro-shear resistance that could explain the change in water retention. In any case, increased water retention plays a key role in sustaining soil productivity in water-limited areas.

ACQUISITION OF SOIL K BY ROOTS AND ROOT SYSTEMS

Root Growth and Morphology

Acquisition of K from soil also depends greatly on the development and spatial distribution of roots in the soil. Changes in root growth and function can cause changes in crop response to K fertilizer, even when soil supply of K is more than adequate (Kovar, 2001).

Root morphology differs tremendously among crop species, especially between monocots and dicots. Root length and density and frequency of root hairs may differ greatly among genotypes within the same species. These differences lead to differences in K uptake. Römheld and Kirkby (2010) reported that visual K deficiency symptoms occurred in legumes and other dicotyledonous crops under drought stress, even when growing in K-rich soils. Root hairs play a significant role in the acquisition of K because their presence increases the surface area of the root cylinder. In many plants, root hairs may contribute up to 70% of the total surface area, thereby increasing the root cylinder surface area up to 27-fold (Jungk, 2001).

For many crop species, it is not clear which fraction of the plant's entire root system is active in nutrient absorption. Studies with winter wheat suggest that K uptake rates may vary among the seminal and nodal roots on the same plant (Kuhlmann and Barraclough, 1987). There also is evidence that some species have five or more types of roots, each with distinct developmental and physiological characteristics (Hodge, 2006).

Soil properties that inhibit root growth, such as soil compaction, insufficient soil water, salinity, and aluminum (Al) toxicity in acid soils, depress K acquisition from the soil because they essentially lower spatial availability of K (Römheld and Kirkby, 2010). When soils are compacted, bulk density increases and the number of larger pores decreases, leading to increased resistance to root growth. Roots growing

into compacted soil must displace soil particles, so that the rate of root elongation decreases as soil strength increases. In soil without significant compaction, roots will grow through soil pores and rapidly extend into the profile.

Soil water contents above and below optimum also affect root growth and function. Seiffert et al. (1995) found that changes in soil bulk density in combination with soil water content affected both maize root growth and K uptake by the plants (Table 1). In dry soils, mechanical impedance is the dominant stress factor. Problems with loss of soil-root contact, as well as ion imbalance in rhizosphere soil solution, may also occur in dry soil. The effect of water deficit is less stressful for plants with root systems that easily and rapidly penetrate the subsoil, where water content is usually higher. Potassium availability can be a problem, however, if subsoil K levels are low (Kovar and Karlen, 2014). In wet soils, loss of aeration and accumulation of phytotoxins are dominant stress factors. Oxygen is necessary for root respiration, as well as the respiration of soil microorganisms. While differences exist among plant species, O_2 concentrations of 10% to 15% are thought to be sufficient to provide uninhibited root growth and function (Drew and Stolzy, 1996). In addition to limited respiration, low molecular-weight solutes that inhibit root growth often accumulate in water-logged soils (Fagerstedt et al., 2013).

When present in sufficiently high concentrations in soil, many elements can adversely affect root growth. Aluminum and manganese (Mn) often have a pronounced effect on root growth of agricultural crops. At low pH, Al, Mn, other trace metals come into solution and hinder root growth (Verbruggen and Hermans, 2013). Potassium fertilizers *per se* can cause problems in that soluble salts close to seedling roots may be harmful. The high solubility of K in manure and compost also can result in excessive levels of soluble salts, particularly if large amounts of these products are applied to lighter-textured soils. In general, the potential for salt injury will depend on the K source, the sensitivity of the crop, and the environmental conditions.

K Uptake from Soil

Several interrelated soil processes govern the acquisition of K and other nutrients by plant roots (Fig. 3; Steingrobe and Claassen, 2000). For uptake to occur, there must be contact between the root and available soil K. This contact takes place when either plant roots grow into soil where K is located, i.e., root interception, or the K in the soil moves to the root surface. Nutrients move through the soil to root surfaces via mass flow and diffusion (Barber, 1962). Mass flow is associated with the convective flow of soil water to roots of transpiring plants. If the amount of K brought to the root surface by mass flow is insufficient to supply the needs of the plant, roots will deplete K from the surrounding soil solution. Diffusion is driven by the concentration gradient that develops near the root surface when K is depleted from soil solution. Diffusion rate is controlled by the water content of the soil, the amount of water-filled pore space, and how well the K concentration in solution is buffered (Barber, 1995)

Potassium brought to the root surface enters root cells through K transporters in plasma membranes (Britto and Kronzucker, 2008; White, 2013). The early work of Epstein and co-workers established that at low external concentrations (less than 1 mM), the uptake of K can be mathematically described with a Michaelis–Menten kinetics model (Epstein et al. 1963). As solution K concentration increases, K influx increases until a root-specific maximum (Imax) is reached. The affinity of roots for the K^+ ion is reflected by the Km value, the solution K concentration at which influx is half that at Imax. This was initially referred to as “Mechanism 1” by Epstein et al. (1963) and later as the high-affinity transport system (HATS) for K (Britto and Kronzucker, 2008). At external concentrations higher than 1 mM, K influx becomes dominated by a kinetically distinct system that demonstrates very little saturation. This linear component of K influx was first referred to as “Mechanism 2” by Epstein et al. (1963) and later the low-affinity transport system (LATS) for K (Britto and Kronzucker, 2008). The two-mechanism model is depicted in Fig. 4. The relationship between K influx and K concentration in soil solution generally follows the sum of HATS and LATS types of K transporters with contrasting kinetic properties (White,

2013). There is also a minimum solution concentration at which roots are no longer able to absorb K, i.e., net K influx equals zero (Nielsen, 1972). This concentration varies greatly among plant species. Potassium influx is affected more by plant K status than root K status (Barber, 1995). Also, K influx per unit of root surface area tends to decrease with plant age

Plant Traits that Improve K Acquisition from Soil

Plants differ greatly in their growth response to K supply, ability to acquire K from the soil, and capacity to utilize the acquired K to produce biomass. Cereals, grasses, and brassicas often attain maximum growth at a lower K supply than legumes, and cereals, brassicas, and legumes often require less supplemental K for maximum yields than many vegetable and root crops (White, 2013). However, this ranking is a generalization, and will be influenced by soil properties and other environmental variables.

Some plant species and genotypes within species have traits that improve soil K acquisition (Barber, 1995; Rengel and Damon, 2008; White, 2013). Root proliferation throughout the soil profile increases the surface area for K uptake and reduces the distance required for K flux to root surfaces. High transpiration rates drive the convective flow of the soil solution towards the root, thus transporting more K to the root. An increase in the rate of K uptake, e.g., a lower Km value, decreases the K concentration in rhizosphere solution, thus increasing diffusion of K to the root. The release of root exudates, such as organic acids, can solubilize nonexchangeable and mineral K in soils and thereby increase the K concentration in soil solution (Fig. 5; Samal et al., 2010). Although the role of K is still poorly investigated in mycorrhizal studies, it appears that plant K nutrition is clearly improved by mycorrhizal associations, especially under K-limiting conditions (Garcia and Zimmerman, 2014).

Research with several perennial grass species has shown that when the roots of these plants grow into nutrient-rich microsites, N and P uptake rates per unit length of root significantly increase (Caldwell et al., 1992; Hodge, 2006). This characteristic allows the plants to take advantage of localized areas of fertile soil (nutrient patches). Although data are limited, the root systems of crop species may react the same way. No literature could be found that assessed K uptake from localized nutrient patches. The role that mycorrhizae may play in K acquisition from nutrient patches also is essentially unknown (Hodge, 2006).

SUMMARY AND PERSPECTIVES

In intensive agriculture, K fertilizer application is necessary to ensure and sustain an adequate supply of available K to crops. The amount of K fertilizer to apply to a soil to obtain a crop yield response is commonly based on a measurement of exchangeable K in the soil. This approach has been quite successful where calibration with crop yield is adequate. In some soils, plants are able to acquire non-exchangeable K, for which there is no routine soil test. Because numerous physical and chemical soil properties that to a large extent, determine the development, distribution, and function of roots in the soil, and thus their ability to acquire K, there is a need for a reappraisal of our current methods for the estimation of K availability and K fertilizer needs.

Mechanistic, mathematical models provide an important tool to enhance our understanding of the complex, interacting processes that control soil K availability and K acquisition by plant root systems, and can enable better management of fertilizer K (Kovar and Brouder, 2015). Current mechanistic models describe soil K supply by mass flow and diffusion to root surfaces. Root absorption of K follows Michaelis-Menten kinetics. Root growth rate is considered; however, model calculations have generally been based on a single, cylindrical root, rather than a three dimensional root system. Recent advances have allowed for consideration of water and nutrient uptake by root hairs and mycorrhizal hyphae (Roose and Schnepf, 2008). Advances have also been made in coupling root architectural models with models of soil processes (Dunbabin et al., 2013). These approaches move us toward the goal of simulating root growth and function in response to heterogeneous soil water and nutrient availability.

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Table 1. Effect of changes in soil bulk density and water content on maize root growth and potassium (K) influx. Data were collected 16 days after planting. Adapted from Seiffert et al. (1995).

Bulk Density	Water Content	Root Growth	K Influx
g cm^{-3}	% (w/w)	10^{-6} cm s^{-1}	10^{-13} mol cm^{-1} s^{-1}
1.2	10.7	1.00a†	1.82a
	14.2	1.95cd	2.82b
	19.0	2.43e	3.38c
1.4	10.7	1.24ab	1.97a
	16.3	1.94cd	3.66c
	19.0	2.24de	4.53d
1.6	10.7	1.12a	2.17a
	14.2	1.63bc	2.09a
	19.0	2.32de	3.62bc

†Means followed by the same letter are not significantly different; Duncan's multiple range test; P = 0.05.

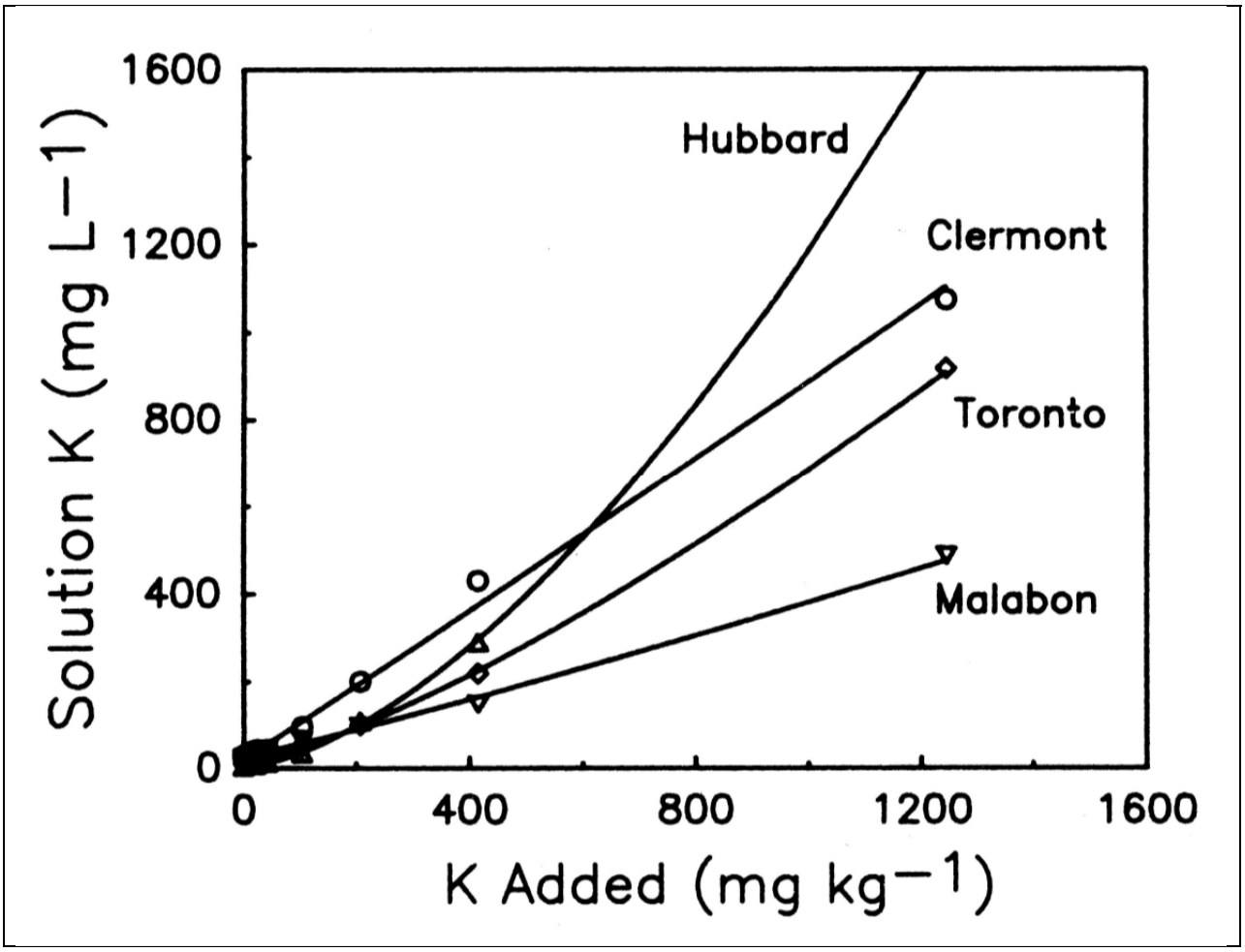

Figure 1. Relation between potassium (K) added and K in soil solution for four soils representing the range found for 33 diverse soils. (Modified from Kovar and Barber, 1990).

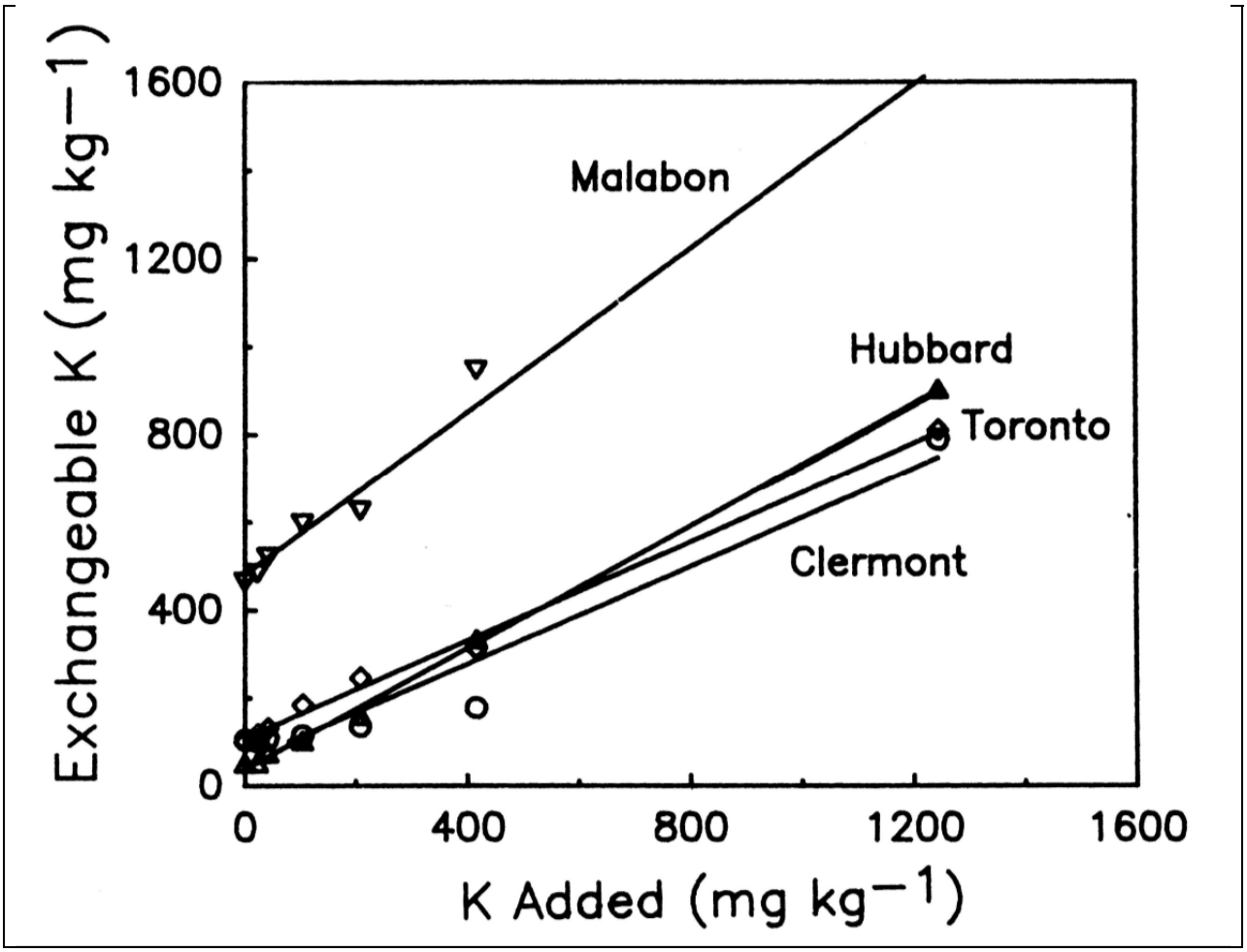

Figure 2. Relation between potassium (K) added and measured exchangeable K for four soils representing the range found for 33 diverse soils. (Modified from Kovar and Barber, 1990).

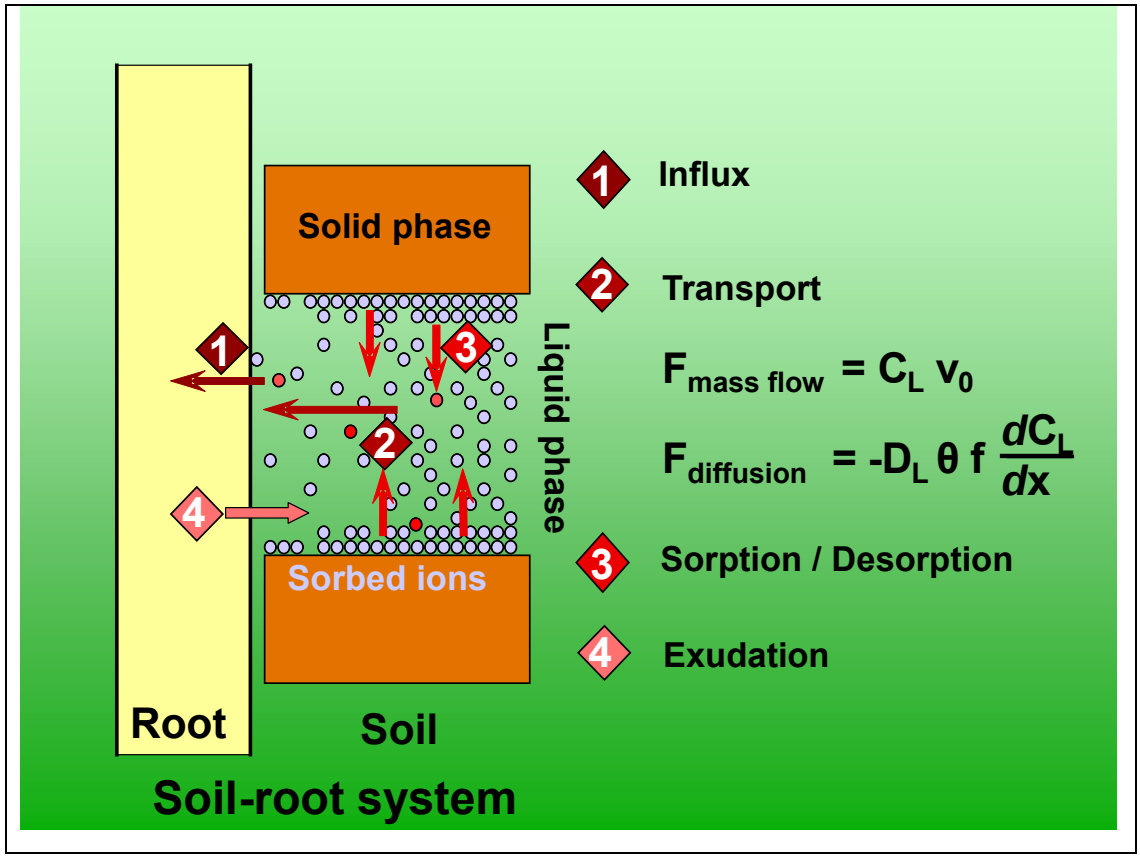

Figure 3. Diagram of the soil-root system consisting of a root segment surrounded by the soil solid phase with sorbed ions (circles) and pore space filled with solution. The main processes of nutrient transport and uptake are depicted. (Modified from Steingrobe and Claassen, 2000).

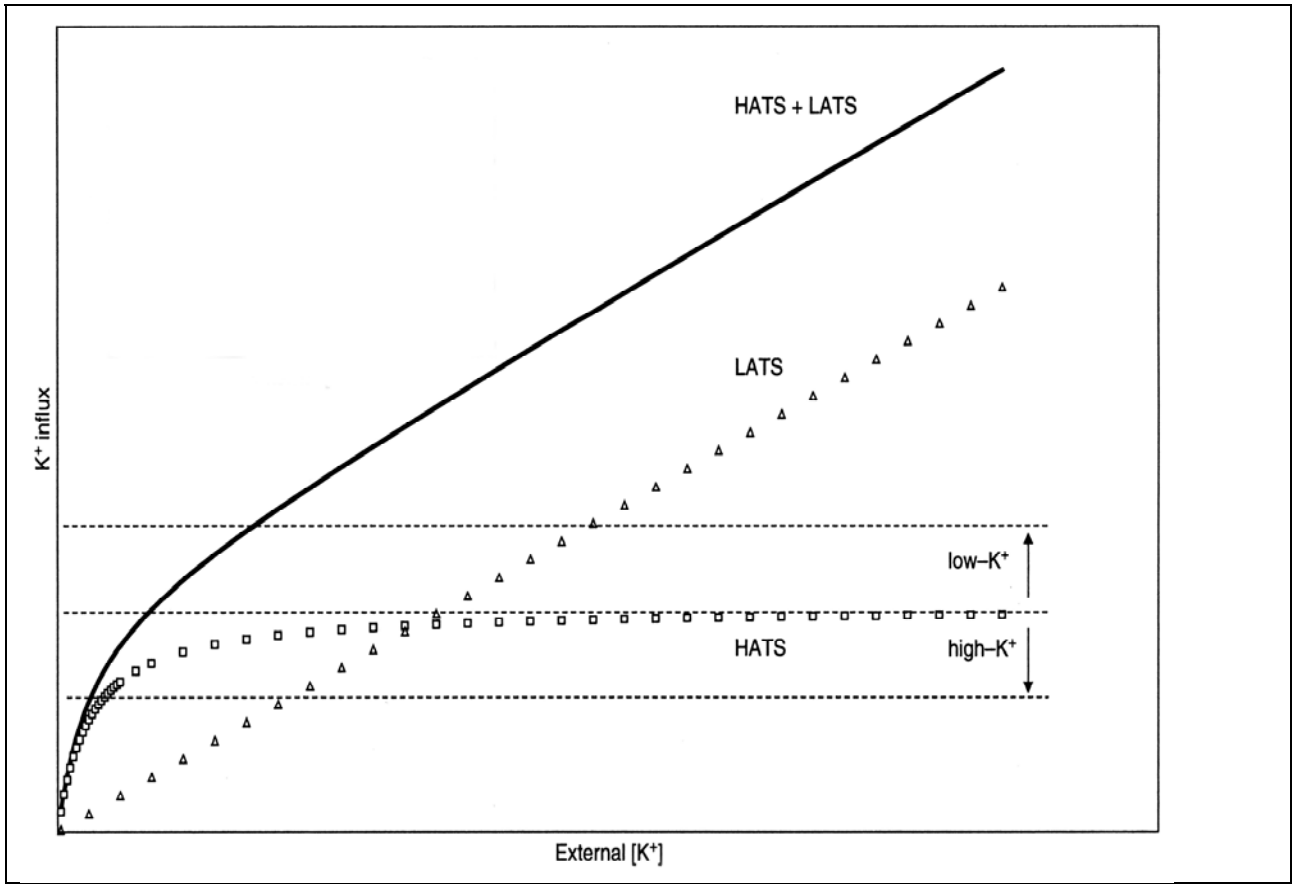

Figure 4. General relation of K influx and soil solution K concentration. Relation for both high-affinity transport system (HATS, open squares) and low-affinity transport system (LATS, open triangles) are shown. Solid line indicates the combined influx. (Modified from Britto and Kronzucker, 2008).

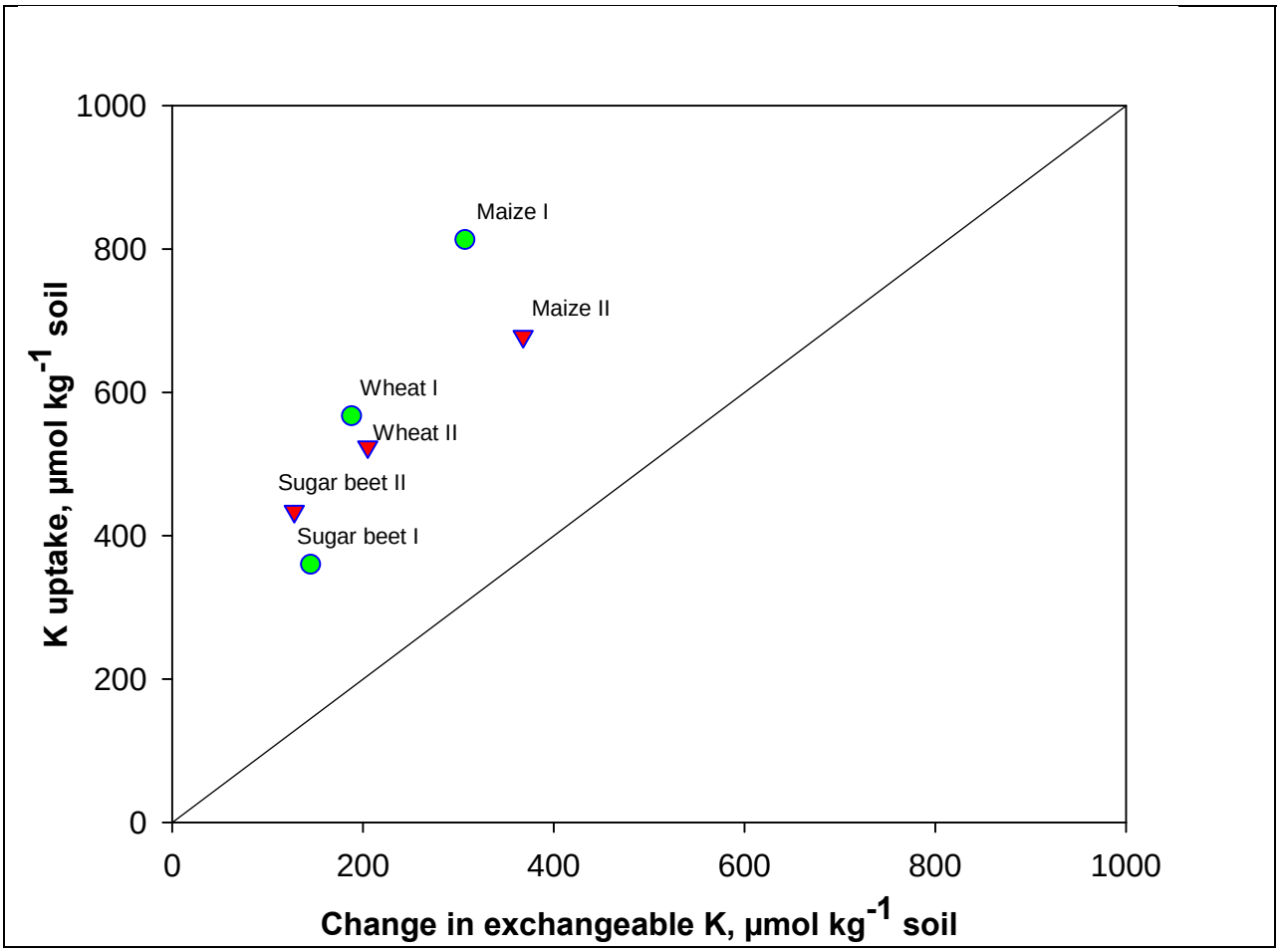

Figure 5. Potassium (K) uptake of maize wheat, and sugar beet and corresponding change in measured soil exchangeable K. Plants were grown on a low available K Taintor silty clay loam soil and harvested two times. (Modified from Samal et al., 2010).

Improving Potassium Rate Recommendations by Recognizing Soil Potassium Pools with Dissimilar Bioavailability

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Abstract
Four pools of potassium (K) in soil are often described: solution K, exchangeable K, interlayer (sometimes referred to as 'fixed' or 'non-exchangeable') K and structural K in primary minerals. Two additional pools may also occur: K in neoformed minerals and K in crop residues. While K from all pools can contribute to plant K acquisition over different time-frames, most commercial laboratory tests typically quantify the combined soil solution and exchangeable K pools as an indicator of plant available K status. These pools typically only represent 1-2% of total soil K but are assumed to be the most readily available to plants. A variety of factors can affect the interpretation of this measure of plant available K in contrasting soil types including CEC, clay content, layer-silicate mineralogy, organic matter concentration, pH and the tortuosity factor (rate of diffusive supply), with local fertilizer decision support systems typically taking into account the net effect of key factors in soil-specific interpretations. However in some soils the soil solution/exchangeable K pools are buffered by the interlayer and structural/mineral K pools, effectively acting as plant available K 'reserves' in times of rapid uptake or, in the case of the interlayer K pool, as a sink for K after fertilizer application. The release of K from these reserve pools is typically inadequate to meet total plant demand during a growing season, but their contributions to the soil solution can significantly reduce the crop fertilizer K requirement. While seasonal factors such as soil moisture fluctuations can influence the availability of interlayer and mineral K, crop-specific factors such as root system morphology (viz. root length densities and specific surface area) and exudation of organic acids can significantly increase access to these reserve K pools. This paper presents examples of how more detailed quantification of soil K pools may improve the ability to predict fertilizer K requirements.

INTRODUCTION

The development of improved K fertilizer recommendations will be based on a combination of an understanding of crop-specific nutrient budgets (i.e., the rate of crop removal), the likelihood of a yield response to applied K fertilizer, and an economic cost:benefit analysis of the return from fertilizer investment. The outcome of this analysis will vary with the normal economic factors (relative costs of fertilizer and value of produce), but also with the crop producer's attitude to risk (how certain do producers need to be that they will get a response to applied K) and the time-frame under consideration (i.e., a return from the current crop, over the crop cycle, or simply maintenance of background fertility reserves). Clearly there can be a number of answers regarding a fertilizer decision for the same field under the same seasonal conditions, but despite this ambiguity there is a fundamental requirement underlying all options – an ability to predict the phyto-available soil K reserves that are available to the crop in the coming season.

Traditionally, soil testing has been used to assess the nutrient status of a soil relative to a critical value below which fertilizer responses are more likely, with those values determined on the basis of potential yields in the absence of that nutrient limitation, usually targeting 90 to 100% of the yield potential when the nutrient is not limiting. However, there are no widely accepted standards concerning how a critical value or range is determined or what percentage of the maximum yield is considered because research data may fit alternative models equally well; economic variables may also be considered (Mallarino and Blackmer, 1992, Mallarino and Blackmer, 1994, Dyson and Conyers, 2013). Moreover, the limitations of soil sampling procedures (sampling depth relative to where root activity and nutrient uptake occur and seasonal restrictions to crop demand) have been well documented (Conyers, 1999). The resulting uncertainties in interpretation have led to the use of critical soil test ranges rather than absolute values (Dyson and Conyers, 2013). However, an even bigger uncertainty lies in the inadequacy of existing soil tests to target particular pools of nutrients available for plant uptake (Conyers, 1999), and this is especially relevant for K. Most tests of soil K status focus on quantifying only the solution and exchangeable K pools as surrogates for plant available K (Fig. 1), despite this approach clearly having limitations that hinder extrapolation among sites and soil types. Given the uncertainties and economic risks, this approach can work surprisingly well in many cases. This paper evaluates the benefits and limitations of this approach, assesses the feasibility and techniques for measuring other K pools, and the potential benefits this additional effort may provide in terms of improving K fertilizer recommendations.

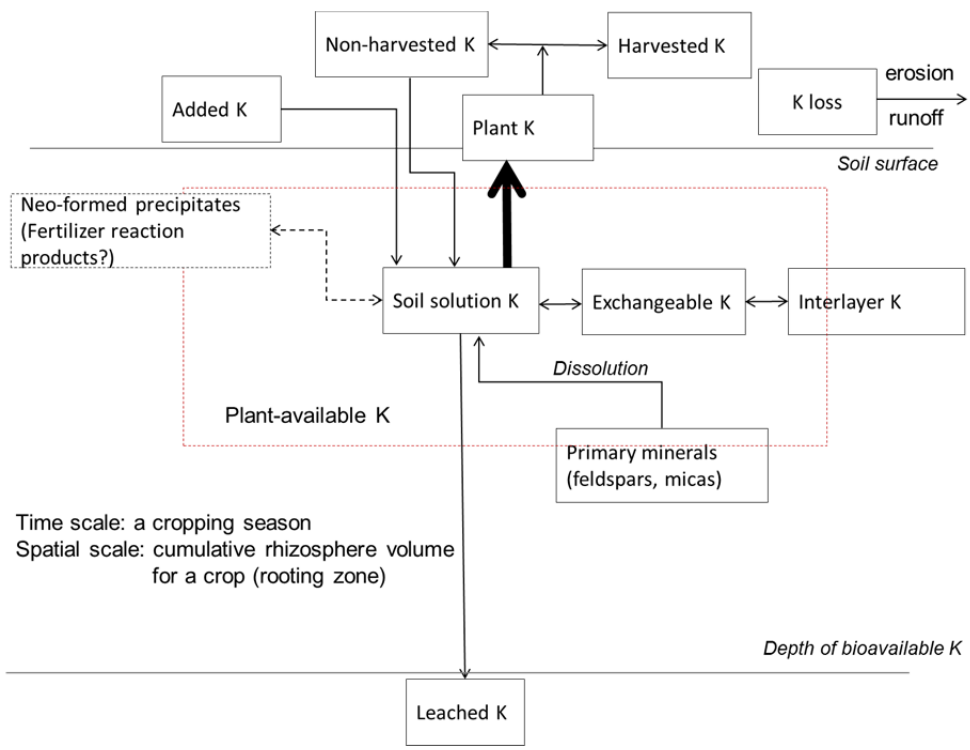

Figure 1. Diagrammatic representation of the K cycle, identifying the soil K pools and fluxes in soil-plant systems discussed in this paper.

POOLS OF K – CONCEPTUAL DIAGRAM AND FLUXES

A conceptual diagram of the K cycle was developed at the First Frontiers in Potassium Science Workshop in Hawaii in 2015, and this highlights three conceptual soil K pools that are linked to plant K uptake through the soil solution K (Fig. 1). We have inserted a fourth soil K pool to account for fertilizer reaction

products (such as taranakites) which may be present as a result of repeated applications of high-K waste materials or application of high rates of band-applied compound fertilizers along with K. Estimates of the relative sizes of the different K pools have been provided in various publications [e.g., Oborn et al. (2005); Hinsinger (2006)], with K in primary minerals (90-98% of total soil K) the dominant form of soil K. Interlayer K in secondary minerals can also be a significant proportion (1-10%, depending on mineralogy), but the most readily available K for plant uptake [exchangeable K (1-2%) and solution K (0.1-0.2%)] represents only a very small fraction of the total soil K.

Whilst these pools are well recognized, it is only the exchangeable K pool, and to a lesser extent the soil solution K, that have well developed diagnostic methods for quantification of pool sizes – albeit recognizing the dynamic equilibrium that exists between these more readily available K pools and the interlayer and mineral K pools that exist in many soils with appropriate mineralogy (Syers, 2003). Procedures used to estimate the mineral and interlayer K pools, such as extraction with sodium tetraphenyl boron ($NaBPh_4$) (Scott et al., 1960) or boiling nitric acid (HNO_3) (Helmke and Sparks, 1996), are typically unable to differentiate between K sourced from either pool (Goulding, 1987, Ogaard et al., 2001) and are sometimes collectively referred to as 'non-exchangeable K' (Hinsinger, 2006). However, a more recent paper by Wang et al. (2016) suggested that differentiation may be possible utilizing time trends of K release with repeated extractions using $NaBPh_4$.

SOLUTION K AND K ACTIVITY – RELEVANCE TO PLANT K SUPPLY

Unless mineral soils have been recently fertilized or amended with manure, soil solution K concentrations are typically low (100-1000 µM) as a result of selective adsorption of K by some clay minerals (Hinsinger, 2006), with Mouhamad et al. (2016) noting that concentrations are more typically at the higher end of this range in soils in arid regions. Thus K is relatively immobile in mineral soils with 2:1 minerals, and leaching losses are commensurately low unless K fertilizer has been recently applied to soils with low cation exchange capacities.

Soil solution K is the form taken up directly by plants (Sparks, 1987), with soil solution concentrations determined by the kinetic reactions with other forms of soil K, soil moisture content and the other cations on the exchange complex and in the soil solution (Sparks and Huang (1985). The small amount of K present in the soil solution in all except recently fertilized soils suggests that the contribution of K uptake from this initial pool is likely to be limited and increasingly less important as plant uptake depletes the small solution K stocks (Barrow, 1966). More important are the rates of K diffusion in the soil solution from surrounding undepleted soil and the quantity of readily-desorbable K on the exchange complex (Evangelou et al. (1994); Barber (1995)). The moderating effects of other major soil solution cations (Ca, Mg and Na) on the kinetics of soil solution K replenishment and subsequent uptake of K by plant roots have been the subject of extensive research [reviewed by Sparks (1987) and Evangelou et al. (1994)], but the complex interactions between soil solution chemistry, rooting density and subsequent competition for K uptake make extrapolation beyond the specific conditions of individual experiments difficult (Barber, 1995). There is, however, a general recognition of the importance of cation exchange capacity (CEC) on both the ability of the soil to buffer soil solution K (BC_K) and also on K supply to the root (Barber, 1981), with less K available for plant uptake in soils with the same exchangeable K as CEC increases (Bell et al., 2009). These relationships have currently not been well defined.

Techniques for quantifying soil solution K (and other solution cations) are well developed [e.g. Sparks (1987); Moody and Bell (2006)], but they are rarely used to predict the K status of a soil and the need for K fertilizer applications. The fact that most other soil K measurement techniques intrinsically include solution K and are better related to the quantity of K that a plant will be able to exploit during a growing season makes the routine measurement of soil solution K somewhat redundant.

EXCHANGEABLE K AS A READILY AVAILABLE K POOL

Exchangeable K refers to the pool of K that is in a form immediately available for movement into the soil solution in response to depletion by plant root uptake (Barber, 1995). Most soil tests for exchangeable K are based on exchange with an excess of ammonium ions, as noted below. In soils that have limited mineral K sources, exchangeable K is effectively an index of the capacity of the soil to supply bioavailable K over an extended period. The exchange of K with other cations can be rapid and highly reversible, depending on the type of clay minerals, the amount of organic matter and the specificity of K adsorption sites [Mengel (1985), Sparks (1987), Lin (2010), Römheld and Kirkby (2010)]. For example, the rate of K exchange on kaolinite and montmorillonite is usually quite rapid (Sparks and Jardine, 1984), while on vermiculite and micaceous minerals it tends to be much slower (Sparks, 1987).

In situations where clay mineralogy allows significant short- or long-term fixation of interlayer K (discussed later), the rates of exchange are variable and difficult to predict, depending on the minerals involved and the specificity of fixation sites for K. Exchange rates have been related to the proportions of planar, wedge and interlayer exchange positions and their affinity for K (Mengel, 1985). Release rates can be slow (Bertsch and Thomas, 1985, Barber, 1995), but Carey and Metherell (2003) found a two-stage release of interlayer K that they related to wedge zones (rapid) and true inter-layer positions (slow).

The factors that influence the reliability of exchangeable K measurements as predictors of bioavailable K in soils are well known, and they include the total mass of K on the exchange complex modified by the CEC, clay concentration, layer-silicate mineralogy, organic matter concentration, redox potential and soil pH (Tinker and Nye, 2000). Some of these factors which affect pore size distribution (such as clay content and clay mineralogy) may also have secondary effects on water movement and pathways by which K moves towards plant roots. If the soils being considered represent a narrow range of locations and mineralogies (Syers, 2003), measured amounts of ammonium-exchangeable K can be a very good indicator of plant available K (Johnston et al., 1998), although not all the exchangeable K pool may be extractable by plants. Schneider et al. (2016) proposed the concept of a lower accessible limit of the exchangeable K pool below which plants may not able to extract K (the ‘plant minimal exchangeable K’), and found the size of this fraction to increase with increasing CEC. This suggests that the ‘plant minimal exchangeable K’ could be a surrogate for a ‘plant minimal solution K concentration’ below which plants are unable to take up K, and that as CEC increases the number of tightly held K-specific adsorption sites also increases.

Analytical methodologies for determining exchangeable K are well developed and widely used in soil testing laboratories. The most widespread are based on the displacement of K with NH_4^+ (NH_4OAc, NH_4Cl or NH_4NO_3), but other extractants [e.g., Bray 1 and 2 (Römheld and Kirkby, 2010), 0.5M $NaHCO_3$- extractable K (Gourley, 1999)] have also been calibrated to specific soils and cropping systems. Differences between the extractants with respect to reproducibility are reported as being only marginal (McLean and Watson, 1985), although there have been many reports that sample handling, especially sample drying (Mallarino et al., 2014), can have a significant impact on exchangeable K determinations in some soils.

MINERAL K

Barber (1995) listed the main forms of mineral K found in soils as micas (specifically biotite and muscovite), feldspars (orthoclase and microcline) and secondary clay minerals, and noted that while absolute K release rates from the primary minerals were slow, the relative order of K release was biotite > muscovite > orthoclase > microcline (Rich, 1968). Song and Huang (1988) noted that this order may be altered in the presence of organic acids (oxalic and citric acids) that can be exuded into rhizospheres around plant root systems.

The release of K from feldspars occurs as a result of irreversible dissolution of the mineral's framework during weathering, while that of micas starts in a similar fashion, but also includes loss of interlayer K as layer charge declines (Barber, 1995, Hinsinger, 2006). During weathering of mica grains, the net negative charge in the layers goes down, allowing not only K to be released from interlayer positions but also allowing for freer exchange of other cations in the interlayer region. Gradually, the weathering dissolution of micas leads to formation of vermiculite and smectite (Thompson and Ukraincyk, 2002).

Low soil solution K concentration is an important driver for the release of K through mineral dissolution, with plant roots playing a key role in depleting soil solution K concentrations in the rhizosphere. Hinsinger (1998) reported that solution K concentrations can decrease by 2-3 orders of magnitude to as little as 2-3 µM in the vicinity of plant roots, and at these concentrations the release of non-exchangeable K can occur at high rates (Springob and Richter, 1998). However it is also clear that this dissolution process is accentuated under acidic conditions. Plant roots are able to exude a variety of organic acids depending on species [e.g. citric and oxalic acid in maize (Pellet et al. (1995), malic acid in rape – (Hoffland et al. (1989), tartaric acid from pak choi (Wang et al. (2000) and radish (Zhang et al. (1997)], and so can further accelerate the dissolution of mineral K. Zörb et al. (2014) suggested that the generation of these exudates is driven by soil solution K concentration, initiating when K concentrations fall to <10 - 20 µM.

INTERLAYER K

Interlayer K is held between phyllosilicate sheets in 2:1 clay minerals, and is typically found in high K-affinity positions (Hinsinger, 2006) from which rates of exchange are quite slow. Smectite and vermiculite are the major clay minerals involved in such reversible fixation of K (Sparks, 1987). The process is governed primarily by the soil solution concentrations of K and competing cations, with the action of plant root uptake (depletion) or fertilizer application (enrichment) determining the net impact on the dynamics of interlayer K (Schneider et al., 2013). The process of fixation and release has been well described in Hinsinger (2006), with release facilitated by the expansion of interlayer spaces when K is replaced by cations with larger hydrated radii (e.g., Ca^{2+} and Mg^{2+}), and fixation when the interlayer spaces contract when cations with lower hydration energies (e.g., K^+ and NH_4^+) return to interlayer positions.

The processes of K interlayer fixation have been studied extensively, due to the focus on exchangeable K as a measure of the bioavailable K pool and the apparent inefficient use of applied K fertilizer in soils where K fixation occurs [e.g. Kovar and Barber (1990)], but there has been less focus on the release process. Sparks (1987), Barber (1995), Oborn et al. (2005), Hinsinger (2006) and Zörb et al. (2014) provide detailed reviews of much of this work, with key points including: (i) release of fixed interlayer K is limited to the effective diffusion distance around roots and root hairs – the zones of greatest solution K depletion, but typically representing <2.5% of the soil volume; (ii) the processes of interlayer fixation and release are strongly affected by soil moisture and by soil solution K concentration; and (iii) release is also favored by a high concentration of H^+ ions (i.e., low pH).

Soils with mineralogy that enables interlayer fixation and release processes can significantly increase the uncertainty of a fertilizer K decision. As noted by Hinsinger (2006), numerous long-term fertilizer trials have demonstrated net release of non-exchangeable K in unfertilized plots, but whether this has been from primary mineral or secondary mineral K pools cannot be determined due to the lack of a definitive soil test that differentiates between the two. Furthermore, in many cases, the soil sampling strategy in these long-term studies is inadequate to rule out depletion of subsoil layers as the source of additional K removed [Kuhlmann and Barraclough (1987), Prasad (2009)], rather than the depletion of non-exchangeable K reserves from the sampled (surface) soil layer. The evidence for the extent of K fixation in some long-term fertilized treatments [e.g., the Rothamsted site in Blake et al. (1999)] is more conclusive, although again the potential for K uptake to be derived from deeper soil layers (rather than

release from secondary mineral interlayer positions) could not be discounted due to the soil sampling depths analyzed.

NON-EXCHANGEABLE K – A FUNCTIONAL POOL BASED ON CURRENT ANALYTICAL LIMITATIONS

The current lack of analytical techniques that can successfully differentiate between K that resides in the mineral K (including neo-formed K minerals) and interlayer K pools shown in Figure 1 presents real problems for predicting the size and behavior of these potentially bioavailable sources of plant K. The two predominant techniques that are used (extraction with boiling HNO_3 or NaTPB) have both been shown to extract K from either pool, or both if they are present in the same soil type (Goulding, 1987). As a result, the bioavailability of the additional K extracted by either method (above that measured in an exchangeable K extract) is unknown and likely to vary considerably with soil type [e.g. Moody and Bell (2006)].

Hinsinger (2006) noted that primary and secondary mineral pools typically represent 90-99% of total soil K and that they are dominated by structural K in feldspars and interlayer K (high K-affinity sites) in micas and minerals derived from micas. However, as these K pools are not able to be easily differentiated in diagnostic assays, Hinsinger (2006) suggested they could be referred to collectively as 'non-exchangeable K'. This approach has merit, as it recognizes the current limitations and uncertainty surrounding diagnostic testing and the variability in interpretation of soil test results across soil types with differing mineralogies.

The quantity of released non-exchangeable K has been estimated at up to 100 kg K ha^{-1} $year^{-1}$, or 80-100% of soil K supply, by (Hinsinger, 2006), far in excess of the geochemical estimates of K dissolution rates of 5-15 kg ha^{-1} $year^{-1}$, because the latter typically fail to account for K uptake by vegetation. It was concluded that considerable amounts of non-exchangeable K can contribute to meeting plant K demand in many agricultural systems, and may even represent a significant proportion of total uptake. The contributions of interlayer and primary mineral K to uptake will obviously vary with soil type and mineralogy. For example, Moody and Bell (2006) demonstrated a significant contribution of non-exchangeable K (measured as the difference between exchangeable K and K extracted using NaTPB) to plant uptake in some soils, but effectively no contribution in others. Subsequent work (Moody and Bell, unpublished) has indicated that the majority of the non-exchangeable K removed by a variety of plant species in the 15-30 soils studied was from mineral K pools, rather than by release from interlayer positions.

Exhaustive cropping remains the most effective way of quantifying the bioavailable fraction of non-exchangeable K, and even then the results may vary considerably with crop species (and perhaps even genotypes) and experimental conditions, for reasons outlined earlier.

IMPLICATIONS FOR SOIL TESTING AND K FERTILIZER DECISIONS

Understanding the size and availability of the phyto-available K reserves in soils will be a key factor in the development of an effective fertilizer application strategy, but given the different pools of K that will be present in soils with different mineralogy, it is improbable that a single diagnostic soil test will provide an accurate assessment. The exception to this will be in the situations where soil K reserves are almost exclusively in the soil solution and exchangeable K pools, where the current exchangeable K soil tests (displacement of K^+ with NH_4^+) will provide a reasonable indicator. Even in these situations, there will be a number of 'modifiers' that will influence the critical soil test range below which a response to applied K is likely for crop-specific (e.g., genotype or species - see White and Bell, these proceedings), soil type-specific (clay content, competing cations and CEC) or region-specific (water availability, tillage practices) circumstances. An additional compounding factor in even 'simple' systems is the depth of soil sampling, as there is clear evidence that significant proportions of plant K uptake can occur from soil

layers that are not traditionally sampled in testing programs (i.e., below the plough layer in tilled systems, and below the top 10-15cm in no till systems). For example, research with long-term experiments in Iowa has shown that the relative amounts of soil-test K and non-exchangeable K (NaTPB) varied greatly at different soil depths as affected by the soil series, K fertilization, and K removal by corn and soybean (Villavicencio and Mallarino, 2011).

In soils where either interlayer K or mineral K or both contribute to the phyto-available K stocks, there is clearly a need to identify that those pools exist, and to characterize: (i) the potential release rates and contribution to plant K uptake and, (ii) the likely dynamics during a growing season (in the case of soils where either interlayer fixation or release can occur in sequence, or even simultaneously in different microsites in the soil matrix, depending on root density and/or microbial action). This will require the adoption of multiple diagnostic tests on the same soil sample, with the difference between the quantum of exchangeable K and the chosen measure of nonexchangeable K (NaTPB or HNO_3, for example) related to the quantity of additional, potentially available K that is released slowly during the growing season. Briefly summarized, previous work in Iowa (Clover and Mallarino, 2009) has shown that in several soil series, only the measurement of soil-test K and NaTB K appropriately explained the effects of K additions and removal by corn and soybean on post-harvest soil K levels.

This information can already be a useful way of exploring the uncertainty in the range of critical exchangeable K soil test values, in that soils with high, relatively available reserve K stocks may have lower critical exchangeable K values due to in-season K release. However, the value of diagnostic methods as a guide to fertilizer practice could be substantially improved if they could: (i) assess the release rates at realistic soil solution concentrations in the rhizosphere [i.e. 2-10 µM - Hinsinger (2006), Zörb et al. (2014)], and (ii) differentiate between interlayer K and primary-mineral K. The former would seem to have far less predictable release rates under field conditions and also has the potential to reduce the availability of applied K fertilizer. The recent work by Wang et al. (2016) and unpublished results by Moody and Bell (pers. comm.) suggest that repeated or graded extractions by NaTPB may offer some scope with respect to the former, while development of something like a single-point K buffer index [analogous to the equivalent P buffer index developed to interpret soil P tests (Moody, 2007; Murashkina et al., 2007)] may help to identify the potential for K fixation and hence the presence of interlayer K mineralogy.

Even with these advances, the biggest challenge for improving the reliability of fertilizer K decisions and the likelihood of an economic response will remain in soils where the mineralogy supports a significant interlayer K pool. The uncertainty in predicting the net effect of interlayer fixation or release on K availability under variable field conditions, combined with the likelihood that if interlayer reserves are strongly depleted then the balance will favor fixation of applied K, ensure that conservative K replacement strategies will need to be adopted. Ensuring that soil K availability can be maintained with relatively low and frequent maintenance rates, rather than depleting K reserves and trying to catch up with high rates and inefficient plant K recovery, would seem a sensible strategy. Selling such a strategy to cash-poor farmers may prove a challenge.

CONCLUSIONS

A better understanding of the phyto-available K pools in agricultural soils will allow the development of more defensible and economically justifiable fertilizer recommendations. This will particularly apply to soils where there are significant amounts of non-exchangeable K in either (or both) of the primary mineral or secondary interlayer pools. The development of such an understanding will require the use of a combination of diagnostic soil K tests in addition to measures of the exchangeable K pool. While this will increase the costs of soil testing, the greater certainty provided around understanding the K status of the particular field under management will add considerable confidence to fertilizer decisions.

Unfortunately the interpretive guidelines for the current suite of diagnostic soil tests in common use are not sufficiently developed to allow immediate adoption, and they are also not suitable for differentiating between mineral and interlayer K – pools which behave quite differently in terms of the dynamics of K release in response to plant K uptake. Further research is clearly required on this topic, as is research on soil sampling protocols that allow quantification of K status in the soil layers from which the crop accumulates significant quantities of K. This is increasingly important given the stratification of soil K under no till cropping systems.

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A New Chemical Grading System for Plant-Available Potassium in Soils

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Abstract

A new grading system for plant-available potassium (K) in soils based on K release rate from soils and plant growth indices was established. In the study, fourteen different agricultural soils from the southern subtropical to the northern temperate zones in China were analyzed by both chemical extraction methods and exhaustive cropping techniques. Based on the change trends in plant growth indices, relative biomass yields of 70% and 50%, K-deficient coefficients of 35 and 22 under conventional exhaustive experiments, and tissue K concentrations of 40 g kg^{-1} and 15 g kg^{-1} under intensive exhaustive experiments were obtained as critical values that represent different change trends. In addition, the extraction method using 0.2 mol L^{-1} sodium tetraphenylboron (NaTPB) suggested soil K release rates of 12 mg kg^{-1} min^{-1}, 0.4 mg kg^{-1} min^{-1} and 0.1 mg kg^{-1} min^{-1} as turning points that illustrated four different release trends. Thus, plant-available K in soils was classified into four categories: high available K, medium available K, low available K and non-available K, and grading criteria and measurement methods were also proposed. This work has increased our understanding of soil K bioavailability and has direct application in terms of routine assessment of agriculture soils.

INTRODUCTION

The importance of potassium (K) in both plant growth and soil fertility is widely recognized and has a close relation to the long-term sustainability of the soil in which a plant grows (Öborn et al 2005; Römheld and Kirkby 2010; Zörb et al 2014; Kulcheski et al 2015). Hence, characterizing the soil K reserve and its availability to plants is important in determining the K supplying capacity of soils. Currently, soil K is understood to exist in four distinct K pools that differ in their accessibility to plant roots, with reversible transfer of K between the pools (Sparks 1987; Öborn et al 2005; Römheld and Kirkby 2010; Zörb et al 2014). The soluble and exchangeable forms are regarded as rapidly available forms of K: they are replenished by non-exchangeable K (NEK) when they are depleted as a result of plant removal and/or leaching (Mengel 2001; Römheld and Kirkby 2010; Zörb et al 2014), and perhaps by large increases in microbial activity (Cox et al 1999; Prakash et al 2002). Wang et al. (2016) reported that the amounts of maximum NEK accounted for 21%–56% of the total K of the soils tested. NEK in soil is bound coulombically to negatively charged clay interlayer surface sites and this binding force exceeds the hydration forces between individual K^+ ions (Sparks 1987; Moritsuka et al 2004). The plant availability of NEK depends primarily on the rate at which it can be released as more labile forms (i.e., both exchangeable and soluble) (Havlin and Westfall 1985; Cox and Joern 1997). Some researchers suggest that the more rapidly NEK is released, the more easily it is utilized by plants (De et al., 1993; Cox and Joern 1997; Sarkar et al 2016). However, there are currently no assessment methods or theories available for grading NEK bioavailability (Wang et al 2016).

Suitable method is a key for developing sound guidelines for evaluating soil K bioavailability. An estimation of rapidly available K by extracting the soil with neutral ammonium acetate, ammonium chloride, calcium chloride, or ammonium fluoride (Mehlich 3) is the most widely used soil test (Barbagelata and Mallarino 2013). Measuring plant-available soil K that is released from NEK reserves is difficult because of the complexity of the dynamic equilibriumamong the various forms of soil K during crop growth. Nevertheless, various methods have been established to assess the slowly or potentially available K in soils; for example, extraction by 1 M HCl, boiling in 0.5 M or 1 M HNO_3 (Ghosh and

Singh 2001; Ogaard and Krogstad 2005; Andrist-Rangel et al 2013) and sodium tetraphenylboron (NaTPB) (Cox and Joern 1997; Carey and Metherell 2003; Wang et al 2010; Holland et al 2014; Wang et al 2016). However, the dilute or concentrated acids extracting methods, on the one hand, may underestimate soil available K supply capacity; on the other hand, extract some structural K which cannot be utilized by plants (Simard and Zizka 1994; Li et al 2015). The NaTPB method allows flexibility as a soil test because the extraction (incubation) time can be varied to alter the amount of K release. It can also take both exchangeable and a portion of non-exchangeable K into account and, thus, would appear to be a good choice to use to determine the relation between the release rate levels of K and the grading of plant-available K in soils.

The hypotheses of the present study were: (i) both the amount of K released into the soil solution and its availability to plants are controlled by the soil K release rate; and (ii) a new grading system for soil plant-available K can be established according to the relations between soil K release characteristic, plant K absorption, plant biomass yield, and K concentration in plant. Thus, the objectives of this study were to: (i) grade plant-available K based on the exhaustion of ryegrass (*Loliumperenne* L.); (ii) rank soil K according to its release characteristics by using NaTPB; and (iii) find the gradations of K deliverability from soil K release rate from soils and plant growth indices.

METERIAL AND METHODS

Experimental soils. Seven types of arable soils collected from 14 sites spanned from the southernsubtropical to the northern temperate zones in China were included in this study (Table5). Surface soil of 100 kg (0–20 cm) were taken from the plough layer (Ap horizon) during the summer of 2013 after harvest of the crop. Each soil sample was air-dried and ground to pass througha 10-mm or 2-mm sieve; the 10-mm sieved soils (about 60 kg) were prepared for pot exhaustive experiments, and the 2-mm sievedsoils (about 1.5 kg) were prepared for soil analysis. The soil properties were measured according to the standard methods (Lu 1999).

Acquisition of soil potassium by using crops. As a reference for plant-available K content in soil, conventional and intensive exhaustive experiments both cropping with perennial ryegrass were chosen. Under conventional exhaustive experiment, the soils (5.0 kg) were put in plastic pots 20 cm in diameter and 20 cm deep and arranged in a completely randomized experimental design with three replicates. There were two K treatments: (i) no K fertilizer was applied throughout the experimental period; and (ii) potassium sulfate (200 mg K kg^{-1} soil) was applied as a K fertilizer. To ensure that the general nutrient supply did not limit plant growth, basal nutrients were applied initially and after each harvest (Cox et al 1999; Darunsontaya et al 2012; li et al 2015). The first basal application was given before initiation of the experiment and soils were allowed to equilibrate for 1 week at field capacity; they were watered with deionized water every 1–2 days to maintain soil moisture close to 80% of field capacity throughout the pot culture period. The whole experiment was carried out in a greenhouse with ambient light at a temperature range of 15–35°C. Ryegrass seeds of 2.5 g were cropped in each pot and the aboveground parts of the plants were harvested after they had grown for 30 d. After harvest, the soil in each pot was thoroughly mixed, the roots of the ryegrass were cut into 0.5–1 cm segments and then returned to the soil before repotting. Ryegrass ultimately died prior to the ninth harvest for WC and GD soils due to K deficiency, and it could not survive to the eleventh harvest of HEB and JM soils due to management misconduct behavior, whereas 12 crops were collected on the other 10 soils.

To enable the rapid removal of K by cropping, an intensive exhaustive experiment was conducted. The soils (5.0 kg) were put in plastic pots measuring 40 cm × 20 cm × 10 cm (length× width× height). Management measures were the same as conventional exhaustive experiment but with no replicates and no K fertilizer. Ryegrass seeds (3.5 g) were cropped in each pot. The aboveground part of the ryegrass (>5 cm in height) was harvested after its length exceeded 20 cm, then harvested again when the length exceeded 20cm again until the ryegrass could no longer grow in the pot. The experiment was repeated,

sowed anew. Ryegrass could not survive for 14 crops without external K when it grew on the soils of GA, WC, JY and GD, whereas 15 crops of ryegrass were collected from the other ten soils.

The biomass of each crop of ryegrass was determined after the leaves were oven dried to a constant weight. Ryegrass leaves were digested with H_2SO_4–H_2O_2 for K determination (Lu 1999). Plant biomass yield (BY) and K concentration (Kc) were used to determine plant K absorption (Surapaneni et al 2002; Barbagelata and Mallarino 2013; Holland et al 2014). Cumulative K uptake was the summation of plant uptake for each crop harvest (li et al 2015).

Extraction of soil potassium with NaTPB.The procedure followed for the NaTPB method to extract soil K was similar to that described by Cox et al. (1999), Wang et al. (2010) and Li et al. (2015). In order to predict the plant-available K in different soils, we used two types of extraction method: the first was weak (less amount of K was extracted) and the second was strong (more amount of K was extracted). Samples of 0.5 g soil, in triplicate, were weighed into 50-mL centrifuge tubes. For the weak extraction, 3 mL 0.2 mol L^{-1} NaTPBwas added and then the tubes were shaken at 200 rpm for each incubation period (5 s, 10 min, 0.5 h, 1 h, 2 h, 4 h, 8 h, 12 h, 24 h, 48 h, 96 h, and 144 h). For the strong extraction method, 3 mL 0.2 mol L^{-1} NaTPB + 1.0 mol L^{-1} NaCl were added to the tubes, which were then shaken at 200 rpm for extracting period of 1 h. Following the final incubation period in each method, 25 mL quenching solution (0.5 mol L^{-1} NH_4Cl + 0.14 mol L^{-1} $CuCl_2$) was added to the tubes to stop the extraction of soil K. The tubes were then heated in boiling water for 60 min to dissolve the potassiumtetraphenylboron (KTPB) precipitate, after which the suspension was vacuum filtered through membrane filters and stabilized by the addition of 1-mL 6 M HCl. The K solution was then measured with a flame photometer.

Statistical analyses. All data are the mean of three repetitions (n=3). Simple linear correlations and nonlinear regressions between variables were calculated using the Linear and Nonlinear Regression functions of SigmaPlot 12.0, respectively. Principal component analysis (PCA) was applied using SPSS software version 20.0 (SPSS Inc., USA) to consider ryegrass growth indices and to confirm their weights to evaluate the K-deficient coefficient of ryegrass under a conventional exhaustive experiment (Mukhopadhyay et al 2016). The principal components extracted from the variables were retained on the basis of the Kaiser criterion of eigenvalues > 1.00.

RESULTS

Acquisition of potassium by conventional exhaustive experiment. Plant biomass yield is a key factor for describing K bioavailability in soils. As indicated by the relative biomass yield (RBY) from all crops (Fig. 1), the ryegrass only grew well on the SHZ, CW (Changwu, Shanxi), and BB (Beibei, Chongqing) soils, with the mean RBY of 12 crops grown during the study varying from 82% to 98%, followed by ryegrass grown in soils in HEB, LY, and JM, with values from 74% to 82%. On soils in FQ, MC (Mengcheng, Anhui), NA (Nanan, Chongqing), JY (Jiangyan, Jiangsu), and CS (Changshu, Jiangsu), the growth of ryegrass was seriously stunted and the mean RBY varied from 51% to 72%. Ryegrass died before the ninth harvest in WC and GD soils because of K deficiency, so there are no data for any subsequent harvests.

The RBY during the growth period decreased slightly if its values were >70% (Fig. 1), but decreased substantially when its values varied from 50% to 70%. However, when the values of RBY were <50%, the curves began to flatten. Thus, RBYs of 70% and 50% were determined to be critical values in the current study.

Values of RBY, tissue K concentration (Kc), relative K concentration (RKc), and relative K uptake (RKu) for ryegrass were occasionally erratic because of differences in the physical characteristics of the soil, which affected the drainage and aeration in the pots[7]. Principal component analysis (PCA) was applied to evaluate the K-deficient coefficient of ryegrass under a conventional exhaustive experiment by

considering all the growth indices (eigenvalues > 1). The results showed that 85 % of the total variance was explained by the first principal components (PCs) (Table 2). The weights of these indicators were assigned based on the percent variance explained by the particular PC. For correlated variables, the weights were divided equally; thus, 3.400 eigenvalues from PC-1 were divided among RBY, Kc, RKc, and RKu. Equation 1 explains the PCA-based K-deficient coefficient index:

$$\text{K-deficient coefficient} = 0.489\ (RBY) + 0.471\ (Kc) + 0.515\ (RKc) + 0.523\ (RKu) \quad [1]$$

The weight values were normalized to a 0–1 scale by dividing each weighted factor by the total weighted factor (∑wi, 1.998; Equation 2).

$$\text{The final K-deficient coefficient} = 0.245\ (RBY) + 0.236\ (Kc) + 0.258\ (RKc) + 0.261\ (RKu) \quad [2]$$

We established the relation between RBY and the K-deficient coefficient of ryegrass under a conventional exhaustive experiment (Fig. 2). A statistically significant correlation ($p < 0.01$) showed that RBY decreased with a decreasing K-deficient coefficient of ryegrass, indicating that K deficiency was the most important growth-limiting factor in our exhaustive experiment. A logarithm equation was found to best describe the relation between RBY and the K-deficient coefficient of ryegrass ($R^2 = 0.891$) (Fig. 2). The critical values of the RBY (70% and 50%) were used to grade the K status in soils to judge available K supplication to plant growth. According to these parameters, the ryegrass K-deficient coefficients of 35 and 22 were obtained as inflexion points in the current study.

Acquisition of potassium by intensive exhaustive experiment. The trends for growth indices of ryegrass grown on different soils under an intensive exhaustive experiment were similar to the trends observed under the conventional exhaustive experiment (Fig. 3). Ryegrass could not survive to produce a 15th crop without external K when it grew on GA, WC, JY and GD soils. The greatest tissue Kc of ryegrass occurred in plants grown in SHZ, CW, HEB, BB, and JM soils for the first to the final harvest, followed by LY, FQ, NA, and CS soils. The cumulative K uptake at the 15th or 14th harvest ranged from 140.5 mg kg^{-1} to 1719 mg kg^{-1} with a mean value of 747.6 mg kg^{-1}.

Fig. 3 shows the relation between tissue Kc and Ku of ryegrass grown in different soils. On average, when the values of Kc were >40 g kg^{-1}, the Ku of ryegrass increased rapidly, and varied from 138 mg kg^{-1} to 1358 mg kg^{-1}. When the values of Kc varied from 15 g kg^{-1} to 40 g kg^{-1}, the Kc of ryegrass decreased quickly, but the amounts of Ku only increased slightly. When the values of Kc were <15 g kg^{-1}, the decrease in Kc and increase in Ku were both slow. Thus, we assumed that the tissue Kc of 15 g kg^{-1} and 40 g kg^{-1} were as turning points in the intensive exhaustive experiments.

Soil plant-available potassium extracted by NaTPB. To obtain appropriate amount of soil K for predicting soil plant-available K, weak and strong extraction methods were used. For the strong extraction method, it extracted higher amount of soil K than by the weak extraction method and only could use to predict the total amount of plant-available K in soils. Thus, we did not discuss it in this section for the main purpose at there was to rank the soil plant-available K.

For the weak extraction, cumulative K released ranged from 230.7 mg kg^{-1} to 2689 mg kg^{-1}, which possibly reflects differences in mineral composition at the different locations[29]. The cumulative released K in soils mainly comprising illite (average of five soils = 1836 mg kg^{-1}) was, on average, 3.2 times more than the cumulative K released in soils where the major mineral was chlorite or smectite (Fig. 4). In all soils, the amount of K released after 5-s and 144-h extraction was 1.2–2.2 times and 2.6–15.3 times more than the NH_4OAc-K released, respectively. In contrast to HNO_3 extracted-K, NaTPB was found to be least effective in releasing K from kaolinitic soils because the bulk of total K in these samples was present

in K feldspars, which are resistant to decomposition by NaTPB[21]. The amount of K released by NaTPB from the sample soils ranged from 1.4 % to 9.8 % of their total K.

The bioavailability of soil K depends primarily on its release rate and the amount available in the soil[11,13,14]. To determine the relation between K release amount and rate, the K release rate was plotted against amount to observe the bioavailability of soil K (Fig. 4). On average, when the release rate of K was >12 mg kg^{-1} min^{-1}, K was generally released rapidly, and the amount was > 400 mg kg^{-1}. When the K release rate was < 0.4 mg kg^{-1} min^{-1}, K was either released slowly or there was no release. Based on this release trend, we classified the soil K into three categories with a release rate of 12 mg kg^{-1} min^{-1} and 0.4 mg kg^{-1} min^{-1} as turning points that represented different release trend: (1) quickly released K, which was rapidly released from the surface of the soil complex; (2) medium released K, which was released from the weathered periphery of the soil complex; and (3) slowly released K, which was released from the micaceous matrix and had the lowest release rate, decreasing successively to zero. SHZ, LY, CW, BB, and JM soils had the highest amounts of quickly, medium and slowly released K, followed by CW, HEB, CS NA, FQ, and JY soils, whereas MC, GA, WC, and GD soils contained the smallest amounts of these three K soil types (Fig. 4).

DISCUSSION

Properties of sample soils. The physicochemical and mineralogical property analyses demonstrated that the selected agriculture surface soils represented a wide range of textures with different K status. In fact, the selected soils more or less covered the reported ranges of TK (10–20 g kg^{-1}), HNO_3 extracted-K (200–1600 g kg^{-1}) andNH_4OAc extracted-K (100–400 g kg^{-1}) contents of the upper 0.2 m of most agricultural soils (Spraks 1987; Zörb et al 2014). This was also the original intention of the sample selection, because the underlying aim of the study was to provide a new grading system of plant-available K to optimize the use of the inherent capacity of agricultural soils to sustain long-term K delivery. Hence, it was desirable that the studied soils represented different conditions likely to occur in the field.

Soil plant-available potassium extracted by exhaustive experiments and by NaTPB. Given that the amount of ryegrass uptake K, the release rate and amount of NaTPB-extracted K represents indexes of K bioavailability under K deficient situations, the soils from SHZ, LY, CW, BB, and JM were hypothesized to release more K more effectively under stress conditions (Fig. 3 and Fig. 4). Similarly, soils from HEB, CS, NA, FQ and JY were hypothesized to release K more effectively under long-term cropping. The lower amounts of ryegrass uptake K and NaTPB-extracted K in soils from MC, GA, WC and GD suggested that these soils would not support enough K nutrition to crops without fertilization under long-term cropping. The lower amounts of ryegrass uptake K and NaTPB-extracted K in these soils could explain by the smaller amounts of illite in the clay mineral compared with the remaining soils (Andrist-Rangel et al 2013; Li et al 2015).

Grading system for soil plant-available potassium. The bioavailability of K in soils was ranked in terms of the potential capacity of a soil to sustain plant growth with no additional K fertilizer, and was mainly related to plant growth and the release characteristics of K in soils (Cox et al 1999; Wang et al 2010; Darunsontaya 2012; Li et al 2015). Table 3 shows the available grading criterion of soil K with the parameters we propose. Three categories are detailed in the table: high available K (HAK), medium available K (MAK), and low available K (LAK). In the grading of HAK, the K release rate, RBY, K-deficient coefficient, and Kc of ryegrass were at the highest level and only showed a slight decline. In the rank of MAK, all the parameters significantly declined. In terms of LAK, K was released the most slowly, ryegrass had the lowest RBY (with some unable to grow), and there was the smallest K-deficient coefficient and Kc.

Based on the bioavailable grading criteria for soil K, the relations between the three plant-available soil K categories taken up by ryegrass and extracted by NaTPB were established (Table 4). NaTPB-extracted K

showed good linear correlations with plant-available K in the categories of high and medium ($p < 0.01$) bioavailability. In the grading of LAK, a slope of 0.33 indicated that plant-available K under intensive exhaustive experiments was less than NaTPB-extracted K. This trend reflects the fact that soil K levels had become too low to support plant growth, but the low soil K was still extracted by NaTPB, similar to the results of Cox et al. (1999). However, the slope and correlation coefficient of the relation between strong NaTPB-extracted K and the cumulative K uptake by plants in the intensive exhaustive experiment showed that 86% of the strong extraction method (NaTPB + NaCl) extracted K during 1 h period was plant available. Thus, it appears that the different plant-available soil K levels can be accurately predicted by the NaTPB method and that the grading criteria for soil K are suitable for ranking plant-available soil K.

A monitoring of soil plant available K is extremely important in order to make precise fertilizer recommendations. Estimations of rapidly and slowly available K by extracting the soil with 1 M neutral ammonium acetate (NH_4OAc) and boiling in 1 M HNO_3 are the most widely used soil test (Barbagelata and Mallarino 2013). However, plant-available K was well related to NH_4OAc-extractable K only in soils with low NEK contribution (Cox et al 1999). The extractant by 1 M HNO_3 is so far not satisfactory for the extraction of plant-available K in soils for at least two reasons. First, it may underestimate soil plant-available K compared to NaTPB[20]. Second, it extract some structural K that is not available to plants (Chardon et al 2006; Li et al 2015). The grading system based on NaTPB method proposed in this article opens up new prospects for reliable estimates of soil plant-available K because this method can take both exchangeable and a portion of non-exchangeable K into account. The grading criterion presented in this paper is a useful addition to the suite of different K forms tests as it determines the defined fraction of plant-available K in soils. As such this grading system can provide useful information to the planners associated with nutrient management strategy development in gearing up the potassium management.

Serial measurement methods for the plant-available soil K categories. Predictive ability and convenience in routine work were important considerations in grading the bioavailable K for routine testing (Cox et al 1999). Thus, to quickly and easily obtain amounts for the three plant-available soil K categories, new serial measurement methods for soil bioavailable K are proposed based on Tables 3 and 4. Specifically, the measurement procedures are as follows:

HAK: the amount of K extracted by 10 min 0.2 mol L^{-1} NaTPB subtracting K extracted by 5 s 0.2 mol L^{-1} NaTPB if the value was <120 mg kg^{-1}, and the concentration of HAK equal to the amount of K extracted by 5 s 0.2 mol L^{-1} NaTPB. However, if the value was >120 mg kg^{-1}, the amount of K extracted by 30 min 0.2 mol L^{-1} NaTPB was considered. If the value of K extracted by 30 min 0.2 mol L^{-1} NaTPB subtracting K extracted by 10 min 0.2 mol L^{-1} NaTPB was <240 mg kg^{-1}, then the concentration of HAK was equal to the amount of K extracted by 10 min 0.2 mol L^{-1} NaTPB. By contrast, the concentration of HAK was equal to the amount of K extracted by 30 min 0.2 mol L^{-1} NaTPB.

MAK: if the value of K extracted by 4 h 0.2 mol L^{-1} NaTPB minus the amount of HAK was <92 mg kg^{-1}, then the concentration of MAK was equal to the value of K extracted by 4 h 0.2 mol L^{-1} NaTPB subtracting the amount of HAK. By contrast, the concentration of MAK was equal to the value of K extracted by 24 h 0.2 mol L^{-1} NaTPB subtracting the amount of HAK.

LAK: the amount of LAK was equal to the value of K extracted by 1 h 0.2 mol L^{-1} NaTPB + 1.0 mol L^{-1} NaCl subtracting the amount of HAK and MAK.

Non-available K (NAK): the total soil K subtracting the K extracted by 1 h 0.2 mol L^{-1} NaTPB + 1.0 mol L^{-1} NaCl.

CONCLUSIONS

A new grading criterion of plant-available K in soils based on the K release rate from soils and plant growth indices was established based on characterizations of soil reserve K and the long-term sustainability of the soil resource. The relation between soil K release amount and rate showed three phases, with release rates of 12 mg kg^{-1} min^{-1} and 0.5 mg kg^{-1} min^{-1} as the cut-off points, based on the extraction method using 0.2 mol L^{-1} NaTPB. In addition, based on the trends in plant growth indices, RBY of 70% and 50%, K-deficient coefficients of 35 and 22 under conventional exhaustive experiments, and tissue Kc of 40 g kg^{-1} and 15 g kg^{-1} under intensive exhaustive experiments were obtained as critical values. Thus, soils K was classified into four categories: high available K, medium available K, low available K and non-available K. Grading criteria and measurement methods were also proposed. Future research should investigate the utility of this method to budget plant-available reserves of K in different soils.

ACKNOWLEDGMENTS

This study was financially supported by the National Department Public Benefit Research Foundation of China (grant No. 201203013), the National Basic Research Program of China (grant No. 2013CB127401), and the National Natural Science Foundation of China (grant Nos. 40971176 and 41271309).

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Table 1. Basic properties of the soil samples tested.

Site abbreviation	pH	CEC (cmol kg^{-1})	OM (g kg^{-1})	Sand (%)	Silt (%)	Clay (%)	TK (g kg^{-1})	HNO_3 extracted-K (mg kg^{-1})	NH_4OAc extracted-K (mg kg^{-1})	Main K-bearing minerals *
SHZ	8.19	20.9	27.7	14.8	61.0	24.2	27.4	1310.8	319.7	I† (24%††)，Ch(11%)，K(13%)
CW	8.28	13.4	15.6	6.1	76.2	17.7	25.2	1431.0	180.7	I(25%)，Ch(21%)， K(10%)
HEB	6.84	30.5	38.6	13.2	68.4	18.4	27.2	1175.1	223.6	I(20%)，K(17%)，Ch(7%)
LY	6.84	6.0	20.9	72.9	19.6	7.5	23.3	972.0	138.9	I(26%)，Sm(12%)，Ch(8%)
FQ	8.53	6.3	13.6	60.1	28.8	11.1	23.1	681.8	88.7	I(15%)，K(15%)，Ch(9%)
MC	7.12	10.1	12.5	8.2	76.6	15.2	17.5	542.5	110.1	I(9%)，K(2%)，Ch(1%)
GA	5.82	17.3	39.2	18.1	60.5	21.4	26.2	829.7	99.5	I(10%)，K(8%)，Ch(2%)
WC	5.42	7.8	34.9	7.4	58.5	34.1	16.8	310.6	76.9	I(8%)，K(4%)，Ch(7%)
BB	5.97	36.1	22.8	31.6	48.2	20.2	28.1	655.7	129.6	I(20%)，Ch(17%)，V(5%)
NA	7.48	20.2	33.7	20.3	47.2	32.5	18.6	357.9	96.0	Ch(15%)，I(14%)，K(8%)
JM	6.31	36.2	35.5	5.3	59.7	35.0	27.6	1067.6	265.7	Ch(25%)，I(19%)，V(7%)
JY	7.70	7.7	21.8	44.7	46.4	8.9	20.2	604.6	193.0	Ch(10%)，I(7%)，V(3%)
CS	7.31	18.0	15.5	8.3	70.0	21.7	22.6	474.2	77.0	I(15%)，Ch(10%)，Sm(7%)
GD	6.51	6.6	6.52	22.7	64.2	13.1	16.3	351.2	33.6	Sm(11%)，K(5%)，I(4%)

† Abbreviations are: I, illite; Ch, chlorite; K, kaolinite; Sm, smectite; V, vermiculite.
†† Numbers in the parentheses represent the K-bearing minerals percentages of the clay minerals.

Table 2. Results of PCA of the K-deficient coefficient of ryegrass.

Principal components	Eigenvalues	Variance (%)	Cumulative variance (%)	Eigenvectors			
				RBY	Kc	RKc	RKu
PC-1	3.400	84.998	84.998	0.902	0.869	0.950	0.963

Table 3. Grading criterion of soil plant-available K.

Plant-available K grading	K release rate in soils by weak extraction method (mg kg^{-1} min^{-1})	RBY of crops (%)	K-deficient coefficient of ryegrass	K concentration of ryegrass under intensive exhaustive experiment (g kg^{-1})
HAK †	>12	>70	>35	>40
MAK	0.4–12	50–70	22–35	15–40
LAK	<0.4	<50	<22	<15

† HAK, MAK and LAK are the high available K, medium available K and low available K, respectively.

Table 4. Comparison of the amounts of the three plant-available levels that extracted by NaTPB and uptake by ryegrass grown in different soils.

Soil abbreviation	HAK†			MAK		LAK		Total bioavailable K	
	Extraction by NaTPB (y_1)	Uptake by ryegrass (x_1) ††	Uptake by ryegrass (x_2)	Extraction by NaTPB (y_2)	Uptake by ryegrass (x_3)	Extraction by NaTPB (y_3)	Uptake by ryegrass (x_4)	Extraction by NaTPB + NaCl over a 1-h period (y_4)	Uptake by ryegrass (x_5)
SHZ	1358	>770	1291	442	428	348		2149	1719
CW	486	>462	448	392	400	611	>132	1489	980
HEB	317	301	361	212	503	541	>107	1070	971
LY	477	448	398	587	454	131	>64	1195	916
FQ	138	86	193	159	214	372	>160	668	566
MC	169	73	202	53	71	192	103	413	376
GA	118	62	113	80	90	242	173	440	377
WC	104	33	64	37		173	76	314	140
BB	403	461	675	511	414	1074	>112	1988	> 1201
NA	151	70	98	95	296	566	>123	812	517
JM	477	392	591	656	664	219	230	1352	1485
JY	275	119	188	125	168	259	220	658	576
CS	132	60	93	91	183	516	>187	739	463
GD	54	9	34	20	54	226	91	300	179
Correlation		$y_1 = 0.838x_1 + 86.846$ $R^2 = 0.918$ $p < 0.01$	$y_1 = 0.941x_2 + 13.581$ $R^2 = 0.922$ $p < 0.01$	$y_2 = 1.020x_3 - 45.809$ $R^2 = 0.754$ $p < 0.01$		$y_3 = 0.327x_4 + 169.71$ $R^2 = 0.494$ $p = 0.119$		$y_4 = 1.158x_5 + 104.61$ $R^2 = 0.864$ $p < 0.01$	

† HAK, MAK and LAK are the high available K, medium available K and low available K, respectively.

†† Values in the row of x_1 are the data under conventional exhaustive experiments, and values in the row of x_2, x_3 and x_4 are the data under intensive exhaustive experiment.

Table 5. Site characteristics of the 14 agricultural sites in China included in the study.

Site	Site abbreviation	Longitude	Latitude	Elevation (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)	Soil type (soil taxonomy)
Shihezi, Xinjiang	SHZ	85°56′43.04″	44°19′24.34″	433	225	7.8	Orthicaridosol
Changwu, Shanxi	CW	107°45′27.56″	35°12′52.61″	1213	588	9.4	Usticisohumosol
Harbin, Heilongjiang	HEB	126°48′35.00″	45°51′34.65″	116	523	4.9	Udicisohumosol
Laiyang, Shandong	LY	120°43′57.73″	37°0′5.04″	41	800	12.0	Udiccambosol
Fengqiu, Henan	FQ	114°24′0.06″	35°00′3.02″	70	615	14.3	Udiccambosol
Mengcheng, Anhui	MC	116°33′9.67″	33°9′40.43″	27	812	15.4	Aquicvertosol
Gaoan, Jiangxi	GA	115°20′59.6″	28°26′28.61″	41	1560	18.1	Udicferrosol
Wangcheng, Hunan	WC	112°49′36.8″	28°16′42.2″	66	1411	17.7	Stagnicanthrosols
Beibei, Chongqing	BB	106°23′25.98″	29°47′22.11″	327	1105	18.2	Udiccambosol
Nanan, Chongqing	NA	106°36′23.28″	29°31′17.01″	538	1089	18.0	Udicargosol
Jingmen, Hubei	JM	112°52′31.90″	30°50′2.77″	46	1179	16.4	Udiccambosol
Jiangyan, Jiangsu	JY	120°6′1.16″	32°25′59.86″	5	992	15.2	Stagnicanthrosols
Changshu, Jiangsu	CS	120°41′57.0″	31°32′45″	4	1054	16.2	Stagnicanthrosols
Guangde, Anhui	GD	119°27′18.68″	31°1′23.46″	34	1150	15.7	Stagnicanthrosols

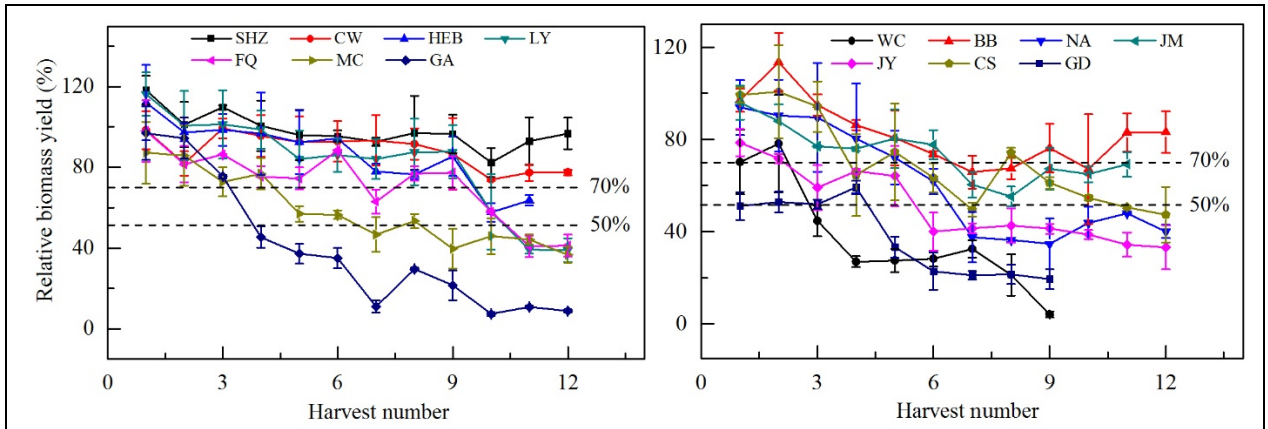

Figure 1. Relative biomass yield for ryegrass at each harvest for 14 soils under conventional exhaustive experiment.

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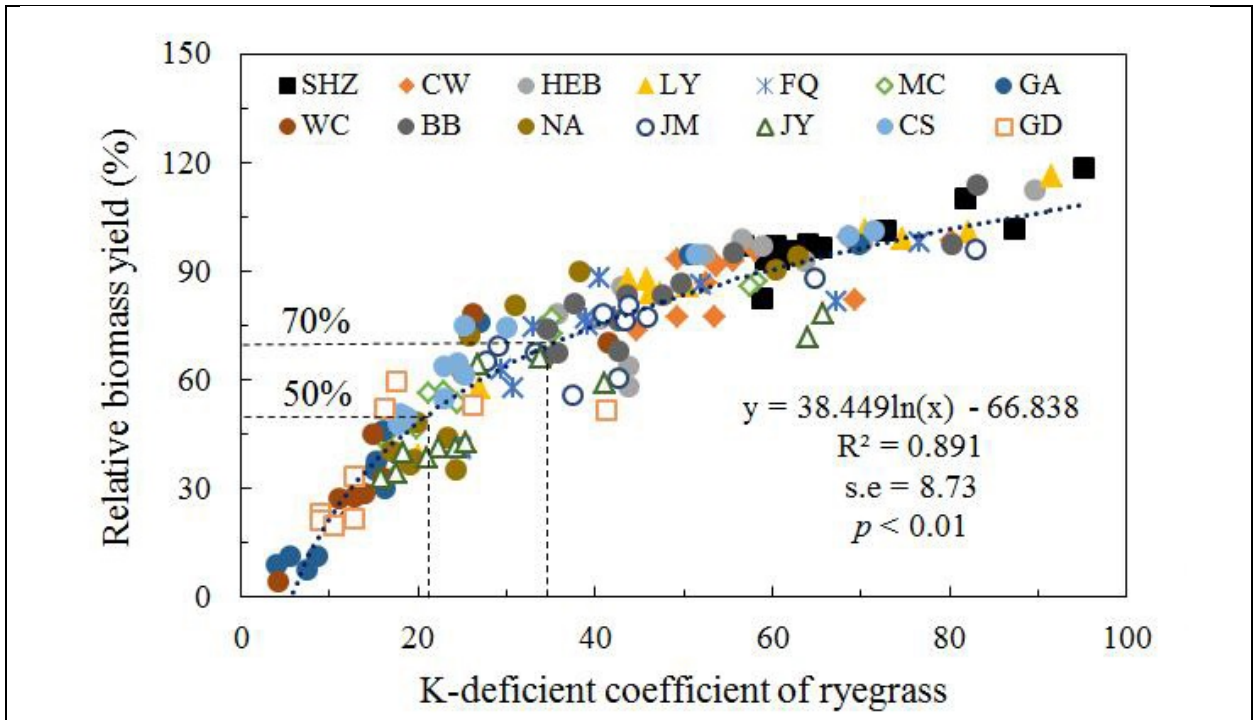

Figure 2. Relation between relative biomass yield and K-deficient coefficient of ryegrass under conventional exhaustive experiment.

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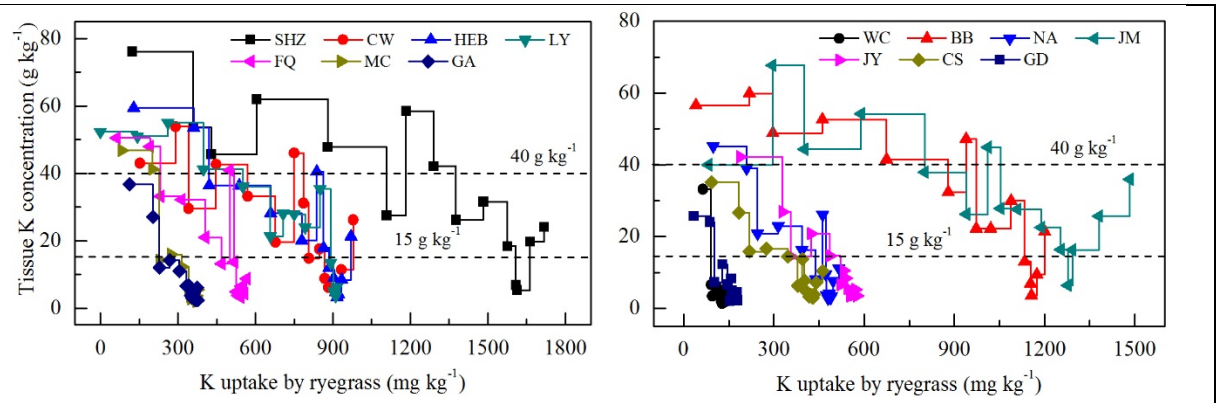

Figure 3. Relation between tissue K concentration and K uptake by ryegrass under intensive exhaustive experiment.

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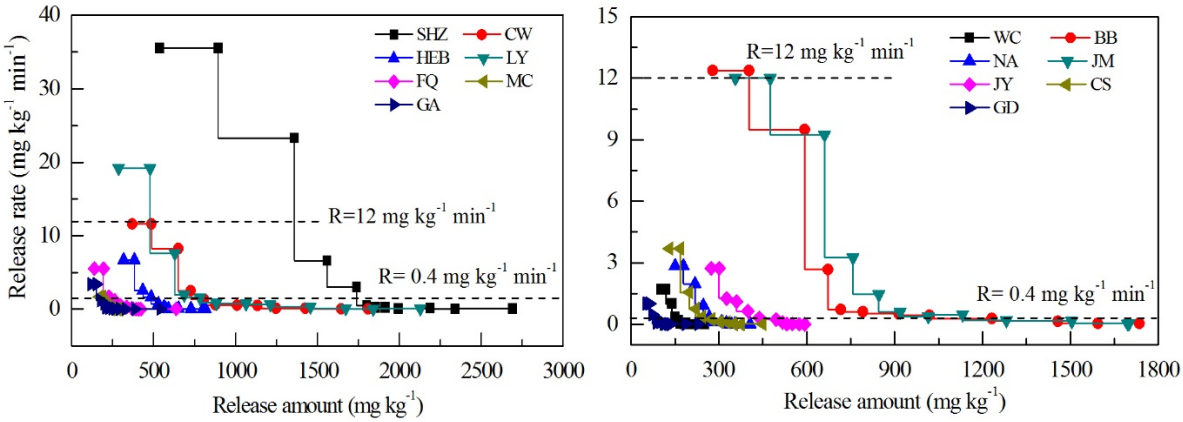

Figure 4. Potassium release amount and rate when extracted by weak extraction method for different soils.

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Observational Data Analysis of Soil Fertility and Leaf Analysis on Maize Grain Yield in the Central United States

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Abstract

Agronomic maize grain production in the central US have advanced significantly over the past 30 years. However, increasingly low soil test K levels have been noted and long term trends show declining K fertility. Nutrient concentration of maize VT-R1 ear leaves collected over a six year period across four Midwest states show K deficiencies occurred the most frequently of six macro nutrients averaging 6.9 - 57% of the samples. An observation study was conducted 2011-2016 across seven states at 118 sites to assess soil fertility and maize VT-R1 ear leaf nutrient levels on grain yield production. Cluster analysis of grain yield indicated high yield clusters had elevated N, K and Cu concentrations. Cluster analysis of soil test K, based on Mehlich 3 extractable K of a composite 0-15 cm sample, indicate little or no relationship with maize grain yield. In contrast maize ear leaf tissue analysis showed a significant correlation with ear leaf K concentrations with sites having greater than 1.9% having the highest grain yields. Six years of cluster analysis of maize ear leaves, based on an optimal plant population of 70,000 - 85,000 plts ha^{-1}, contrasting low and high ear leaf K show significantly lower grain yields for sites with ear leaf K less than 1.8% averaging 2.97 Mg ha^{-1} over the five years. Results show decreased ear leaf K is associated with elevated ear leaf Mg concentrations. Based on DRIS macro nutrient ratios, sites with low ear leaf K also had elevated Mg:K nutrient ratios >0.16; N:K nutrient ratios >1.6; and lower N:Mg ratios < 10.0. These results show that VT-R1 leaf analysis provides an effective tool for assessing crop nutrition and elevated Mg:K ratios are indicative lower maize grain yields in the Midwest US.

INTRODUCTION

Soil testing is the foundation for maize nutrient management decisions in Central US, and is based test method research and calibration models in the Midwest generated by Land Grant Universities (LGU) over the last 75 years. The successes of soil testing over the past three decades has been in large part been due to the inherent value of the testing method, monitoring over time, and adoption of precision Ag technology. Increasingly, declines in soil test concentrations of potassium (K) have been noted across the Midwestern US by the International Plant Nutrition Institute, IPNI (Fixen, et al. 2010). Results from soil testing laboratories serving Iowa and Minnesota show year over year declines with an ever increasing percentage of soil test Mehlich 3 K (M3-K) levels less than 180 mg kg^{-1} (Table 1). Agronomic theories for these declines, have ranged from increased crop yields, grower decreases in use of K fertilizers during associated with price spikes and changes in agronomic practices (i.e. tillage, plant population and maize hybrids). However, despite declines in soil test K yields in this region maize yields have been increasing an average of 135 - 175 kg ha^{-1} per year over the past thirty years (http://quickstats.nass.usda.gov/results).

Maize potassium nutrient requirements have been reported by Jones (1997). A survey of 3670 maize ear leaf samples collected at growth stage VT-R1 over the past six years by agronomists from Ceres Solutions in western Indiana from 2010-2014 indicates K deficiencies, based on a critical level of 1.75% (Schulte, E.E. and K. A. Kelling, 2013 and used by Midwest University Extension programs), range from 6.9 - 57.3% of samples (Table 2). Observations were based on a 20 leaf composite collected from grower fields across a range of soil textures, plant populations, hybrids and agronomic practices. K deficiencies as a percentage of all observed nutrient deficiencies was the highest of all essential nutrients for five of

the six years. Similar K deficiencies ranging from 27 - 58% of samples for a database of 15,000 ear leaf samples by agronomist in Minnesota and Wisconsin (Beck, 2015). A yearly comparison of maize ear leaf K concentrations show cool moist growing conditions had reduced K deficiencies whereas warm dry conditions had the highest incidence of deficiencies. In addition elevated ear leaf Mg levels were noted in years when tissue K levels were the lowest. Overall, these results show maize K deficiencies are weather dependent in the early growing season, but consistently dominate observed macro nutrient deficiencies.

Maize ear leaf nutrient ratios have been used to evaluate plant nutrition by Sumner (1977) and Elwali et al. (1985), Walworth et al. (1988), Dara et al. (1992) and Soltanpour et al. (1995). The approach is based on the Diagnosis and Recommendation Integrated System (DRIS) whereby diagnostic reference norms are developed for the essential elements. Key to the system is to assess nutrient ratio norms based on site database where yield is not limited by plant nutrition. With respect to K primary ratios identified in previous research are N:K, Mg:K, P:K and K:Ca. While research into DRIS nutrient ratios has shown it to be effective in diagnosing maize nutrition issues, it has not been evaluated in the Midwest US in over twenty years and has largely been dismissed by the commercial testing and consulting industry.

Observational data analysis (ODA) has proven effective identifying major factor effects in populations with regard to medical and environmental research. As a data analysis tool ODA can provide unique insight on factor dynamics within a population. With this in mind, the objective of this research was to assess the impact of soil fertility and maize ear leaf nutrition on grain yield across a range of agronomic practices and multiple years in the Midwestern US.

MATERIAL AND METHODS

Over the past five years a potassium fertility research study has been conducted at 81 grower field sites across seven Midwestern states to assess grain yield response of multiple potassium fertilizers applied pre-plant and side dress at growth stage V3-V5. For the purpose of this paper results are limited to the data collected from the research check plots - no treatments. Individual sites represented a range of soil types, tillage practices, crop histories, maize populations, irrigated and dryland management, and fertilizer management programs. Research was conducted using small plots (7.0 x 18.9m) with eight replications per location. Soils data collected included soil pH, phosphorus, macro nutrients, SOM and micro nutrients, based on both a 0-15 cm composite and 5.0 cm depth increment to 20 cm. Maize ear leaves were collected at VT-R1 based on a 30 leaf composite from each plot replicate and analyzed for concentrations of N, P, K, S, Mg, Ca, Fe, Mn, Cu, Zn and B. Harvest population, grain yield, grain moisture data was determined based on a subplot composite collected from a 2.4 x 12.3 m area. Grain yields were calculated based on 15.5% moisture content. In 2016, an additional 37 locations were included across six states where only check plots were monitored in grower fields based on four replications and additional data was collected on maize stalk nutrient concentrations at harvest using on a 20.0 cm stalk basal segment, eight sample composite. Cluster analysis was used to evaluate soil and plant analysis factors as they related to grain yield. 2015 data was not included in cluster analysis due to a limited number of field sites.

RESULTS

Over the six years soil, tissues and yield data was collected from a total of one-hundred seventeen sites across seven states (see Table 3). Annual mean soil test K concentrations over the six years ranged from 146 to 212 mg kg^{-1}, mean grain yields ranging from 10.41 - 15.20 Mg ha^{-1}, with the lowest yields noted in 2012, a drought year across the central US and the highest in 2016, with optimum growing conditions. Mean ear leaf K concentrations ranged from 1.71% to 2.18 % over the six years with the highest incidence of maize K deficiencies (based on a diagnostic critical value of 1.75%) occurring in 2012 on 56.3% of field sites.

Cluster analysis of the sixteen sites observed in 2014, based on two clusters representing the lowest and highest K concentrations, for soil test K, ear leaf tissue and grain yield results is shown in Table 4. Comparisons of the two clusters show no significant differences in soil test K, plant populations or ear leaf N content, whereas there were statistical significant differences in ear leaf K, and Mg contents. There were no differences between clusters for ear leaf P, S, Zn, Mn, B or Cu, and 26% higher Ca concentrations associated with the low ear leaf K cluster. A comparisons of ear leaf Mg:K and N:Mg ratios shows statistically significant differences between the two clusters, but not for N:K ratios. Mg:K ratios exceeding 0.16 and N:Mg less than 10.0 for corn ear leaves at growth stage VT have been shown by Elwali et al, (1985) to be beyond the expected DRIS diagnostic reference norms. Ratios for these two macro nutrients for the low ear leaf K cluster are clearly outside this range, whereas those of the high ear leaf K cluster are within expected DRIS reference norms. Mean nutrient ratios for N:S, N:P and P:S were nearly identical between the low and high clusters for 2014 and within DRIS diagnostic reference norms. Cluster comparisons of maize grain yield show a 3.12 Mg ha^{-1} difference, but not statistically significant at the 0.05 level.

Soil test K cluster analysis comparing the five lowest and five highest soil test K levels show a statistically significant difference in means, with of 111 mg kg^{-1} for the low cluster and 182 mg $kg^{-1}$for the high cluster. There was slightly lower ear leaf K associated with the soil test K cluster, non significant, but no differences in leaf Mg, Mg:K, N:Mg or N:K ratios. There was no statistical difference in grain yield for the two soil test K clusters, although the high soil test K cluster had 1.50 Mg ha^{-1} higher grain yield.

Maize grain yield cluster analysis comparing the five lowest and five highest yield levels for 2014 show a mean of 15.44 Mg ha^{-1} for the high yield cluster and 10.06 Mg ha^{-1} for the low, a statistically significant difference of 5.38 Mg ha^{-1}. Soil test K results indicate a non significant difference between yield clusters with test concentrations of 125 and 156 mg kg^{-1} for the low and high clusters respectively (Table 5). Ear leaf tissue analyses indicate statistically significant higher leaf N for the high yield cluster with a mean concentration of 3.18%, but no differences in ear leaf Mg content, or the N:Mg ratio. Ear leaf K, Mg:K and N:K ratios indicated a trend with increased K and lower Mg:K ratios for the high grain yield cluster, but no differences in the N:K ratio. There were no significant differences between grain yield clusters for P, Ca, S, B, Mn, and Zn, or the N:P and N:S ratios. The exception was Cu which indicated 40% higher ear leaf concentrations for the high grain yield cluster, significant at the 0.05 level.

Cluster analysis of ear leaf K was evaluated for each of the six years of field observations (See Table 6). Results indicate, contrasting the lowest and highest ear leaf K clusters, differences in cluster mean ear leaf K concentrations ranged from 0.33% - 1.46%. There were significantly higher cluster mean Mg:K ratios and lower mean grain yields for the low ear leaf K cluster across all years. Generally mean Mg:K ratios for the low K cluster were 2X higher than that of the high ear leaf K cluster, with the exceptions of 2013 when it was 2.7X higher and 2016 when it was 4.1X higher. Similar differences in clusters were noted for N:Mg ratios across all years evaluated. Grain yield results indicate differences ranging from 2.33 to 3.94 Mg ha^{-1} with an average of 2.97 Mg ha^{-1} between the low and high ear leaf K clusters over the six years.

DISCUSSION

Cluster analysis of observation data from maize grower fields, based partitioning of ear leaf K at growth stage VT-R1, shows very significant shifts in ear leaf Mg, Mg:K, N:Mg and grain yield across 118 site years in the Midwestern US. As the maximum uptake rate of K for maize occurs between vegetative growth stages V5 and V14, any constraints in K uptake associated with soil K deficiency and/or, slowed root zone K diffusive supply impacts plant growth and results in increased Mg accumulation.

An assessment of mean leaf K clusters with respect to mean soil test K indicated no significant differences between the low and high clusters across the six years, albeit trends indicated lower levels were always associated with the lowest ear leaf K cluster. Although high soil test K (i.e. > 180 mg kg^{-1}) levels are often associated with higher maize ear leaf K concentrations, multiple factors impact plant K uptake, which include: soil moisture limited diffusion, soil depth stratification of K, and rapid plant growth associated with optimum temperatures during V5-V14 vegetative development. These results indicate that Mg:K ratios shift with V5-V12 growth weather increasing in drought years such as 2012 and decreasing in wet years such as 2016. Thus the interpretation of the Mg:K ratio cannot be done based on a static critical value, but adjusted based on growing weather. With respect to supra optimal ear leaf Mg accumulation, one possible theory was that these sites were associated with high soil test Mg, however a review of the six years of observational data showed no relationship with increased ear leaf Mg or decreased K concentrations.

Research of Seggewiss and Jungk, (1988), has shown that Mg uptake by ryegrass increased abruptly when rhizo-soil solution K fell below 20 umol K l^{-1}. In maize with decreased root K uptake, Mg uptake increases during maize stalk development resulting in supra-optimal Mg concentrations in the ear leaf and other maize aerial components. Research of Grimme, et al. (1974) have shown for oats, with decreased K diffusion there is an increase in Mg uptake, and a subsequent decrease in grain yield. These Midwest field observations support those of previous research on other cereal crops that with limited K uptake, aerial Mg concentration increases, and is associated with decreased grain yields.

ODA analysis of Midwest US soil test K and maize ear leaf analyses over six years indicate ear leaf K, Mg:K and N:Mg ratios are strongly associated with maize grain yield, with a mean difference 2.97 bu ac^{-1} in ear leaf K clusters. Over six years ear leaf K clusters with a mean K concentration > 1.9% and a mean Mg:K ratio < 0.16 had a mean grain yield > 13.5 Mg ha^{-1}. These results confirm diagnostic norms of Elwali et al (1985) and are significant as field sites represent a diverse range of soils, agronomic practices and maize hybrids. Further cluster analysis indicates little or no relationship of soil test K with maize ear leaf K, Mg, Mg:K or grain yield. With respect to yield cluster analysis, VT-R1 ear leaf N was highly significant, and trends indicted higher concentrations of N, K and Cu were associated with the high yielding cluster. These research findings provide strong supporting evidence that maize ear leaf analysis is an effective tool for the evaluation of K nutrient management and when used in combination with macro nutrient ratios is effective in diagnosing nutrient deficiencies that limit maize grain yield.

ACKNOWLEDGMENTS
The authors wish to thank Midwest Independent Soil Samplers (MISS), Winfield Solutions, The Climate Corporation, Nachurs, Compass Minerals, Potash Corp, the Fluid Fertilizer Foundation and Wilbur Ellis for their funding support of this research. Thanks to Sure-Tech labs, Indianapolis, IN; AgSource - Ellsworth, IA; and Solum Laboratory, Ames, IA for their analytical support. Thanks to the ninety-one grower cooperators for providing the field locations. Special thanks to Tom McGraw, Dr. Larry May, Jerry Floren, Mike Lindaman, Irene May, Kirk Struve, Matt Struve, Dave Mowers, Scot Benson, Mark Kottmeyer and Jason Gibson for their assistance with field research field data, harvesting plots, processing grain and managing the research data.

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Table 1. Soil test potassium levels for southern Minnesota and northern Iowa, 3 years.

Soil Test K	Percent samples less than specified K level each year [1]		
mg kg^{-1}	2012	2013	2014
< 90	3.7	4.7	6.6
< 120	17.3	16.4	24.8
< 150	40.0	43.1	47.3
< 180	61.3	63.6	69.4

[1] Data source: Minnesota Valley Testing Laboratory, 242,000 samples, Mehlich 3 method.

Table 2. Maize ear leaf nutrient deficiency percentages, Ceres Solutions, western Indiana, six years.

Nutrient	Deficiency threshold [1]	Percent of samples deficient each year [2]					
	% less than	2010	2011	2012	2013	2014	2015
N	2.76 %	5.1	5.0	33.1	10.5	16.6	44.7
P	0.25 %	0.6	1.1	20.4	2.7	1.1	13.2
K	1.75 %	29.4	15.3	57.3	17.9	21.4	6.9
S	0.16 %	1.1	0.1	8.1	2.4	4.0	33.3
Mg	0.16 %	23.9	6.2	1.7	13.2	19.1	43.4
Ca	0.30 %	1.7	0.0	0.8	0.6	2.9	15.1
Zn	19 mg kg^{-1}	4.5	7.2	0.6	6.6	3.0	20.4

[1] Source: http://www.extension.purdue.edu/extmedia/NCH/NCH-46.html
[2] 3670 maize ear leaf samples collected over six years.

Table 3. Soil test K, maize ear leaf K and grain yield for Midwest field observation sites 2011-2016.

Year	Number of sites [1]	Mean soil K test	Mean leaf K	Percent of sites ear leaf K deficient [2]	Mean grain yield
		mg kg^{-1}	%	%	Mg ha^{-1}
2011	25	197	2.21	23.4	12.83
2012	22	200	1.74	56.3	10.41
2013	12	180	1.71	41.7	12.41
2014	16	146	1.87	31.3	12.65
2015	6	185	1.92	-	15.10
2016	37	212	2.18	29.7	15.20

[1] Sites, growers fields across seven Midwestern states.
[2] Based on critical deficiency level threshold 1.75%.

Table 4. Comparison of low and high ear leaf K at T-R1 clusters, maize field observation sites 2014.

Parameter	Units	Low leaf K cluster [1]		High leaf K cluster	
		Mean[3]	Stdev	Mean	Stdev
Soil test K (0-20 cm)	mg kg^{-1}	149	27	165	21
Plant population	plts ha^{-1}	75,080	6,420	74,590	5,560
Ear leaf N[2]	%	2.80	0.51	2.95	0.27
Ear leaf K	%	1.60 *	0.12	2.17 *	0.14
Ear leaf Mg	%	0.34 *	0.04	0.23 *	0.03
Ear Leaf N:K ratio		1.76	0.35	1.36	0.16
Ear leaf Mg:K ratio		0.210 *	0.022	0.104 *	0.021
Ear leaf N:Mg ratio		8.4 *	1.5	13.3 *	1.7
Maize grain yield	Mg ha^{-1}	10.76	1.61	13.92	1.82

[1] Clusters established based on five sites with highest leaf K and five with lowest leaf K.
[2] Ear leaves collected maize growth stage VT-R1, 30 leaf sample composite.
[3] Mean values (*) are significant at the 0.05 level.

Table 5. Comparison of low and high grain yield clusters, maize field observation sites 2014.

Parameter	Units	Low grain yield cluster [1]		High grain yield cluster	
		Mean [3]	Stdev	Mean	Stdev
Soil test K (0-20 cm)	mg kg^{-1}	125	26	156	44
Plant population	plts ha^{-1}	75,090	3,180	74,100	4,770
Ear leaf N[2]	%	2.64 *	0.31	3.18 *	0.15
Ear leaf K	%	1.69	0.21	2.01	0.25
Ear leaf Mg	%	0.32	0.11	0.26	0.06
Ear Leaf Cu	mg kg^{-1}	10.5 *	2.0	14.8 *	2.1
Ear Leaf N:K ratio		1.58	0.23	1.60	0.21
Ear leaf Mg:K ratio		0.192	0.072	0.133	0.037
Ear leaf N:Mg ratio		9.4	3.9	12.4	2.1
Maize grain yield[2]	Mg ha^{-1}	10.05 *	1.24	15.44 *	0.55

[1] Clusters established based on five sites with highest grain yield and five with lowest grain yields.
[2] Yield based on mean of eight replicates per site, corrected to 15% moisture.
[3] Mean values (*) are significant at the 0.05 level.

Table 6. Comparison of low and high ear leaf K clusters, maize field observation sites 2011-2016.

Year	Low K cluster mean			High K cluster mean			Delta Yield
	Leaf K %	Mg:K Ratio	Yield (Mg ha^{-1})	Leaf K %	Mg:K Ratio	Yield (Mg ha^{-1})	Mg ha^{-1}
2011	1.77	0.171	11.30	2.64	0.089	13.85	2.57
2012	1.52	0.305	10.29	1.91	0.154	14.28	3.94
2013	1.67	0.331	11.16	1.95	0.124	13.46	2.33
2014	1.60	0.210	10.76	2.17	0.104	13.87	3.12
2015[2]	-	-	-	-	-	-	-
2016	1.47	0.284	13.19	2.93	0.069	16.10	2.91

[1] Clusters comparisons five sites in 2011, 2012 and 2014; four in 2013; and eight 2016.
[2] Limited sites in 2015, six.

How can Potassium be Managed to Improve the Synchrony of Soil Supply and Plant Demand?

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Abstract
Potassium (K) demand by crops is almost as high as that of nitrogen (N), and it plays a crucial role in plant metabolism, aiding crops to cope up with abiotic and biotic stresses. Insufficient K application to results in soil K mining, deficiency symptoms on plants, and decreased crop yields. Even soils like Entisols and Inceptrisols primarily made -up of fine-grained micasillite clay known as natural K suppliers to plants also exhibits K response in various crops. Reports show that K deficiency is wide spread across the globe, ranging from tropical to temperate environments. Evidences from long-term experiments (LTEs) in different cropping systems strongly indicate significant yield responses to K application and negative K balances where K application is either omitted or applied sub-optimally. Crop K demands varies with crop growth behaviour, nutrient needs at different stages and crop productivity level. The current review assesses the synchrony of K management from indigenous soil system and from external sources vis–a-vis plant demand under different cropping systems. Aspects considered include K budgeting, K removal and use efficiency under different cropping system. In addition to above, research results on right timing and rates of K application for a synchronized soil supply and crop demand under different cropping systems are discussed.

Keywords: Potassium-use efficiency, cropping system, K budget, Split K application

INTRODUCTION

Potassium is required by plants in large quantities, equal to or more than nitrogen N, and plays a key role in many metabolic processes in the plant. K deficient plants, besides producing low yields, become susceptible to drought, excess water, high and low temperatures, and to pests, diseases and nematodes. Soil K availability is largely governed by soil mineralogical composition. Extent and pathways of weathering of primary K-bearing minerals, and the dynamic equilibrium between different K fractions in soils give rise to soils of varying K-supplying capacity. Most soils of great alluvial flood plains in Asia were considered to have high K fertility due to abundant presence of K-rich clay minerals in the soil (Dobermann et al. 1998; De Datta & Mikkelsen 1985), and K was rarely found a limiting factor in crop production (Bajwa 1994). Later studies, however, indicated continuous soil K depletion due to higher K withdrawal than its supplement (Dobermann et al. 1998; Bijay- Singh et al. 2003; Yadvinder-Singh et al. 2005; Singh et al. 2013; 2014).

Recent studies conducted in intensively cultivated areas of India showed imbalanced N use, optimal to sub-optimal P use, and complete neglect of K application by the farmers (Dwivedi et al. 2001; Singh et al. 2014, 2015). Timsina et al. (2013) associated soil K fertility depletion with high nutrient demand and excessive extraction of K in intensive production systems of Asia. Soil K mining is further aggravated by the general practice of removing crop residues from the field for other competitive uses. This has led to widespread K deficiency in many soils of the region, including the fine-textured soils that originally had high soil K contents. The examples include alluvial illitic soils of India (Singh et al. 2015), lowland rice soils of Java (Sri Adiningsih et al. 1991), and vermiculitic clay soils of Central Luzon, Philippines (Dobermann & Oberthuer 1997). Evidences from LTEs in different cropping systems in India and

elsewhere showed significant yield responses to K application, and negative K balances where K application is either omitted or applied sub-optimally. Depletion of soil K has been considered as a possible cause of yield decline of rice and wheat in the LTEs under in rice-wheat systems (RWS) of Indo-Gangetic Plains (IGP) of South Asia (Ladha et al. 2003; Regmi et al. 2002).

Potassium demand of crops varies with crop growth pattern, nutrient needs at different physiological stages and crop productivity level, and the economic produce. High K demand of crops is associated with its high extraction from soils, which may lead to declining K fertility unless the extracted K is replenished through external sources. The use efficiency of applied K varies with cropping systems (Singh et al. 2014; 15), soil indigenous supplying capacity, source, rate, time and method of K application. These factors, along with the variable K availability in soils, needs to be taken into account while formulating K management strategies in cropping systems. The current review assesses the synchrony of K supply through soil and external sources *vis–a-vis* plant demand. Aspects considered include soil characteristics, indigenous K supply, residue management, crop growth behaviour, uptake pattern, and the importance of synchronizing soil K supply and plant need for sustainable high crop productivity and farm income.

POTASSIUM BUDGET IN SOILS

Apparent nutrient balance estimation provides information about how the nutrients in the crop production system are managed. In general, K use in most of the developed countries, particularly in Europe, has been historically sufficient for sustainable crop production even at high yield levels. However, it has declined in recent past. As a result, crop K removal exceeds K input, and farmers take advantage of mining soil K that had accumulated over time. Contrary to this, in many developing countries of Asia, Africa and Latin Americas, apparent K input-output budgets in agriculture are mostly negative (Sheldrick et al. 2002). Although K use has increased on agricultural land in China during the past 20 years, its overall annual K budget remains highly negative at about minus 60 kg K ha^{-1} (Dobermann et al.1998). Such estimates for India and Indonesia suggest annual K losses of about 20 to 80 kg Kha^{-1}, and those have been increasing steadily during the past 50 years (Tiwari et al. 1992). Naidu (2010) reported that the K depletion rate in Indian soil is about 10.2 million tonnes (Mt) $year^{-1}$ with K mining index of 8. An average annual K loss of nearly 20 kg Kha^{-1} was estimated for the whole of Sub-Saharan Africa (Stoorvogel et al. 1993).

POTASSIUM REMOVAL AND ITS USE EFFICIENCY UNDER DIFFERENT CROPPING SYSTEM

Soil K depletion is faster with its continuous inadequate replenishment. It is further aggravated when crops remove more K than required as luxury consumption. The data presented in Table 1 indicate that except for the crop sequences with a pulse or potato as component crops, all other sequences remove more K than N and P. The higher output: input ratio for K as compared with N and P indicated insufficient K addition under different cropping systems that may lead to depletion of soil K (Tiwari et al. 1992; Singh et al. 2015). On the other hand, relatively smaller output: input ratio and improved recovery efficiency of K under pulse/legume-based cropping systems indicated that pulses might have induced conducive environment for higher K availability and its utilization by the crops grown in the system. Multi-locational studies conducted (Singh et al. 2014) revealed that omission of K in RWS resulted in annual mining of 158–349 kg K ha^{-1} from soil reserves, and the authors cautioned that continuous inadequate application of K in intensive RWS may not be able to sustain high productivity over time. In a LTE on rice-rice system at Gazipur in Central Bangladesh, Milhat et al. (2008) reported that rice grain yield decreased sharply in a clay-loam soil from about 10 t ha^{-1} in 1985 to 6.2 t ha^{-1} in 2000 in the K omission plots, while K application at 50 kg ha^{-1} resulted in positive K balance and maintained rice yields. In another study on RWS in northwest Bangladesh, application of 54 kg K ha^{-1} increased average grain yield by 25-30% of rice and that of wheat by 53%–86% across a range of demonstration plots on farmers' fields (Milhat et al. 2008).

POTASSIUM MANAGEMENT FOR ITS SYNCHRONY WITH PLANT DEMANDS

The growing environment has a profound effect on native K supply. For example, soil solution K remains high in flooded rice soils because large amounts of soluble Fe^{2+}, Mn^{2+}, and NH_4^+ ions brought into solution displace cations from the clay complex, and exchangeable-K is released into the soil solution. The displacement and release of K from the exchange complex, however, ceases on return to aerobic conditions during succeeding crops like wheat, maize etc. In fields with adequate drainage, K and other basic cations can be lost *via* leaching. The leaching losses of K can be substantial in highly permeable soils with low cation-exchange capacities. Yadvinder-Singh et al. (2005) found that leaching losses of K were 22% and 16% of the applied K, respectively, in sandy loam and loamy soils maintained at submerged moisture regimes. In Bangladesh, such losses were as high as 0.1–0.2 kg K ha^{-1} d^{-1} (Timsina and Connor 2001). In RWS of South Asia, common practice is to apply full dose of K as basal at puddling of rice and at sowing of wheat. In well-drained soils having low cation exchange capacity, basal application of potassium to rice should be avoided. As both rice and wheat require large quantities of K, a sustained supply is necessary till heading stage or reproductive stage is over. On-coarse textured soils, split application of fertilizer K in both rice and wheat may give higher nutrient use efficiency than its single application due to reduction in leaching losses and luxury consumption of potassium (Tandon and Sekhon 1988). Tiwari *et al.*(1992) cited several references showing distinct benefits of split application. In Indian Punjab, Kolar and Grewal (1989) reported an yield advantage of 250 kg grains ha^{-1} by split application of K (half at transplanting + half at active tillering stage of rice) as compared to single application at transplanting.

On-farm studies conducted in RWS in the IGP indicated that the initial non-exchangeable soil K before rice ranged from 1228 to 3145 mg kg^{-1} across 60 farmer's fields, and the yield gain from applied K was relatively constant across the range of non-exchangeable K (Fig. 1). The relatively small difference in yield gain from applied K across the exchangeable soil K range of 60 to 162 mg kg^{-1} raises concerns about the effectiveness of soil testing based only on assessment of exchangeable soil K to detect the probable crop response to applied K for RWS in northern India. Non-exchangeable soil K might be particularly important in the illite- dominated soils of the IGP, and release and plant uptake of K from this soil fraction might mask the supply of K from the exchangeable K fraction (Bijay-Singh et al. 2003).

Studies in the Indian IGP under rice-maize system showed that application of 75 kg K ha^{-1} in two splits at basal, and panicle emergence in rice and before silking in maize had significant effect on grain yield and K uptake compared with complete amount applied as basal. Residue retention in zero-till maize on surface under rice- maize system and systemhad higher K uptake indicating better K synchrony with crop demand (Table 2). Use of decision support tool Nutrient Expert® for developing K recommendation as per plant demand and indigenous soil supplying capacity in rice- wheat, rice- rice, rice-maize and maize-wheat systems proved superior in most cases over existing state recommendations for higher yield and agronomic efficiency of applied K (Singh & Mishra 2016). Potassium is required in large quantities by cotton, from 3 to 5 kg K ha^{-1} day^{-1} (Halevy 1976). The rate of K uptake was slow during the seedling stage, about 10% of the total, but increases rapidly at flowering and reaches a maximum of 4.6 kg ha^{-1} day^{-1} between 72 and 84 days (Halevy, 1976). Mullins and Burmester (1990) reported maximum accumulation of K in cotton at the start of flowering and rate of K uptake reaches maximum during mid-bloom and declines rapidly as the boll matures, with a maximum K uptake rate of 2.5 to 3.9 kg $Kha^{-1}day^{-1}$ at flowering from 63 to 98 days after planting. Obviously lack of synchrony between the plant demand and native K supply from the soil results in decreased fiber quality and lowered yields. In Pakistan, application of 100 kg K_2O ha^{-1} as two equal splits, and 200 kg K_2O ha^{-1} as four equal splits produced 3.6% and 7% higher seed-cotton yield, respectively, compared to the full K fertilizer dose applied at sowing (Muhammad et al. 2016)). The K requirement dramatically increases during boll formation of cotton and therefore K application becomes crucial during reproductive stage for higher yield (Abaye 2009). Potassium requirement of cotton can be met by pre-plant soil application and/or mid-season side-dressing of applications of K. Foliar K applications offer the opportunity to correct the deficiency,

especially at latter growth stages when soil application may not be effective. Studies conducted at the University of Tennessee reported an increased yield response from foliar K fertilization when applied in a no-till system (Abaye 2009). Three to four foliar applications of K (2.0% w/v K_2SO_4) is recommended during peak boll development at 7 to 10 day intervals beginning about 2 weeks after flower initiation.

In sugarcane-based cropping systems of northwest India, application of K at120 kg ha^{-1} to both plant crop as well as to succeeding ratoon crop had highest productivity compared with K application to plant crop only. Further, application of K in 2 splits (basal and at grand growth stage) resulted in higher yield, K use efficiency and juice quality (Singh et. al, 2008). In Florida, recommended K dose has been as high as 450 kg K_2O ha^{-1} for the first growth cycle (ratoon), but reduced to 270 kg K_2O ha^{-1} for the second and third ratoons (Rice et al. 2006). Hunsigi (2011) suggested application up to 350 kg K_2O ha^{-1} and 117 kg K_2O ha^{-1} for the first and second ratoons, respectively. Singh et al. (2008) settled on a standard rate of 150 kg K_2O ha^{-1} in their experimental studies in India, while de- Oliveira et al. (2016) concluded that 98 kg K_2O ha^{-1} would be sufficient to obtain a stable sugarcane yield of 80 Mg ha^{-1}.

CONCLUSION

The forgoing discussions established the significance of judicious K input for enhancing productivity and use efficiency of K and other nutrients in cropping systems. The myths of adequacy of soil K in the alluvial soils as those of IGP have been negated by profuse crop responses to K fertilization in these regions. Studies on synchronizing K supplies with crop demand are, however, scare despite their significance in rationalizing K recommendations. Future investigations should involve crop and soil specific comparison of split application vis-à-vis conventional one time application with respect to crop yields, use efficiency, native K mining and losses from root zone.

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Table 1: Nutrient removal, output-input ratio, and recovery efficiency of K (RE_K) under different cropping systems

Cropping system	Nutrient removal (kg ha^{-1})			Output- input ratio			RE_K (%)
	N	P	K	N	P	K	
Rice-wheat	243	41	268	0.78	0.64	2.25	61
Rice-rice	269	47	281	0.74	0.69	2.31	68
Rice-chickpea	251	37	185	1.32	0.62	1.95	77
Rice-potato	299	47	208	0.88	0.65	1.30	72
Maize-wheat	307	64	397	0.93	0.78	2.97	54
Pigeonpea-wheat	283	41	201	1.17	0.65	1.63	73
Sugarcane-ratoon-wheat	369	156	547	0.92	0.76	3.56	69
Sesbania (GM)-rice-wheat	`245	39	259	0.63	0.61	1.37	71

Source: Singh et al. 2002; 2015

Table 2: Interactive effect of tillage and crop establishment options, residue management and K rates on total K uptake (kg ha^{-1}) under rice maize system (Data pooled for 5 years)

Tillage and crop establishment	Rice				Maize			
	-R		+R		-R		+R	
	-K	+K	-K	+K	-K	+K	-K	+K
TPR/CTM	168.4aB	206.9aA	178.4aB	206.4aA	156.0cC	187.7Ab	172.9cB	199.1cA
CTDSR/CTM	161.8bC	195.0bA	172.6abB	201.1aA	169.4bC	198.9bB	191.7bB	215.5bA
ZTDSR/ZTM	162.4abB	188.1cA	171.5Bb	198.9bA	183.6aC	215.9aB	211.5aB	238aA

Values followed by different letter(s) within a column are significant at $p < 0.05$.
Values followed by different capital letter(s) within a row are significant at $p < 0.05$
TPR= transplanted puddled rice; CTM= Conventional till maize; CTDSR Conventional Till direct seeded rice; ZTDSR= Zero till direct seeded rice; ZTM= Zero tilled maize

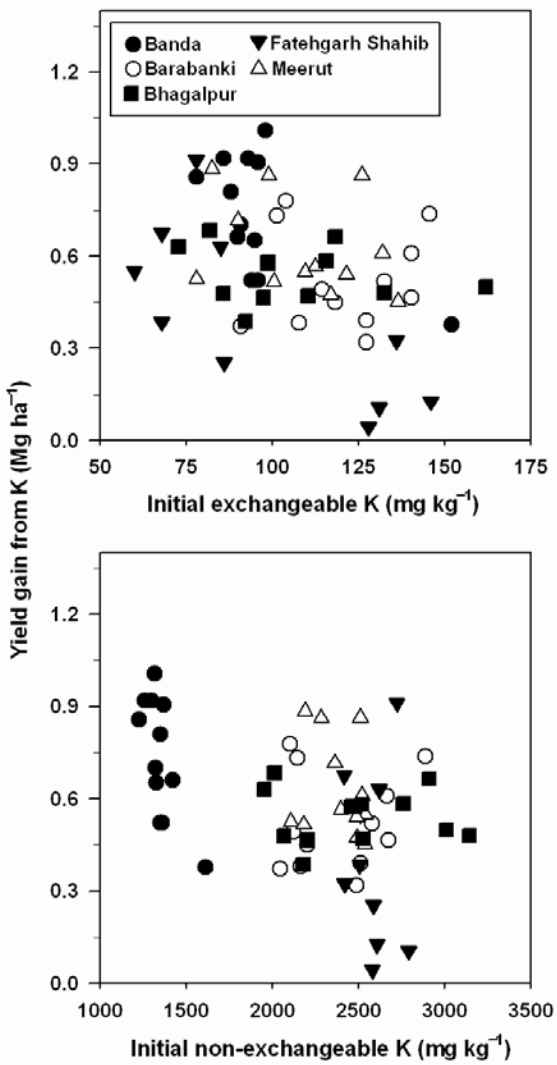

Fig. 1. Relationships of exchangeable K and non-exchangeable K with yield gain in rice from applied K across five locations in northern India.

Soil Characteristics and Cultural Practices that Influence Potassium Recovery Efficiency and Placement Decisions

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Abstract
Placement strategies are a key determinant of efficient use of applied fertilizer potassium (K), given the relative immobility of K in all except the lightest textured soils or extreme rainfall environments. This is further compounded by the general lack of root proliferation in localized soil zones enriched with K alone compared with response to N and P, the moderating effect of K fixation reactions in soils with certain clay mineralogy and the declining concentration and activity of soil solution K with increasing clay content. Variation in root system characteristics among crops in a rotation sequence and fluctuating soil moisture conditions in fertilized soil horizons in rain-fed systems increase the complexity of fertilizer placement decisions to ensure efficient K recovery and use. This complexity has resulted in extensive exploration of fertilizer K application strategies, including comparisons of broadcast soil applications versus direct foliar fertilization and broadcast versus banded soil applications. In addition, the timing of K application (pre-crop, at sowing and in season) and the impacts of co-location of K with other nutrients have been studied. In this paper, we provide examples of these complexities, and while research findings are often specific to the crop, soils and seasonal conditions under which they are conducted, we attempt to identify strategies that will most consistently deliver improved crop recovery and utilization of fertilizer K.

INTRODUCTION

Plants typically accumulate potassium (K) in similar quantities to nitrogen (N), with the potential to luxury accumulate K to a greater extent than N in some situations. The scale of crop K requirements and the time-critical nature of K uptake, with maximum uptake rates typically well in advance of biomass accumulation, mean that soil K availability and appropriate fertilizer application methods will be critical to ensure adequate crop K nutrition. While foliar applications of K are practiced in some situations like cotton (Coker et al., 2009) or horticultural crops (Jifon and Lester, 2011) they are typically limited to supplementing K uptake from soil, with the quantity of foliar K supplied relatively small. This paper is therefore clearly focused on soil K fertilization strategies.

FACTORS AFFECTING EFFICIENCY OF K RECOVERY

The main factors affecting the efficiency of applied K recovery involve: (i) the interactions between crop root systems and the soil physical and chemical properties that affect movement of K to plant roots and (ii) the replenishment of depleted soil solution K concentrations in response to plant K uptake. Plant root factors refer primarily to the temporal coincidence of active crop roots and soil K enrichment, the proportion of the crop root system that is in the enriched zone, and the mobility of K through the soil profile (and hence the potential expansion of the zone of enrichment beyond the original fertilized volume). Important physical properties such as pore size and pore continuity can influence the diffusion path length (or tortuosity) and hence the rate of diffusive re-supply of soil solution K that has been depleted by plant uptake. The chemical factors are those that influence the impact of applied K on the

activity of K in the soil solution (i.e., the K buffer capacity - BC_K) which is a function of the number and specificity of potential K sorption sites (i.e., the cation exchange capacity) and the presence of clay minerals that can fix (usually temporarily) some of the applied K. These chemical factors will also influence the relative importance of diffusion and mass flow in meeting crop K requirements.

Crop root distribution

Underlying genetics determine the potentially different patterns of root distribution between species and genotypes. While some of those differences are fundamental (e.g., the contrast in root system morphology and distribution between monocots (fibrous-rooted cereals like wheat) and dicots (tap-rooted crops like cotton and grain legumes), the finer-level differences between genotypes can also have important implications for functional traits like accessing water stored deep in the soil profile (e.g., (Liakat Ali et al., 2015) and potentially for responding to nutrient-rich patches like fertilizer bands or layers in cropped fields. However, the contribution of these differences to performance of the root system and the crop it supports will be largely determined by the interacting effects of soil characteristics and seasonal conditions in the field (Rich and Watt, 2013). As a result, the combination of soil type and seasonal conditions, modified by management inputs such as tillage system and irrigation, can have major impacts on the root distribution of the same genotype of a given species. Statistical analyses of many studies suggest that 70% of the root mass of many crop species is usually found in the upper 30 cm of the soil profile (Jackson et al., 1996), with irrigation (Gan et al., 2009) and the adoption of reduced or zero tillage systems (Williams et al., 2013) tending to increase the density of roots in the upper horizons. This zone of high root density tends to coincide with the zones of greatest nutrient enrichment, including fertilizer application, microbial activity and nutrient cycling. Therefore acquisition of nutrients from these layers is clearly important.

There is limited evidence that applications of K fertilizer impact the root distribution within the soil profile (e.g., Brouder and Cassman (1994)), except perhaps for the situation where K application contributed to a reduced severity of crop water stress and an extended period of biomass accumulation and root growth (Grzebisz et al., 2013). The only recent reports of root proliferation in a fertilizer K-enriched soil volume were a report for maize by Perna and Menzies (2010) that showed some evidence of root proliferation when 6-12% of the available root volume was enriched with K, while a split-pot study with wheat by Ma et al. (2007) reported that roots proliferated in K-enriched compartments relative to the unfertilized chambers. A parallel maize study showed no additional K uptake in the treatments where root proliferation was recorded, while similar uptake analyses were not conducted for the wheat study. Collectively, the literature suggests that large changes in rooting patterns are unlikely to occur in response to the application of fertilizer K alone, suggesting that either the volume of K-enriched soil needs to be large enough to encompass a significant proportion of the crop root system or that other strategies to enhance root activity in the fertilized zone are warranted. The minimal effect of K on root proliferation may partly explain, along with salt effects, the usually small starter K effects on early crop growth and yield, compared to effects of N and P (Kaiser et al., 2005, Mallarino et al., 2010).

Mobility of K in soil

Fertilizer K applied to soils initially enriches the soil solution K pool, with that soil solution K subsequently being depleted by plant uptake, by rapid adsorption onto exchange sites on clay or organic matter surfaces, or by more gradual fixation in wedge and interlayer positions of some clay minerals (e.g., illite, vermiculite, and high-charge smectite – Goulding (1987)). The most important factors affecting mobility of K in soil are the cation exchange capacity (CEC) of the soil and the specificity of exchange sites for K (both determined by the clay and organic matter content as well as the type of clay present), the presence of K-fixing minerals, the formation of sparingly soluble reaction products in bands containing K and other nutrients and the seasonal moisture dynamics – specifically the frequency of wetting and drying cycles (affecting K fixation and release) and the extent of through drainage or leaching (Luo and Jackson, 1985, Sparks and Huang, 1985). In light-textured soils with low CEC and organic

matter content, there is a limited capacity to adsorb significant amounts of K on the exchange complex. In such situations, a large proportion of applied K will remain in the soil solution and may be subject to leaching into deeper soil horizons. In terms of increasing the volume of K-enriched soil in the crop root zone, this can be a good thing; but in high rainfall environments, it may result in leaching of K too deeply to be accessible to plant roots. In contrast, soils with even moderate CEC will typically adsorb K leached from crop residues or applied as fertilizer, such that K is considered as sparingly mobile or effectively immobile in the soil profile. While the former situation requires careful management of K applications to ensure efficient use by crops rather than leaching losses, the latter situation represents real challenges in ensuring that applied or recycled K reaches the crop root zone, rather than being concentrated in top soil layers that can be frequently dry in rain-fed cropping environments. The latter situation is particularly applicable in minimum or zero-tillage cropping systems, where physical mixing of profile layers has been minimized or eliminated entirely and plant-available K reserves become increasingly stratified near the soil surface e.g., (Grant and Bailey, 1994, Mallarino and Borges, 2006).

Movement of K to plant roots

In most situations the concentration of K in the soil solution is low, primarily due to the propensity for rapid adsorption of K onto exchange surfaces. As a result, the extent to which mass flow contributes to K supply to the plant root is limited to typically <5% of overall plant uptake (Jungk, 2001), although this proportion can be higher when soil solution K concentration is high. Examples include when high rates of K are applied to light-textured soils with low CEC (Rosolem et al., 2003), or when soils are irrigated with wastewaters containing elevated K concentrations (Arienzo et al., 2009). In most situations K supply is dominated by diffusion through the soil solution along a concentration gradient established between the plant root and the undepleted soil solution (Barber, 1985). The efficiency of that process is determined by a variety of soil and seasonal factors, including: (i) the moisture content of the soil – effective diffusion rates increase with increasing volumetric water content; (ii) the impedance or tortuosity of the diffusion path - effective diffusion slows as clay content increases or as soil structure is degraded; (iii) the concentration gradient established between the rhizosphere and surrounding undepleted soil - soil solution K concentrations typically decrease as BC_K increases, lessening the potential concentration gradients; and (iv) the soil temperature – diffusion rates increase with increasing temperature due to lower viscosity of the soil water.

These factors obviously interact with the crop root system, with root density and inter-root competition in a given soil volume affecting the root depletion profile and hence the uptake of K per unit of root length (Jungk, 2001, Mengel et al., 2001). Species differences in root hair length and mycorrhizal colonization will also impact the volume of soil depleted.

FERTILIZER K APPLICATION STRATEGIES IN SOIL

Potassium fertilizer application strategies typically involve applications that are broadcast onto the soil surface or banding of K fertilizers (alone or in combination with other nutrients), with or without subsequent incorporation with tillage implements. The latter application method is particularly prevalent in reduced or no-till systems where soil structure and retention of surface residue cover are important management considerations. There is also some use of K in ‘starter’ fertilizer programs, where small amounts of nutrients (typically compound fertilizers containing N-P or N-P-K with trace additives) are placed in the seeding row or in bands immediately beside or below the seeding trench to ensure early contact between developing roots and the nutrient source. However, the amount of K applied in this approach is often limited by the risk of salt-induced damage to the developing seedlings and their root systems, and the yield impact of this application method has been shown to be inconsistent and sometimes detrimental (Mallarino et al., 2010).

Whilst broadcast applications to the soil surface are typically more cost effective in terms of rate of land area treated, their efficiency in supplying K to the crop depends on the extent to which either tillage or

rainfall/irrigation can redistribute K deeper into the soil profile where roots can access the applied fertilizer. In light-textured soils, the low water-holding capacity, high internal drainage rates and low capacity to adsorb K on the exchange complex can facilitate the redistribution of broadcast K into deeper profile layers, but in some situations the K can be leached completely from the crop root zone (Alfaro et al., 2003, Askegaard et al., 2004). More typically, broadcast K redistributes down the profile too slowly to benefit the current crop, and the rate of leaching is often exceeded greatly by crop uptake and deposition on the soil surface in crop residues. The result is 'stratification' of soil K, where the concentration of labile K in the top 5-10 cm typically exceeds that in the layers immediately below e.g., 10-30cm and beyond, depending on root distribution and K removal rates (Saarela and Vuorinen, 2010). This situation is exacerbated by minimum and no till systems, where the physical redistribution of K throughout the cultivated layer by ploughs or discs has been discontinued (Robins and Voss, 1991, Holanda et al., 1998, Vyn et al., 2002).

Whilst the existence of stratified rooting zones is not necessarily a constraint to crop K acquisition, provided those topsoil layers are moist for extended periods and characterized by an extensive network of active roots, the development of depleted zones in the upper layers of the subsoil represents a decline in profile K reserves and requires increasing reliance on optimal conditions in the topsoil layers throughout the period of maximum K uptake. Even in growing areas where reliable in-crop rainfall for grain production ensures moist top soils for K uptake, significant periods of temporal drought may limit K availability. In growing areas relying on stored soil moisture, the situation is worse and so alternatives to traditional broadcast applications like banding are implemented (Bordoli and Mallarino, 1998, Borges and Mallarino, 2001), or occasional tillage operations are undertaken to 'redistribute' stratified K reserves (Yin and Vyn, 2004).

The alternative to broadcast application strategies is to apply K in bands, with this application method particularly prevalent in reduced- and no-tillage systems. The strategies employed for banding of K have been developed on the basis of a number of key principles, including: (i) not placing high fertilizer concentrations close to the seed row, to avoid high salt concentrations that have a negative impact on germination and seedling establishment (Gelderman, 2007); (ii) trying to ensure bands are placed to maximize root interception and crop K acquisition (e.g., below and/or beside the plant line, or in the planting hill); and (iii) co-locating other nutrients with K to encourage root proliferation in and around the fertilizer band (Officer et al., 2009). Bands can be particularly effective in situations where the rate of root development and access to a larger soil volume is constrained by cold soils or high soil strength/compaction (Oborn et al., 2005), with the higher soil solution concentration in the vicinity of the band allowing rapid K uptake. Banding K deeper than the common 5-10cm depth is sometimes beneficial in conditions where the topsoil is frequently dry but deeper soil layers have moisture (Bordoli and Mallarino, 1998). However, as the crop grows and the K demand increases, the proportion of plant K that can be supplied from a localized fertilizer band diminishes and the importance of accessing a larger soil volume with adequate K status becomes more important.

Where soil K supply to plants proves inadequate, foliar applications of K fertilizer are sometimes made to supplement the crop K status. However, while responses in product quality (Haq and Mallarino, 2005, Lester et al., 2005) and occasionally yields (Haq and Mallarino, 2000, Haq and Mallarino, 2005, Coker et al., 2009) can sometimes be attributed to a foliar K response, many reports focus on applications of products containing multiple nutrients so the response to foliar K can be difficult to determine e.g. Ling and Silberbush (2002). Regardless, foliar K applications can be best considered complementary to soil-applied K as a way of achieving adequate crop K uptake, but the source and application rate must be chosen carefully because foliar-applied K sometimes reduces crop yield, probably due to salt-induced leaf damage (Haq and Mallarino, 2000).

The forms of K fertilizer applied to soil are typically muriate of potash (KCl) and sulfate of potash (SOP - K_2SO_4), although in some high-value horticultural crops, use of the more expensive potassium nitrate (KNO_3) is also significant. The most commonly used product is typically KCl, which is usually the cheapest form kg^{-1} K applied, although in some situations (e.g., saline soils, or in sensitive crops like potatoes and tobacco) use of SOP is preferred (Mikkelsen and Prochnow, 2015). There are also situations where the lower solubility and salt index associated with SOP make it more suitable for in-furrow ('pop-up' or 'starter') products than KCl.

Most soil K applications are applied as granular products, either alone or in compound blends with other nutrients like nitrogen (N) and phosphorus (P). There have been examples of clear improvements in crop nutrient recovery and yield response when fluid forms of some nutrients have been deployed at similar rates (of the element) compared to granular products. The improved availability of fluid P over granular P to crops grown on highly calcareous soils in South Australia is a good example (Lombi et al., 2004). The mechanism for this response was shown to be increased P diffusion away from the point of fertilizer injection, thus enhancing the volume of soil enriched with P and so accessible to plant roots. However, there are no reports of similar advantages for fluid forms of K fertilizer over granules. Choice of a fluid K formulation would be based on factors related to ease of application and the ability to blend different products rather than an expected increase in K use efficiency.

QUANTIFYING FERTILIZER K RECOVERY

There has been less research focus on the efficient recovery of applied K fertilizer by crops and the utilization of that K in the production of crop or forage biomass and harvestable yield than there has for nutrients that are more mobile and likely to cause off-site impacts in the atmosphere or adjacent water bodies (i.e., N and P). While concerns about excessive K applications after land application of wastewaters (Arienzo et al., 2009) do arise, most scientists consider excessive K application as reducing the profitability of crop production and an inefficient use of a natural resource, but not having off-site impacts on the environment. The K fertilizer placement method can have an impact on the K recovered by plants and what is removed from the field with harvest or recycled to the soil, but studies focusing on this issue are scarce. Research with corn and soybean has demonstrated that banded K fertilizer almost always greatly increases the K uptake during vegetative growth periods relative to broadcast K application for several tillage systems (Mallarino et al., 1999, Borges and Mallarino, 2000, Borges and Mallarino, 2003), although the persistence of these effects through to maturity was not measured. However the impact of increased K uptake with banding on net K removal will depend greatly on the crop species (Oltmans and Mallarino, 2015) and the crop part being harvested (e.g. forage or silage production *cf.* grain harvest).

Regardless, the frameworks developed to quantify nutrient recovery and use efficiency developed for these other nutrients and reviewed by (Dobermann, 2007) can be also applied to K (Fixen et al., 2015). When considering the interactions between soil and fertilizer K response in crops, the two most useful metrics are (i) Agronomic Efficiency (AE_K), the productivity improvement gained per unit of K input and calculated as $AE_K = (Y_K - Y_0)/K$ application rate; and (ii) the Apparent recovery efficiency by difference (RE_K)**,** the proportion of the applied K fertilizer that was actually taken up by the crop, and calculated as $RE_K = (Up_K - Up_0)/K$ application rate.

The range reported for these parameters for published data from cereal crops (primarily maize, rice and wheat) is from 8-20 kg grain kg^{-1} applied K for AE_K and 30-50% for RE_K. These ranges place AE_K considerably lower than equivalent indices for applied N (15-30 kg grain kg^{-1} applied N) and P (15-40 kg grain kg^{-1} applied P), but show RE_K intermediate between that of N (40-60% crop recovery) and P (15-25% crop recovery).

The reported RE_K figures may underestimate the recovery of applied K, as there is an assumption that only the additional crop K uptake in the fertilized treatments is due to fertilizer recovery. Given the

impact of K fertilizer on soil solution K concentrations, especially in the vicinity of bands, and hence the likely improved efficiency of diffusive supply across a stronger concentration gradient to a plant root, there may well be some unaccounted preferential fertilizer K exploitation in the fertilized layers and some sparing of soil K reserves elsewhere in the soil profile. This phenomenon has been commonly observed for P through the use of radioactive P isotopes, but there seems to have been little published work on the topic for K. There are real opportunities to re-examine the use tracers like rubidium (Rb), either by enriching a K fertilizer band (Hafez and Rains, 1972) or simply by using relative abundance of K and Rb in unfertilized and fertilized treatments (Hafez and Stout, 1973) to provide more accurate determinations of RE_K and thus better assess the efficiency of different K application strategies.

CROP CHARACTERISTICS INFLUENCING K APPLICATION STRATEGY

To optimize recovery of applied K there must be a spatial coincidence of active roots and enriched K layers or patches. While several studies by Barber and collaborators, summarized in Barber (1995) have suggested that optimal K recovery required fertilizer K to be mixed through a greater proportion of the root zone than for P, for example, the implications for fertilizer application strategy will vary with the physiological characteristics of the root cells, inherent root distribution of the different plant species or genotype and with the continuity of moisture availability in the fertilized soil layer.

A recent review by Fan et al. (2016) suggested that at least half of the total root mass of agricultural crops grown in temperate regions could be found in the top 20 cm of the soil profile, and Gan et al. (2009) have suggested that these proportions would be conservative for a range of winter cereal, oilseed and pulse crops (i.e. >75% of roots in the top 20 cm). These reports showed slightly shallower root distributions in temperate systems than the broader global analysis of Jackson et al. (1996), suggesting that effective K fertilizer strategies in temperate environments should be able to focus on the upper part of the soil profile – a zone that is relatively easily accessible to most fertilizer application/tillage equipment. However the applicability of these results to rain-fed cropping systems in the more variable rainfall environments of the tropics and subtropics (Bell et al., 2009), or to flood-irrigated cotton on heavy clay soils (Bell et al., 2015) is questionable. In such environments, either extended dry periods or excessive moisture and low oxygen availability limit root activity and nutrient acquisition from the uppermost zones of the soil.

An additional complication is apparent in no-till systems. Whilst the proportional allocation of root biomass in the topsoil can be pronounced, the spatial heterogeneity of the root distribution may limit the effectiveness of exploiting this zone for K. For example, an analysis by White and Kirkegaard (2010) suggested that 20-30% of wheat roots at 20 cm were confined to pores and cracks wider than normal root diameters, with this proportion rapidly increasing to 60% by 60 cm and effectively 100% at depths of 80-90 cm. This ‘clumping’ or roots around existing pores and root channels rather than being distributed through the bulk soil, has significant implications for acquisition of a relatively immobile nutrient like K. New roots will exploit the same (previously depleted) soil volume around these channels, while homogenous fertilizer K distribution will be much less effective at replenishing depleted K soil around such biopores. These effects are clearly more pronounced in subsoils (i.e., >20cm depth), where the interaction between the location of K bands, crop row spacings and biopores density may explain the lack of consistent response to deep bands in the literature.

Given the limited evidence of increased root density in response to soil K enrichment in zones/patches, it could be assumed that enrichment of as much of the active root zone as possible would be a desirable strategy. Such an approach requires either re-distribution of surface broadcast K into deeper layers with soil water movement (in light-textured soils), or through soil inversion/tillage – including occasional strategic tillage operations in otherwise no-till systems (Dang et al., 2015). The effectiveness of this general approach to K replenishment in the entire rooting zone will be determined by soil properties that regulate the extent to which K application increases soil solution K activity (e.g., K buffering) and the extent to which fertilizer K is fixed into slowly available forms by clay minerals.

An alternative approach is used when fertilizer K is banded. The effectiveness of this strategy for applying K could be considered risky in some soils, given the greatly reduced volume of fertilized soil and hence the lesser chance that enough roots will encounter K-enriched soil to optimize crop K uptake. However, co-location of K with other nutrients that do cause root proliferation such as P (Barber, 1995, Ma et al., 2011) can be used to increase root density around the fertilizer band and enhance recovery of banded K. There are limited reports of the benefits of this approach in the literature, although Brouder and Cassman (1994) were able to demonstrate enhanced K uptake in cotton in response to root proliferation in zones where K had been co-located with NH_4^+-N. A possible limitation with a strategy of nutrient co-location in bands is the potential to precipitate insoluble K minerals, as a result of radical changes in the pH and ionic strength of the soil solution over short periods. Circumstantial evidence of this phenomenon has been recorded in Australian studies (MJ Bell and DW Lester, unpublished data), but further definitive research is needed.

Finally, the K accumulation dynamics of different crop species may also influence the fertilizer application strategies. Different K application strategies may be suitable for crops in which the intensity of K demand varies within the growing season, e.g., due to the duration of the period of rapid K uptake or internal redistribution. As an example, crop K accumulation in a uniculm species like maize occurs mainly in a sharply defined period early in the growing season, well in advance of maximum dry matter accumulation (Welch and Flannery, 1985), while that of species with a greater reliance on staggered tiller addition (e.g., grain sorghum), or in less determinate species such as cotton (Mullins and Burmester, 1990) or soybean (Hanway, 1985) are characterized by lower rates of K uptake over a longer period, mirroring dry matter accumulation. These differences in crop K demand may influence the choice of application method (banding *vs*. broadcast), the timing of K application relative to crop establishment, and the use of supplementary foliar K applications during periods of rapid K uptake (maize) or redistribution (boll loading in cotton).

SOIL CHARACTERISTICS INFLUENCING K APPLICATION STRATEGY

The most obvious soil characteristic influencing K application strategy is the bioavailable K status of the soil itself. The consistent reports of negative K balances in many agricultural systems (Oborn et al., 2005, Rengel and Damon, 2008, Bell et al., 2010) suggest depletion of native soil K reserves, while the incidence of K-deficient crops is increasing in frequency. The first pre-condition for growers to commence a K fertilizer program will be a determination of the phytoavailable K status and an assessment of the likelihood of an economic response. As outlined in other papers in this conference, most commercial laboratory tests typically quantify the combined soil solution and exchangeable K pools as an indicator of plant-available K status, as these pools represent the most readily available K to plants. However, in some soils these pools are buffered by clay-bound and mineral K pools that may act as plant-available K ‘reserves’ in times of rapid uptake or as sinks for K after fertilizer application. Identifying different K pools in the soil for which a fertilizer recommendation is being developed is the first step to determining a successful K fertilizer strategy. Dissolution of mineral K may reduce the fertilizer K requirement (Moody and Bell, 2006), while fixation or release of K from clay minerals during the growing season may reduce or increase the fertilizer K requirement. Unfortunately, the current lack of quantitative diagnostic tests to link the presence of these K pools to their likely release rates under varying rhizosphere conditions can make the decision to apply fertilizer K challenging. This aspect is addressed in greater detail elsewhere in this conference.

In soils with low BC_K [e.g., those with low CEC and low clay content - Barber (1985)], even small application rates of K dispersed through the soil volume can significantly increase the concentration of K in the soil solution, ensuring the development of stronger concentration gradients and more rapid diffusion rates of K to plant roots. In these situations, fertilizer K dispersed through the cultivated layer would be expected to result in high RE_K, because such applications would ensure exposure of a large proportion of the root zone to elevated soil solution K. In such soils, comparable RE_K values might be

expected from banded applications only where soil structure and porosity were such that diffusive supply could efficiently occur over larger distances, such as in the Ferrosol soils studied in (Bell et al., 2009). In high rainfall environments a subset of these soils with very low CEC (<5 cmol (+) kg^{-1}) may experience leaching losses of K, and in these cases split applications of broadcast K may be an appropriate way to ensure fertilizer K is available to meet crop demands.

Conversely, in soils where BC_K is high (e.g., high CEC, high clay contents), a high rate of applied K dispersed through the soil volume is required to generate significant increases in either soil solution K concentration or AR_K. However, when the applied K is concentrated in fertilizer bands there is a much higher effective K application rate in a small soil volume and a much more substantial impact on soil solution K and AR_K. In these soils banded applications should provide the opportunity for higher RE_K, provided that sufficient root proliferation can be generated in the vicinity of the fertilizer band or that the spatial density of banding is sufficient to ensure that a greater proportion of the crop root system has access to zones of elevated solution K. Clearly, more research is needed to explore the trade-offs between BC_K in different soil types and the effectiveness of banded or dispersed fertilizer K application strategies.

Similarly, soil physical properties are also likely to impact the effectiveness of K application strategies within BC_K classes, with issues such as poor soil structure (e.g., in sodic soils) or compaction likely to reduce the effective diffusion path length, and hence the efficiency of K supply to roots. In such situations an appropriate response may be to increase the density of K fertilizer bands to ensure a greater number of enriched K patches to compensate for the restricted diffusion path lengths around each band. In a similar vein, soils and cropping systems where moisture availability is seasonally limited will also experience reduced K diffusion rates (Mengel et al., 2001), potentially increasing the frequency of K responses provided crop demand is not is not substantially decreased simultaneously. Such conditions may prompt use of either higher K application rates (to ensure stronger concentration gradients) or placement strategies that ensure fertilizer K is placed where soil moisture status is more favorable for longer in the growing season (e.g., by placing K bands deeper in the soil profile).

There is little published information about how fertilizer K application strategies could be modified for soils where K fixation is significant. As noted by (Blake et al., 1999), RE_K is typically lower on soils with significant K fixing capacity (only 70% of that recorded on comparable non-K fixing soils in long-term fertilizer trials). A common application strategy is simply to increase fertilizer K rates to compensate for the lower recoveries. Theoretically, large rates of K addition would be needed to saturate the K-specific fixation sites before application rates that matched crop removal could be safely adopted (Mengel, 2007). For nutrients like P, where strong precipitation or fixation reactions can reduce the fraction of the applied nutrient that is available for crop uptake in some soils, a strategy of minimizing the interaction between the fertilizer and the bulk soil by banding has been successfully used to slow the decline in plant-available nutrient and to improve crop recovery. The effectiveness of such a strategy for K in soils with significant fixation capacity or specific tillage systems may offer some benefits, and it may already be occurring in situations where the advantages of banding over broadcast K have been recorded (Bordoli and Mallarino, 1998, Borges and Mallarino, 2001). This is another area requiring further research.

CONCLUSIONS

In many soils the relative immobility of K in soil water dictates that agricultural K inputs must be managed to ensure a coincidence of K-enriched soil with a significant proportion of the active root system during periods of high K demand. This creates challenges for fertilizer application strategies and equipment, particularly in systems where soil inversion and other forms of aggressive tillage are no longer practiced. A better understanding of the capacity of crop and pasture root systems to utilize K-rich patches (typically fertilizer bands) will be a key prerequisite for developing successful K management strategies, as will an understanding of the potential benefits that can be achieved through co-location of different nutrients with K in bands to encourage root proliferation. The appropriate placement strategy

(e.g., depth, band spacing) will also be critical, and it will vary with soil type (e.g., water holding capacity in rainfed situations), climate (temperature and the frequency of effective rainfall events) and irrigation availability and method. However, in soils where CEC is moderate to high, there are real advantages in being able to manage K inputs across a crop rotation rather than on a crop-by-crop basis.

Conversely, in light-textured soils with low CEC and limited capacity to adsorb K, redistribution of applied K into deeper profile layers is possible if there is sufficient drainage, so a broader range of placement options appear to be available. The challenges in these systems relate more to the timing of K applications, to ensure that K remains in the crop root zone through the periods of peak K demand, and that leaching losses do not reduce the efficiency of K recovery and use. In these situations K fertilizer management is likely to be on a crop-by-crop basis, possibly even requiring split applications within a crop season where the potential for leaching losses are high.

Successful K management will therefore need to reflect the interaction of plant, soil and environmental factors. Development of management strategies will require an improved understanding of the availability of fertilizer K added to soil, plant root system characteristics for different species in a rotation sequence, the response of roots to dispersed or concentrated patches of K (and other nutrients), and the dynamics of K accumulated in crop biomass and returned to the field in residues. This improved understanding will facilitate optimization of K application strategies that may achieve more efficient use of the fertilizer K resource.

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Root Traits and Rhizosphere Characteristics Determining Potassium Acquisition from Soils

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Abstract

Plants acquire K^+ ions from the soil solution, and this small and dynamic pool needs to be quickly replenished by the other soil pools, either the exchangeable pool via desorption of K adsorbed onto clay minerals and organic matter, or the nonexchangeable pool via weathering of K-bearing silicates. Because of these chemical interactions with soil solid phases, K^+ concentration is kept low, restricting its mobility. Mass-flow therefore only partly contributes to K^+ transfer to the root surface, and K^+ depletion occurs as a consequence of K^+ uptake by roots, which is the driving force for the diffusion of K^+ in the rhizosphere. Because of this restricted mobility of K in soils, plants have evolved efficient strategies of root foraging. Therefore, root traits related to root system architecture (root angle, branching, depth), root length and growth, as well as root hairs and mycorrhiza-related traits play an important role in determining the capacity of plants to cope with the poor mobility of soil K, as well as its distribution in the whole soil profile, with potential significant contribution of subsoil K in many soils. Another consequence of the root-induced depletion of K^+ is a shift of the exchange equilibria, enhancing the desorption of exchangeable K, as well as the release of nonexchangeable, interlayer K from micaceous minerals in the rhizosphere. This means that both of these pools can be bioavailable, provided that plant roots can take up significant amounts of K at low K^+ concentrations in the soil solution (in the micromolar range). This is thus an important physiological root trait determining the acquisition efficiency of plants. Besides, roots can significantly acidify their environment or release large amounts of exudates, these two processes ultimately promoting the dissolution of K-bearing silicates such as micas and feldspars in the rhizosphere, which contributes the mining strategy evolved by plants. There are thus a number of root or rhizosphere-related traits (either morphological or physiological) that determine the acquisition efficiency of crop species and genotypes. The aim of this paper is to provide a detailed overview of these.

INTRODUCTION

Responding to global change represents a major challenge for the human race in the 21st Century, with the often competing demands of maintaining food security to feed a growing world population while reducing the impacts on the environment a case in point. While the Green Revolution achieved considerable increases in crop production and yield, almost matching the rate of population growth, it relied on the intensification of agriculture through the combination of improved crop genotypes, much increased use of fertilizers and pesticides, increased mechanization and irrigation (Tilman 1999). The widespread use of fertilizers has deeply modified the biogeochemical cycles of major nutrients (Vitousek et al. 1997), with impacts of nitrogen (N) and phosphorus (P) flows beyond the so-called planetary boundaries (Rockström et al. 2009). Losses from agricultural land are by far the largest contributors (Steffen et al. 2015), with excess use of N and P fertilizers in regions of intensive agriculture such as parts of the USA, Western Europe and China (Steffen et al. 2015). This has led to environmental damage through the emission of N_2O, which has a significant impact on global warming, and more locally to the pollution of groundwater bodies by nitrate and the eutrophication of surface waters in lakes and coastal sea waters. Potassium (K) fertilizers do not have such negative impacts when used in excess but, like P fertilizers, are derived from finite ores that are far from evenly distributed internationally (Manning et al. 2010). The increasing demand for N, P and K fertilizers and the energy cost of their fabrication and transportation result in rising prices and price fluctuations, with increased volatility expected in the coming decades (Brunelle et

al. 2015). This price volatility can have dramatic impacts in terms of food security, with a recent example occurring in 2008. A major challenge will be to use fertilizers in agriculture more efficiently worldwide, diminishing their use in regions where overuse is well documented, but increasing their use in situations where large nutrient deficits are being recorded. Many countries in Africa are in the latter situation (Manning et al. 2010). Further intensification of agroecosystems will require a paradigm shift, with sustainable development (i.e. aiming for ecological or sustainable intensification) as the primary target (Cassman et al. 1999; Tillman 1999). As noted by Lynch (2007) in his paper entitled "The Roots of the Second Green Revolution", part of this paradigm shift resides in dedicating greater research and breeding efforts to identifying plant traits determining nutrient (and water) acquisition, by focusing on root and rhizosphere[1]-related traits. This is the topic of this chapter. Lynch (2007) stressed that, while the Green Revolution selected crop genotypes responsive to high fertility (breeding for intense use of fertilizers and other inputs), the Second Green Revolution shall rather breed genotypes able to cope with low fertility, hence the need to place greater emphasis on belowground traits to achieve improved potassium acquisition efficiency (White 2013; White et al. 2013).

SOIL FEATURES DETERMINING THE FATE OF POTASSIUM AT THE SOIL-ROOT INTERFACE

A number of soil characteristics determine K mobility[2], availability and bioavailability (as defined below) to plants. These properties, together with the actual distribution of the various pools of K in the soil profile and horizons, ultimately determine the most desirable root and rhizosphere-related traits to search for to improve K acquisition efficiency in crops.

Potassium Mobility – Mass-Flow versus Diffusion in the Rhizosphere

Potassium is present as K^+ in the soil solution, which experiences rather strong interactions (adsorption/desorption) with the many soil constituents contributing to cation exchange capacity, notably clay minerals and organic matter (Sparks and Huang 1985; Sparks 1987; Bell et al. 2017). The consequences of such interactions are two-fold. First, they buffer the concentration of K^+ in the soil solution to values that commonly range from one to several hundred micromoles per dm^3 (Asher and Ozanne 1967; Hinsinger 2006), which are significantly greater than those of phosphate but less than those of nitrate. Second, they limit K mobility in the soil. Thus, compared with nitrate, K leaching occurs in significant amounts only in fertilized, light-textured soils. In addition, while mass-flow can contribute significantly to the transport of nitrate towards the root surface as a consequence of transpiration-driven water uptake and corresponding solute movement, its contribution to the supply of K^+ and phosphate ions is rather negligible (Barber 1995). Hence most K^+ is transported to the root surface by diffusion, as a consequence of the concentration gradients that develop in the rhizosphere (Tinker and Nye 2001; Jungk 2002). Barber (1995) estimated in the Chalmers silt loam (mollisol) that diffusion contributed about 80% of the K delivered to maize roots.

Potassium Availability and Bioavailability – Exchangeable versus Nonexchangeable Pools in the Rhizosphere

The environmental availability of a nutrient is an intrinsic property of the soil that is usually assessed by chemical methods designed to extract that fraction of the nutrient that is likely to replenish the soil solution in response to depletion by nutrient uptake (Harmsen et al. 2005; Harmsen 2007). It is usually expressed as a concentration, while the environmental bioavailability is best defined as the actual flux of a nutrient into a living organism (Harmsen et al. 2005; Harmsen 2007), which means that it varies for a

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[1] Rhizosphere is here defined as the volume of soil around living roots that is influenced by root activities (e.g. Hinsinger et al. 2009)

[2] The mobility is meant here to describe the ability of K^+-ions to be transferred in soils, either vertically through leaching or laterally, through mass-flow and diffusion (e.g. Hinsinger 2004).

given soil, nutrient and set of environmental conditions, as well as the organism of interest (e.g. the plant species or genotype). This is due to both differences in uptake capacities and abilities to alter the availability in the bio-influenced zone (Harmsen et al. 2005), which corresponds to the rhizosphere for plants (Hinsinger et al. 2011). For K, it was long assumed that the only available pools were K^+ in the soil solution and adsorbed onto negatively-charged soil constituents (Sparks and Huang 1985; Sparks 1987), which is often assessed via an extraction with ammonium salts. These correspond to the so-called exchangeable K pool that represents typically about 1-2% of total soil K (Bell et al. 2017). It has been well documented that plants can exploit this pool, which is therefore bioavailable. Most of soil K is, however, non-exchangeable in the sense that it cannot be extracted by an ammonium salt. There are two main non-exchangeable pools, corresponding to either K^+ contained in the interlayer of micaceous minerals (primary minerals such as micas and secondary minerals such as illites and illite-like clay minerals) or in the structure of other K-bearing silicates, feldspars being the most abundant ones (Sparks and Huang 1985; Sparks 1987). These are called interlayer K and structural K, respectively, and used to be considered as poorly available or non-available. However, there has been growing evidence that they are bioavailable to some plants, as further explained below (Hinsinger 2006; Hinsinger 2013).

Potassium Distribution – Topsoil versus Subsoil K Availability

It is often assumed that the topsoil is enriched in nutrients compared to the subsoil, or at least exhibits greater nutrient availability. This occurs in many natural ecosystems due to the role of vegetation in the rapid recycling of nutrients through uptake and litterfall as well as throughfall, the latter being especially important for K. Nutrients therefore accumulate in the topsoil, and whenever uptake occurs at greater depth, this ultimately contributes to nutrient uplift (Jobbagy and Jackson 2001). In agroecosystems, the topsoil can be enriched by K fertilization but there is also some evidence for K uplift (Barré et al. 2009), which points to a significant uptake of K occurring in the subsoil. This overlooked component of the soil, namely the subsoil and the potential reservoir of available nutrients it can represent, has been recently reviewed by Kautz et al. (2013), who stressed the need to assess its contribution to plant nutrition further. Kuhlmann (1990) provided some quantitative assessment of the contribution of the subsoil to wheat K nutrition, which ranged from 7 to 70%, with an average of 34% in luvisols of Northern Germany. The contribution may be less in deeply weathered soils such as oxisols and ultisols, which contain less exchangeable and nonexchangeable stocks. However, for deep-rooted plants such as eucalypt in deep oxisols in Brazil, we have recently shown that significant root-soil interactions occur at considerable depths, affecting the fate of K to at least 4 m (Pradier et al. 2017). This reinforces the need to take subsoil K into consideration in future research and in K-fertilizer prescriptions, as well as when designing more K-efficient ideotypes of crops in breeding programs.

ROOT MORPHOLOGICAL TRAITS DETERMINING THE ACQUISITION OF POTASSIUM BY PLANTS

Because of the restricted mobility of various nutrient ions, including K^+, NH_4^+ and phosphate in soils, plants have evolved a range of strategies to forage for them by increasing of the volume of their rhizosphere, i.e. the actual volume of soil from which they can acquire these poorly mobile nutrients (Hinsinger 2004; Lynch 2007; Hinsinger et al. 2011).

Root System Architecture and Plasticity

Plant species can differ considerably in root system architecture (RSA) with the tap-rooted systems and fibrous systems found in crops good examples (Kutschera et al. 2009). Tap-rooted systems usually enable plants to access deeper horizons, while colonizing the topsoil less densely than fibrous systems. Witter and Johansson (2001) compared forage species and estimated that the tap- and deep-rooted alfalfa obtained about 67% of its K from the subsoil, while ryegrass, with its fibrous root system, obtained only 42% of its K from the subsoil under the same conditions. While the type of RSA (e.g. tap-rooted vs fibrous) is genetically determined, it has been shown that there is considerable variation in RSA within a given species, which is a promising avenue for selecting more efficient crop genotypes of a broad range

of species (Lynch 2007 and 2015; Hammond et al. 2009; White et al. 2013; Mi et al. 2016; Thomas et al. 2016). While most of the work done so far has been conducted for N or P, some of these results can be easily extended to K. The root angle and distance between lateral roots are traits that will largely determine inter-root competition and the overlapping of the rhizosphere of neighboring roots, which is of greater importance for mobile resources, such as water and nitrate, than for poorly mobile nutrients such as K or P (Ge et al. 2000). Lynch and co-workers have shown in common bean and maize that shallow-rooted genotypes may perform better than deep-rooted genotypes whenever there is a strong vertical gradient of fertility, with much greater nutrient availability in the topsoil than in the subsoil (Ge et al. 2000), and that past breeding schemes have resulted in selecting more shallow root systems in maize in the USA (York et al. 2015). Their work has also shown considerable plasticity of RSA traits that can vary substantially with sowing density for instance. Such plasticity is an intrinsic property of root systems, which further complicate their study and phenotyping, but which plays a major role in the adaptive strategy of plants. In contrast to N and P, plants do not seem to respond to K-rich patches by enhanced root proliferation (Drew 1975; Hermans et al. 2006), which may restrict the options for effective fertilizer K placement, unless co-located with N or P. Nevertheless, although breeders are still reluctant, there is considerable progress to be expected from integrating RSA-related traits into breeding programs, and this is urgently needed to obtain genotypes that can cope better with spatially restricted availability of nutrients such as N, P or K (Lynch 2015).

Root Length and Growth

For poorly mobile nutrients it has long been known that root length or root area are amongst the most relevant traits determining their acquisition (Barber 1995). In their sensitivity analysis, Silberbush and Barber (1983) showed that the predicted K acquisition by soybean was increased more by an increase in root area than by the same relative increase in any other parameter in their classic Barber-Cushman model. More recently, Wissuwa (2003) predicted that a 22% increase in the root surface area of rice was enough to give a 3-fold increase in P acquisition under P-limiting conditions. Given that the mobility of K^+ is greater than that of phosphate in soils, it is likely that an even smaller change of root surface area would have a significant impact on K acquisition. In this respect, the modelling work by Pagès (2011), conducted with a more realistic distribution of roots based on RSA, rather than an evenly distributed root system as in the Barber-Cushman models, revealed that greater root length was ecologically relevant for the acquisition of poorly mobile nutrients, such as P, but not for mobile ions, such as nitrate (due to large overlapping of nitrate depletion zones). The results for K^+ and ammonium ions were intermediate.

Genotypes within a species can exhibit considerable variation in root length as shown for example for potato (Wishart et al. 2013) or maize (Erel et al. 2017). While the relationship between crop performance (growth or yield) under nutrient-limiting conditions and root length was not consistently significant or positive, these studies suggests exploring the impact of root length variation is worthy of more detailed investigation. While root length was weakly correlated with K uptake in a range of lentil genotypes, Gahoonia et al. (2006) showed that root hair length was an even more relevant root trait for poorly mobile nutrients such as K or P. As for RSA, root length and related traits such as specific root length or root surface area are not just genetically determined but are also highly plastic, responding to many environmental factors and biological stimuli. Plant growth promoting microorganisms are an example of the latter, with some of these directly altering root growth or proliferation (Vacheron et al. 2013).

Root Hairs and Mycorrhiza

It has been well documented for the least mobile nutrients, such as P, that morphological/anatomical features other than RSA and root length related traits can play a major role in extending the rhizosphere volume, and hence the actual amount of nutrient acquired. These include root hairs that can extend up to several mm from the root surface (e.g. Gahoonia et al. 1997), and mycorrhizal hyphae, which can access even greater volumes, extending up to several cm from the root surface (e.g. Jakobsen et al. 1992; Thonar et al. 2011). Their direct implication for the acquisition of K^+ is less well documented, but there are a

number of reports on the potential role of root hairs and mycorrhiza-related traits for improving the foraging capacity of plants for soil K. In their modelling of K uptake Samal et al. (2012) showed that, assuming root hair surface areas ranging from 0.38 to 0.47 cm^2 cm^{-2} root, root hairs contributed slightly less to K uptake than the roots alone (without their root hairs) in wheat and maize, but more than the roots alone in sugarbeet. The significant role of root hairs in K acquisition is also supported by the good correlation between root hair length and K acquisition found among crop species in decreasing order of efficiency: oilseed rape, tomato, ryegrass, maize, onion (Claassen and Jungk 1984; Jungk 2001) or rye, ryegrass, oilseed rape, alfalfa, barley, pea, red clover (Høgh-Jensen and Pedersen 2003). Høgh-Jensen and Pedersen (2003) also reported some plasticity for this trait as root hairs exhibited greater length at lower K supply, suggesting a relevant, adaptive strategy for improving K acquisition. Mycorrhizal hyphae can access a much greater volume of soil than roots and, thereby, increase the effective radius of the rhizosphere. While their quantitative impact on K acquisition has been studied much less than for P acquisition, the K uptake transport systems involved in the mycorrhizal symbiosis are now well documented (Garcia and Zimmermann 2014). Additional research is needed on the functional side of this symbiosis before identifying relevant traits worthy of being pursued for improving K acquisition efficiency.

ROOT PHYSIOLOGICAL TRAITS DETERMINING THE ACQUISITION OF POTASSIUM BY PLANTS

As potassium is present only as K^+ in soils, which interacts strongly with negatively charged soil constituents or is part of the crystal lattice of silicate minerals, K acquisition by plants is dependent on the mobilization of K from these sources. Depletion of K^+ in the rhizosphere solution and the excretion of protons and other K-mobilizing exudates (a 'mining' strategy) can increase the availability of K for plant nutrition (Hinsinger et al. 2011).

Traits Related to Potassium Uptake and Depletion in the Rhizosphere

For poorly mobile nutrients, such as P or K, the uptake capacity of root cells, determined by the rate of transport of ions across the plasma membrane, is not the limiting step for their acquisition. This contrasts markedly with the situation for more mobile nutrients, such as nitrate, as confirmed by sensitivity analysis of Barber-Cushman and other models (Rengel 1993). Nevertheless, in the case of K, the uptake of K^+ is a driving process for accessing both the exchangeable pool and even a significant part of the nonexchangeable pool (Hinsinger 2006, Hinsinger et al. 2011; White et al. 2013). When roots take up K^+ from the soil solution, there is a rapid depletion of K^+ in the rhizosphere. This was first observed in the early 1960s using autoradiography of a radioactive analogue of K, ^{86}Rb, which demonstrated the occurrence of a depletion zone extending a few mm from the surface of maize roots (Walker and Barber 1962), and was later confirmed by a range of approaches, based on direct measurements or modelling (e.g. Kuchenbuch and Jungk 1982; Claassen et al. 1986). The latter studies also demonstrate that K^+ uptake by roots can deplete the exchangeable pool of K by causing a shift in the cation exchange equilibria towards enhanced desorption of K^+ ions. As plant roots are capable of decreasing the concentration of K^+ from several hundreds of micromoles per dm^{-3} in the bulk soil down to concentrations in the micromolar range at the root surface, they can even shift the equilibria determining the release of interlayer K in micaceous phyllosilicate minerals (illites, illite-like clay minerals and micas), ultimately depleting the large pool of nonexchangeable K contained in soils (Kuchenbuch and Jungk 1982; Niebes et al. 1993; Moritsuka et al. 2004) and altering soil mineralogy (Kodama et al. 1992; Barré et al. 2007 and 2008). We demonstrated the occurrence of this mechanism in the rhizosphere of ryegrass by using a phlogopite mica as sole source of (almost exclusively interlayer) K, which released significant amounts of interlayer K and caused the concomitant transformation of the mica into a vermiculite clay mineral within only a few days of growth (Hinsinger et al. 1992; Hinsinger and Jaillard 1993). Barré et al. (2007) further confirmed this alteration of soil mineralogy for illitic clay minerals in the rhizosphere of ryegrass in a pot experiment, and this was also shown recently in a field experiment with maize (Adamo et al. 2016). Springob and Richter (1998) have shown that the rate of release of nonexchangeable K in soils can be

considerably enhanced below a threshold K^+ concentration of about 2-3 micromoles per dm^{-3}, which is the order of concentrations occurring close to root surface as a consequence of K^+ uptake and subsequent depletion of K in the rhizosphere (Claassen and Jungk 1982; Hinsinger 2006). In this respect, two important uptake characteristics to account for are the C_{min} value (minimal concentration below which plant cannot take up K) and the capacity to achieve a large K uptake rate at low K^+ ion concentrations, which depends on the K_m parameter of the Michaelis-Menten equation. In other words, plant species or genotypes showing very low C_{min} values (Asher and Ozanne 1967) and high affinity (low K_m) of their K transporters, would be better equipped for depleting K^+ ions to concentrations low enough to induce a significant release of interlayer K and thus access the large pool of nonexchangeable K that would be otherwise unavailable. Such K uptake traits differ between and within plant species and might be worth considering for screening K-efficient crop genotypes (White 2013; White et al. 2016).

Traits Related to pH Modification in the Rhizosphere

It should be noted that a number of field experiments have reported an increase of some K pools, notably the exchangeable K pool, in the rhizosphere instead of a depletion. This has been shown mostly in perennial tree species, e.g. by Courchesne and Gobran (1997) in a Norway spruce forest, Bourbia et al. (2013) in an olive grove and Pradier et al. (2017) in a eucalypt plantation. These observations strongly suggest the occurrence of root-induced weathering processes, resulting in an increase of exchangeable K at the expense of the nonexchangeable K pool through other processes than those mentioned above. For instance, Pradier et al. (2017) showed that root-induced acidification of the rhizosphere of eucalypt trees may have partly contributed to the increase of exchangeable K that was observed throughout the soil profile down to a depth of 4 m. Plant roots can modify rhizosphere pH considerably and root-mediated acidification of up to 2-3 pH units has been observed repeatedly (e.g. Römheld 1986; Hinsinger et al. 2003; Blossfeld et al. 2013). Such a decrease of pH can have a dramatic effect on the weathering rate of minerals such as K-bearing silicates, through proton-promoted dissolution (Berner et al. 2003; Taylor et al. 2009; Hinsinger 2013).

The ability to modify rhizosphere pH varies between plant species. For instance, faba bean reduces rhizosphere pH more effectively than maize (Liu et al. 2016) and oilseed rape induces a dissolution of the phlogopite mica as a consequence of rhizosphere acidification, while ryegrass does not (Hinsinger et al. 1993). The latter phenomenon has not been widely studied in crops to our knowledge, but a number of studies have been conducted in the context of forest trees. For example, Arocena et al. (1999) showed that the acidification occurring around ectomycorrhizas could have been involved in the dissolution of micas and feldspars. The capacity of roots to change the rhizosphere pH is not a simple trait to target, as root-mediated pH changes are essentially the consequence of an imbalanced uptake of major cations and anions (Hinsinger et al. 2003). Rhizosphere acidification occurs when a net surplus of major cations (K^+ being often predominant in the cation budget of plants) are taken up relative to the sum of major anions. Thus, there are many ways to increase rhizosphere acidification but it is not expected to be related to a single trait, as the underlying mechanisms are largely determined by the environmental context. Nevertheless, plant species or genotypes could be screened quite easily for their capacity to acidify their rhizosphere in a given context (Gahoonia et al. 2006).

Traits Related to Exudation in the Rhizosphere

Besides protons, roots can release large quantities of diverse exudates, including some that can also promote the dissolution of K-bearing silicates. Examples of these include carboxylates such as citrate, oxalate and malate, which are able to complex cations contained in the crystal lattice of these minerals (Jones 1998). These exudates can thus be involved in the ligand-promoted dissolution of feldspars and micas (Razzhage and Robert 1979; Robert and Berthelin 1986; Song and Huang 1988; Barman et al. 1992; Lawrence et al. 2014), and thus enhance the release of nonexchangeable K, i.e. structural and interlayer K, respectively, together with the other metal cations contained in these silicates. Screening wheat and maize and sorghum genotypes for their release of malate and citrate, respectively, to detoxify

Al has been successful, which shows that such a trait can vary substantially within some plant species (e.g. Ryan et al. 2011). However variations are certainly greater between species, with some crops such as white lupin or chickpea being renowned for their large carboxylate exudation capacity (Jones 1998). Even minute amounts of malate or citrate exuded at the root tip may provide sufficient protection against Al toxicity (Ryan et al. 2011), but much high concentrations would be needed to induce significant release of K through ligand-promoted dissolution of K-bearing silicates. There is no direct evidence to our knowledge that such exudation traits are worth pursuing for improving K acquisition efficiency in crops. Exudation is nonetheless a complex and major process occurring in the rhizosphere, which stimulates the microbial communities and has potential implications in the dissolution of nutrient-bearing minerals (e.g. Philippot et al. 2013), as reviewed for fungi by Hoffland et al. (2004).

CONCLUSION

A number of root or rhizosphere-related traits determine the K acquisition efficiency of crops, influencing both their foraging and mining for K^+. To deal with the restricted mobility of K^+ ions in soils, the foraging strategy of plants is based on a number of root traits: densely branched root system architectures with substantial portions exploring the topsoil and the subsoil, with a large root surface area or length are desirable traits. In addition, roots can extend the volume of exploited soil and the K depletion zones considerably by developing long root hairs or supporting strong mycorrhizal symbioses. In addition to this foraging strategy, which extends the size of the rhizosphere, plants have also evolved various mining strategies to increase the availability of the so-called poorly-available pools of K in the rhizosphere. The corresponding traits are related first to the ability of roots to sustain high fluxes of K at very low concentrations in the soil solution. This induces a shift in the exchange equilibria and an enhanced desorption of exchangeable K, as well as an enhanced release of nonexchangeable, interlayer K contained in micaceous minerals. Second, roots can promote the dissolution of K-bearing silicates such as micas and feldspars through rhizosphere acidification and/or exudation of complexing ligands such as some carboxylates. How to make better use of these traits in the context of a sustainable intensification of agroecosystems is not so obvious though, and breeders have not been integrating belowground traits in their breeding schemes. To do so may introduce additional challenges, such as potential trade-offs with those traits required for the acquisition of other resources (water, N, P, micronutrients).

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Potassium Placement Considerations for Plant Nutrient Balance Optimization in Modern Maize Hybrids

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Abstract

The typical broadcast K fertilizer applications that accompany maize production systems in the US Corn Belt states may be less than optimum in the no-till and shallow conservation tillage systems that are so dominant today. Potassium stratification with soil depth, although not always as severe as that following broadcast P systems, can limit maize growth and development. Plant K uptake is especially restricted if soil moisture stress also occurs during late vegetative development stages. Our research group has shown that high maize yields are dependent on optimum N versus K concentrations at the whole-plant level, and that K uptake requirements and uptake timing also change at the higher plant population densities that are now common with modern hybrids. Zone tillage with deep nutrient banding is one management option to possibly achieve higher leaf K concentrations and higher grain yields. This presentation will highlight Indiana research on K placement research in the context of whole-plant K uptake by maize and maize yield responses. Specific attention will be focused on relative K versus N concentrations in plant tissues of older-era versus modern-era maize hybrids. Critical K concentrations in the ear leaves at flowering, for example, may need to be higher than those accepted by scientists 20 or 30 years ago. Optimum K placement may vary with tillage and crop residue management practices, but continued evaluations of K sufficiency standards and K balance in modern hybrid production systems is essential to advance the science of K placement recommendations.

Cereal and Legume Crop Responses to Deep-placed K with and without P in NE Australian Vertosols

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Abstract

Cereal, legume and fibre crops grown on Vertosols formed in-situ on upland slopes in NE Australia have demonstrated greater yield responses to deep-placement (≈ 0.20 m) of K and P together, rather than just K alone. Beginning in 2013, eight sites were established across central and southern Queensland and northern New South Wales. Treatments consisted of an untreated control, four K application rates (0, 25, 50 or 100 kg K/ha) with a basal P application (20 kg P/ha) and two K rates (0, 100 kg K/ha) without the P.

Crop responses in this period showed some effect of seasonal conditions. Pulse species (chickpeas particularly) appearing generally more sensitive to K, whilst responses by grass species (wheat, barley, sorghum) varied with growing season conditions.

The cumulative response to fertilizer applications has highlighted the importance of making balanced nutrient applications, with the largest yield increases often resulting from a combination of P and K. Single crop grain yield increases in response to a combination of deep-placed nutrients have been as large as 1070 kg/ha (a 56% gain compared to traditional farmer practice) in a sorghum crop. The longevity of treatment response over a rotation cycle is providing insight into potential future nutrient management strategies.

INTRODUCTION

The sub-tropical cereal belt in eastern Australia extends from the Liverpool Plains region of New South Wales (about 32°S) to the Central Highlands of Queensland (about 22°S) (Fig. 1a) and constitutes around 21% of the Australian grain area (National Land and Water Resources Audit 2002). Across this region, rainfall is typically summer dominant in the north but transitions to an equal distribution in the south. Cropping frequency is related to soil moisture accumulation during bare fallows, utilizing the high water holding capacity of the heavier textured soils. The major cropping soils are black, grey and brown Vertosols, black, red or brown Sodosols, red and brown Chromosols and Ferrosols (Webb et al. 1997). Climatic conditions allow production of either winter (spring wheat, barley, canola and chickpea) or summer (sorghum, mungbean and cotton) crops.

Historically, nitrogen and phosphorus were the nutrients that most commonly limited crop growth within this production region (Dalal and Probert 1997). Nitrogen generally represented a significant proportion of annual variable costs, with phosphorus typically used as a starter application in or beside the seeding trench. Potassium was identified as a nutritional limit at several sites in Queensland during studies conducted in the early 1980's (Grundon et al. 1985), but little field work followed up these screening studies. More recently, multiple nutrient deficiencies have been recorded on many soils, with both P and K (as well as N) commonly limiting yield (Lester and Bell 2011).

Traditionally, fertiliser application has only been made to the surface 0-0.1 m layer. Nitrogen is typically applied pre-sowing and phosphorus applied in the seed trench during the sowing operation. Despite increased used of nitrogen and phosphorus fertilisers, the National Land and Water Resources Audit (2001) reported high levels of nutrient export from the major areas of the northern grains region with negative farm gate nitrogen and phosphorus balances in Queensland and the North-West Slopes and Plains of New South Wales. There is typically no potassium fertiliser applied, so negative potassium balances also exist.

While soil sampling for nitrogen considers the whole rooting depth (0-0.9 or 1.2m, depending on site), sampling for other nutrients has focused mainly on predicting starter P responses using samples from the 0.0-0.1 m layer (Chisholm and Strong 1984). Recent research, however, has highlighted the importance of the 0.1-0.3 m layer for supplying crop needs of less mobile nutrients like phosphorus and potassium (Guppy et al. 2012). Many fields with low subsoil K are characterized as upland Vertosols (formed in-situ) of the eastern Highlands region, rather than the contrasting coalluvial plains of the Murray-Darling system (Webb et al. 1997).

Bell et al (2017) reported responses to bands of phosphorus and potassium placed in the 0.1-0.3 m profile layer, with yield responses greater when both phosphorus and potassium were applied together, rather than just applying a single nutrient. However this work was conducted with high application rates (40 kg P/ha and 200 kg K/ha) as a proof-of-concept research (does it make a difference). The work reported in this paper investigates crop yield response over several years at sites where potassium was deep-placed at a range of rates, with or without co-located phosphorus and benchmarked against local commercial practice.

MATERIALS AND METHODS

Eight experiments were established across central and southern Queensland and the north-west slopes of New South Wales in eastern Australia. Treatments at all bar the Chelmsford site included an untreated control (labeled FR or “farmer reference”) representing the site production from current practice. In addition, all sites had treatments in which four rates of K (0, 25, 50 and 100 kg K/ha) were applied as potassium chloride (50% K) and co-located with a P application of 20 kg P/ha as mono-ammonium phosphate (10%N, 22%P). Two additional treatments consisted of two K rates (0 and 100 kg K/ha) applied without the mono-ammonium phosphate. The deep banding operation was typically conducted several months prior to the next intended sowing to allow sufficient time for seed bed reconsolidation, with bands commonly applied at ≈ 0.2± 0.05 m depth on 0.5 m row spacing using a 75 x 25 mm shank. Basal N, S and Zn treatments were applied to all K fertiliser plots. There were four replicates at Dixalea, five at Chelmsford and six at all other sites.

Sowing and other agronomic practices were conducted by the farmer co-operator as for the rest of the field. At physiological maturity, biomass cuts from selected treatments were collected to quantify crop growth and nutrient uptake. Biomass cuts where dried at 65 ^{o}C, weighed, mulched and finely ground. Samples were digested prior to nutrient analysis using ICP. Grain harvest was undertaken using a plot harvester, with grain yield corrected to the relevant moisture standard for receival into storage.

Initial site chemical fertility is described in Table 1, with chemical methods described in Rayment and Lyons (2011). Colwell P analysis refers to the sodium bicarbonate extraction (0.05 M NaHCO3, pH 8.5) method originally published by Colwell and Esdaile (1968). Cations were extracted using the ammonium acetate extraction. The soil test values for the two sites (Table 1) indicate low to very low Colwell P values in both top-soils and subsoils, with the 0-0.1m results below the 95% critical soil test range for sorghum (17-30 mg/kg), field pea (21-28 mg/kg) and wheat (18-30 mg/kg) (Bell et al. 2013, Bell et al. 2013) and all 0.1-0.3m results under the tentative subsoil critical value of 10 mg/kg (Guppy et al. 2012).

The exchangeable K values in the 0-0.1m layer were around the critical soil test range predicted for northern Vertosols (~0.4-0.6 cmol(+)/kg), (Guppy pers. comm.), while there have yet to be any critical ranges for exchangeable K developed for the 0.1-0.3m layer. All soils in the experiment had relatively high ECEC, ranging from 20 to 70 cmol(+)/kg.

RESULTS AND DISCUSSION

Yield responses to deep-placed K and P treatments

Yields from fourteen site years are displayed in Table 2, with each experiment reporting yields from one to three growing seasons. Six sorghum crops have been grown, 3 wheat, 2 chickpea, and 1 each of barley, mungbean and cotton. Responses have differed between sites and years and between crops at a site, but because crops and years/seasonal conditions are confounded, it is difficult to assess whether there are different patterns of treatment response for different species. However some high level response patterns appear consistent at most locations.

Firstly, the treatments with subsoil disturbance but no P or K (0K-P) generally record higher yields than the FR (untreated control) e.g. Capella, Gindie, Dixalea, Jimbour West (Table 2). This suggests some positive effect of the tillage operation and/or the application of basal nutrients (most probably N), S or Zn with yield gains of 16, 12, 8 and 11% respectively. This disturbance effect is also expressed in similar studies exploring deep-placement of phosphorus and can persist for several years (D. Lester, unpublished data).

The remaining effects can be clustered into two categories: 1) no effect, 2) or some increase of either K only, P only or a more substantial additive gain with application of both nutrients together.

The ‘no response’ years can commonly be characterized as either too dry (Jimbour West 2014-15, mungbean) or too wet (Terry-hie-hie 2015, wheat). Dry conditions limited overall crop yield potential and nutrient demand, but responses to K can still be (relatively) substantial. For example, the Terry-hie-hie cotton crop in 2013-14 received very little in-crop rainfall (119 mm) but had a 75% yield increase with 100 K+PS (Table 2). In contrast, the Jimbour West mungbean crop was double-cropped following barley in the 2014 winter season, but only received 50 mm in-crop rainfall, yielded poorly and did not respond to any treatment.

While wet conditions allow higher yields and greater nutrient demand, they also allow crops to utilize the relatively nutrient-rich surface soil layer, resulting in a reduced reliance on deeper-placed nutrient. The wheat grown at Terry-hie-hie in 2015 demonstrated no treatment response, but the in-crop rainfall of 190 mm may have allowed better utilization of native soil K in the 0-0.1m layer.

In other situations a lack of phosphorus and/or potassium response was due to other nutritional constraint. The Dysart 2015-16 sorghum crop is an example where crop nitrogen supply limited yields (indicated by low grain protein concentration, data not shown). This was the third cereal crop on the experimental site and the yield responses in the previous two crops would have removed more nitrogen in grain and reduced soil mineral N supplies. Unfortunately the grower had not increased the fertilizer nitrogen input in response to the higher yield potentials and grain removal facilitated by the phosphorus and potassium applications.

Other non-significant results can be attributed to site variability (e.g. the Chelmsford 2014 wheat crop). In this instance the trend for higher yields with K and P treatments (e.g. 400-700 kg increase was not statistically significant due to high standard errors (data not shown). Using grower co-operators to undertake sowing and other field operations can positively (e.g. timeliness of operation) and negatively (e.g. poor sowing seed) impact on the data produced in these larger scale experiments.

Significant yield increases have been measured with the 0K+P treatment, demonstrating deep-placing P alone can offer some benefit if phosphorus is the main yield constraint. Some large yield increases were recorded in these situations, especially in the sites in Central Queensland. Individual responses to deep phosphorus bands alone included a 17% (556 kg/ha) yield increase in the 2013-14 sorghum crop at Dysart and a 40% (780 kg) increase in 2015-16 sorghum crop at Capella. Responses to deep phosphorus alone have not always been positive, with slight yield decreases recorded at Chelmsford and Terry-hie-hie. The reasons for this effect are not known.

The most consistent and largest yield increases were recorded where potassium and phosphorus were applied together. Application of 100 kg K/ha with P typically increased yields by 100 to 300 kg/ha (roughly 10%) compared to the 0K+P treatment, although at Chelmsford in 2014/15 yields increased by 860 - 900 kg/ha in response to 100 kg K/ha, with or without phosphorus.

Crop K uptake from deep-placed K and P treatments

A subset of site data is presented in Table 3, with other analyses still being conducted. The disturbance effect associated with deep-placement (0K-P) only affected nutrient uptake in the barley and sorghum crops at the Jimbour West site, with other sites unresponsive. Crop recovery of potassium has not been large, although most sites displayed highest uptake with the 100 K treatments. Accurately measuring dry matter production in large field plots with variable plant stands requires large biomass samples, which are themselves difficult to homogenize for chemical analysis, so deriving accurate estimates of differential nutrient uptake are challenging. In addition, differences in crop nutrient content may underestimate fertilizer uptake efficiency if there is substitution of fertilizer for background soil nutrient supply.

Future research directions

The combination of fertilizer rate and band spacing determines the concentration of phosphorus and potassium in the vicinity of the band, which in turn influences the gradient in soil solution concentration from the band to the surrounding unamended soil. Steep gradients will increase the rate of diffusive supply, and potentially the efficiency of nutrient uptake. This is potentially significant for potassium uptake in soils with larger cation exchange capacity, where soil solution concentrations are typically low and strongly buffered by the exchange complex. How different species interact with these combinations of rate and band spacing, and the co-location of nutrients in the band to encourage root proliferation, are areas of future research. Two experiments exploring the application rate x row spacing combination for potassium are currently underway in southern Queensland and northern New South Wales.

A better understanding of potassium fertilizer recovery is needed to predict the potential longevity of these deep band responses and so the frequency of application needed. The use of rubidium as a reverse-tracer has been explored (Hafez and Rains 1972, Hafez and Stout 1973) and revisiting this may be worthwhile to confirm results from the standard mass balance approach.

CONCLUSIONS

Low levels of plant available K in the subsoil (> 0.1m) are restricting cereal, legume and fibre crop yields under some seasonal conditions. Results from the experiments in this study illustrate the complexity of interactions that can occur when multiple immobile nutrient limitations occur under rainfed conditions in clay soils, with the additional complexity of matching nitrogen supply to higher yield potentials that result when constraints are overcome. The residual benefits of deep bands suggest both phosphorus and potassium can be managed holistically across a crop rotation, improving yields but minimizing the frequency of tillage operations in otherwise no-till cropping systems. Research is continuing to explore the longevity of responses, and allowing more data to be gathered on the crop x growing season interaction for prediction of future crop responses.

Further research to explore the interaction of deep placed P and K would be beneficial, as will the exploration of the interaction between different rate/row spacing combinations and the root morphologies of different rotation species.

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ACKNOWLEDGEMENTS
Research has been funded by the Grain Research and Development Corporation (GDRC) under projects DAQ184 and UQ00066. Cotton Research and Development Corporation (CRDC) funded research under UQ1302.

The dedicated field and laboratory work of many technical and farm staff, plus the contribution from our farmer cooperators is gratefully acknowledged.

Table 1. Selected chemical characteristics for K experimental sites.

Depth (m)	pH CaCl2	Colwell P (mg/kg)	Ca (cmol/kg^{-1})	Mg (cmol/kg^{-1})	Na (cmol/kg^{-1})	K (cmol/kg^{-1})	ECEC (cmol/kg^{-1})
Kilcummin (22.15°S; 147.55°E)							
0.0-0.1	7.4	6	36.7	15.3	0.94	0.65	53.6
0.1-0.3	7.9	< 2	34.3	16.4	2.50	0.25	53.5
0.3-0.6	8.0	< 2	30.2	17.9	4.73	0.26	53.0
Dysart (22.49°S; 148.63°E)							
0.0-0.1	7.3	5	25.2	9.9	0.28	0.25	35.6
0.1-0.3	7.5	< 2	19.3	8.7	0.65	0.12	28.8
0.3-0.6	7.8	< 2	18.9	10.9	1.46	0.09	31.3
Capella (22.94°S; 147.80°E)							
0.0-0.1	7	8	51.02	15.58	0.09	0.78	67.5
0.1-0.3	7.2	3	52.31	15.56	0.16	0.32	68.4
0.3-0.6	7.3	< 2	52.04	17.19	0.26	0.24	69.7
Gindie (24.02°S; 148.44°E)							
0.0-0.1	6.7	12	17.4	7.5	0.22	0.31	25.4
0.1-0.3	6.9	4	15.5	7.2	0.43	0.09	23.2
0.3-0.6	6.9	2	18.1	10.1	1.15	0.12	29.5
Dixalea (23.95°S; 150.32°E)							
0.0-0.1	6.5	17	15.8	5.2	0.39	0.23	21.6
0.1-0.3	7.9	3	18.0	6.9	1.54	0.12	26.5
0.3-0.6	8.2	< 2	15.4	9.5	3.40	0.10	28.4
Chelmsford (26.30°S; 151.80°E)							
0.0-0.1	6.4	16	20.81	19	0.57	0.21	40.6
0.1-0.3	7.2	2	20.75	20.69	1.03	0.14	42.6
0.3-0.6	7.8	< 2	19.1	23.68	1.99	0.12	44.9
Jimbour West (26.87°S; 151.08°E)							
0.0-0.1	7.2	37	16.1	9.4	1.26	0.40	27.2
0.1-0.3	7.5	8	13.6	12.3	2.86	0.18	28.9
0.3-0.6	8.1	4	12.9	15.5	5.13	0.22	33.8
Terry-hie-hie (29.68°S; 150.13°E)							
0.0-0.1	7.4	15	20.2	3.7	0.37	0.14	24.4
0.1-0.3	7.7	3	21.2	5.3	0.19	0.30	27.0
0.3-0.6	7.6	< 2	20.2	8.0	0.18	0.80	29.1

Table 2. Change in yield (kg/ha) from Untreated Control (labelled "FR") with K and PS treatments under different crops by site.

Year	FR	0K-P	100K-P	0K+P	25K+P	50K+P	100K+P	LSD (P<0.05)
				Kilcummin				
15 Cp	1765	49	-7	391	414	532	577	130
				Dysart				
13-14 Sg	3178	210	269	556	785	849	792	123
14-15 Sg	2966	114	96	329	434	641	576	124
15-16 Sg	2533	-31	68	108	447	271	197	290
				Capella				
15-16 Sg	1964	312	600	781	782	1019	1071	180
				Gindie				
16 Cp	1677	208	377	463	526	418	482	†
				Dixalea				
16 Wh	3930	295	419	363	428	303	464	†
				Chelmsford				
14 Wh	NA	0	428	445	551	710	627	NS
14-15 Sg	NA	0	864	-245	245	496	655	234
				Jimbour West				
14 By	4162	445	355	519	430	755	820	190
14-15 Mg	425	1	71	-10	-15	55	-4	NS
15-16 Sg	3128	-9	8	74	60	159	197	130
				Terry-hie-hie				
13-14 Ct	239	11	118	44	80	128	176	38
15 Wh	4167	148	106	-88	131	50	31	NS

Cp = chickpea; Sg = sorghum; Wh = spring wheat; By = barley; Mg = mungbean; Ct = cotton
† = not analysed yet; NS = not significant at 5% level

Table 3. Potassium uptake in whole tops at maturity (kg K/ha) from selected K and P treatments under different crops by site.

Year	FR	0K-P	100K-P	0K+P	25K+P	50K+P	100K+P
			Kilcummin				
15 Cp	38	39	36	44	47	43	45
			Dysart				
13-14 Sg	50	50	73	55			82
14-15 Sg	52			35	43		61
			Chelmsford				
14 Wh	NA	71	96	78			90
14-15 Sg	NA	94	118	81	93	99	95
			Jimbour West				
14 By	52	65	73	67			89
14-15 Mg	82						
15-16 Sg	69	80	86	75	79	82	90
			Terry-hie-hie				
13-14 Ct	16	15	27	16			28
15 Wh	64	57	76	59			79

Cp = chickpea; Sg = sorghum; Wh = spring wheat; By = barley; Mg = mungbean; Ct = cotton

Nutrient Expert® – *A* Nutrient Management Decision Support Tool for Soil Health Management and Environmental Sustenance

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Abstract
India is one of the most populous and intensively cultivated regions in the world. Smallholder farmers of India have major dependence on cereal (rice, wheat, and maize) based cropping systems in terms of acreage and number of farmers cultivating those crops. Consequently, maintenance of soil fertility is a must for sustainable agriculture and future food security. However, the fertilizer recommendations for cereals available to farmers are "blanket" and therefore do not take into account the spatial variability in indigenous nutrient supplying capacity of different farms. The situation becomes severe especially with potassium as in large area of Indian soil has high level of exchangeable K leading to the impression for decades that Indian Soil is sufficient in K, ignoring the depletion of non-exchangeable fraction. Moreover, targeting a yield as per the potential of the seed is not becoming possible without balanced application of potassium. IPNI studies have shown that omission of K in the nutrient application can lead to a yield drop of about 1 t/ha. Therefore, a farm specific 4R Nutrient Stewardship compliant precision potassium management is a need for farm profitability, better nutrient use efficiency, and avoiding nutrient mining from soil, all needed towards better soil health for the future. *Nutrient Expert®* for maize, wheat, and rice, developed and validated by IPNI and its partners including CIMMYT, NARES, SAUs, and Industry Associates, is a recent innovation for developing field specific precision fertilizer recommendation tool for individual farmers. *Nutrient Expert®* tool works on the principle of 4R Nutrient Stewardship and utilizes the concept of site-specific nutrient management (SSNM). Farmers' field validation conducted by IPNI have shown that use of *Nutrient Expert®* for fertilizer, especially K recommendation, provides the opportunity to bridge the nutrient-related yield gaps and increase farm profitability while maintaining soil health in an environmentally sustainable manner.

Keywords: 4R Nutrient Stewardship, decision support system, SSNM

INTRODUCTION

Ever increasing world population demands higher production and productivity of crops towards ensuring global food security. At the same time, maintenance of soil fertility is a must for sustainable agriculture and future food security, especially in the South Asian countries like India having higher production demand. Sustenance of inherent fertility of soils depends largely on the replenishment of plant nutrients to the soil that are removed through intensive cultivation practices (Majumdar et al., 2016). However, current nutrient management strategies practiced by most Indian, particularly eastern Indian farmers mainly follow the nutrient management plans based on their own perceptions or influenced by the peers with less input from scientific intervention. In most of the cases this leads to imbalanced nutrient application, resulting lower productivity, lower economic return and larger environmental footprint. This is especially true for smallholder farming system of eastern India. With the limited opportunity for expansion of cultivated area, the needed increase in cereal production can be met by intensifying production of wheat, rice, and maize to reach 70–80% of their potential yields (Cassman, 1999; Dyson, 1999; Dobermann and Cassman, 2002). Intensification will therefore need nutrient management that produces high yields while preserving soil quality and protecting the environment (Pampolino et al., 2012). The challenge gets aggravated when the negative nutrient balance leads towards nutrient mining, especially in the case of potassium leading towards permanent and irreversible damage of soil structure (Majumdar et al., 2015). Therefore a novel strategy is required for more precise plant nutrient

management tailored to the technologies, dynamics, and spatial scales relevant to the cropping system (Dobermann and Cassman, 2002).

As a way forward towards addressing the challenge, International Plant Nutrition Institute (IPNI) with its global partners have come up with the concept of 4R Nutrient Stewardship. The application of 4R Nutrient Stewardship Principles i.e. application of right source of fertilizer at right rate and time through a right placement and method has the potential to reduce nutrient mining from soils. These core principles help manage nutrients in a manner that crop productivity is sustained or improved without soil fertility depletion, farm production economics is improved while environmental impact of agricultural nutrients is minimized. Site-specific nutrient management (SSNM) is a set of nutrient management principles, that aims to supply a crop's nutrient requirements tailored to a specific field or growing environment (Pampolino et al, 2012). The SSNM principle helps implementing 4R Nutrient Stewardship at farm gate. SSNM aims to (a) account for indigenous soil nutrient sources, including crop residues and manures; and (b) apply fertilizer at optimal rates and at critical growth stages to meet the deficit between the nutrient needs of a high-yielding crop and the indigenous soil nutrient supply.

However, implementation of SSNM sometimes become challenge for front line extension system especially for South Asian countries due to the requirement of understanding the subject and comparatively complicated approach (Gabinete and Buresh, 2009). Nutrient Expert® (NE) is a computer based decision support tool that helps crop advisors formulate fertilizer guidelines based on SSNM principles in a way that could be easily used by the extension professionals. The strength of the NE lies in its consideration for the most important factors affecting nutrient management recommendations in a particular location and enables crop advisors to provide farmers with fertilizer guidelines that are suited to their farming conditions. The tool uses a systematic approach of capturing site information that is important for developing a location specific recommendation. Yet, NE does not require a lot of data nor very detailed information as in the case of many sophisticated nutrient decision support tools, which could overwhelm the user. If a soil test is available it can be included, but is not necessary to get a recommendation. It allows the users to draw the required information from their own experience, the farmers' knowledge of the local region, and the farmers' practices. NE can use experimental data, but it can also estimate the required SSNM parameters using existing site information (Majumdar et al., 2014).

Present study highlights the impact of NE® based recommendation for reducing the yield gap while protecting the soil health through the balanced application of potassium across different regions of eastern India vis a vis protecting environment with improved potassium use efficiency.

Impact of Nutrient Expert® (NE) - Maize

Nutrient Expert® (NE) – maize validation and dissemination studies were conducted across different regions of Eastern India where the grain productivity were compared along with other parameters among different nutrient management options including NE and farmers' own fertilizer application practices (FFP). IPNI conducted field experiments across different regions of India. NE maize trials were conducted across different agro-climatic regions and observed significant yield improvement. More in depth study highlights that variation in the rate of potassium application is one of the most important factors for this yield improvement. For example, maize is one of the major crops in one of the eastern India and the maize grain yield were compared across two different seasons (Kharif and Rabi) for a period of four years across 272 locations in the eastern India. It was observed that the fields receiving nutrient management plan through NE significantly ($p \leq 0.01$) improved the grain yield over FFP. The NE plots received significantly ($p \leq 0.001$) higher amount of K_2O and P_2O_5 ($p \leq 0.01$) while rate of N application did not differ significantly ($p \geq 0.05$) (Table 1). It is noteworthy to mention that higher productivity was obtained with the application of the NE recommendation that not only includes change in rates but also change in source, time and place of fertilizer application highlighting the importance of the front line application of the concept of 4R Nutrient Stewardship.

Table 1: Field evaluation of NE maize in comparison with FFP (n = 272).

Parameters	Unit	FFP	NE	NE - FFP
Grain Yield	kg/ha	4,956	6,245	1289***
Fertilizer N	kg/ha	142	139	(-) 3 ns
Fertilizer P_2O_5	kg/ha	53	48	(-) 5*
Fertilizer K_2O	kg/ha	50	68	18***
Fertilizer Cost	INR/ha	4,327	4,409	82*
GRF	INR/ha	67,534/-	86,144/-	18,610/-**

***, **, *: significant at <0.001, 0.01, and 0.05 level; ns = not significant; 1 GRF = gross return above fertilizer cost; Prices (in INR/kg): Maize = 14.50; N = 11.40; P_2O_5 = 32.20; K_2O = 18.80; 1 USD = INR 68 at present exchange rate.

Impact of Nutrient Expert® (NE) - Wheat

A similar validation and dissemination of NE – wheat study was conducted across different parts of eastern India where the wheat grain productivity were compared in different management plans grouped as FFPs and NE based recommendations. NE wheat trials were studied at the farmer's field in 146 locations. In the case of NE - wheat it was observed that NE based recommendations significantly ($p \leq 0.001$) improved the average grain yield over FFPs (Table 2). The difference in nutrient management options in NE over FFP highlights that nutrient management has a great influence in productivity enhancement. The study more specifically suggests that K_2O application significantly ($p \leq 0.001$) influenced the grain increase along with P2O5 ($p \leq 0.001$) and N ($p \leq 0.01$).

Table 2: Field evaluation of NE wheat in comparison with FFP (n = 146)

Parameters	Unit	FFP	NE	NE - FFP
Grain Yield	kg/ha	4,030	4,400	370***
Fertilizer N	kg/ha	112	117	5**
Fertilizer P_2O_5	kg/ha	64	57	(-) 7***
Fertilizer K_2O	kg/ha	39	78	39***
Fertilizer Cost	INR/ha	4,071	4,636	565**
GRF	INR/ha	61,458/-	66,864/-	5,406/-**

***, **, *: significant at <0.001, 0.01, and 0.05 level; ns = not significant; 1 GRF = gross return above fertilizer cost; Prices (in INR/kg): Wheat = 16.25; N = 11.40; P_2O_5 = 32.20; K_2O = 18.80; 1 USD = INR 68 at present exchange rate.

Impact of Nutrient Expert® (NE) – Rice

Nutrient Expert – Rice validation trials were conducted across 57 different locations. In this study NE – rice based recommendations were compared with FFPs. It was observed that there was significant ($p \leq 0.001$) yield improvement in NE plots compared to FFPs (Table 3). This could be attributed to the balanced fertilizer application approach with significantly ($p \leq 0.001$) higher application of K_2O and P_2O_5 ($p \leq 0.001$) compared to existing fertilizer application practices considered by the farmers. The highest change was observed in K_2O application where the application suggested by NE – rice was on an average more than three times of the average K_2O application in FFP.

Table 3: Field evaluation of NE wheat in comparison with FFP (n = 57)

Parameters	Unit	FFP	NE	NE - FFP
Grain Yield	kg/ha	3,628	4,334	706***
Fertilizer N	kg/ha	122	110	(-) 12 ns
Fertilizer P_2O_5	kg/ha	40	31	(-) 9**
Fertilizer K_2O	kg/ha	18	55	37***
Fertilizer Cost	INR/ha	3,017/-	3,286/-	565**
GRF	INR/ha	50,314/-	60,424/-	10,110/-**

***, **, *: significant at <0.001, 0.01, and 0.05 level; ns = not significant; 1 GRF = gross return above fertilizer cost; Prices (in INR/kg): Rice = 14.70; N = 11.40; P_2O_5 = 32.20; K_2O = 18.80; 1 USD = INR 68 at present exchange rate.

Summary:

Present report highlights the Nutrient Expert performance for three different cereals across different locations of eastern India and have shown that NE is an effective means of providing nutrient recommendation that can increase yields and profits, compared to the farmers' current nutrient management practices. NE accounts for the important field specific factors affecting its recommendations, that makes it an excellent tool for providing tactical information to crop advisors and farmers as well as strategic information to high-level decision makers.

It is noteworthy to mention that nutrient mining in soils have the potential to create food security challenges in India, especially in eastern India. Along with crop removal there are several other avenues, including leaching, and erosion through which native nutrients can be lost from soils. Replenishing soils through adequate nutrient application based on the 4R nutrient stewardship guidelines, and rigorously factoring in nutrient off-take from the agricultural fields, is necessary to maintain soil fertility levels in intensive production systems. This is especially true for potassium in Indian context as there is a very few applications of this particular nutrient. Nutrient Expert based fertilizer application provides farmers recommendations that consider K_2O application while considering the other agronomic management practices to provide a practical solution. Present study also highlights the requirement of higher dose of K_2O compared to existing fertilizer application practices that can not only improve the yield and economic benefits but also can be considered as sustainable mean for maintaining soil health status.

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Frontier Science to Practice: The Role of Precision Ag

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Abstract

Precision agriculture (PA) tools, technologies, and information management strategies are becoming more and more mainstream in many regions of the world. Several technologies such as automated guidance, yield monitoring, and georeferenced soil sampling are no longer considered premium services, but are standard offerings from many agricultural providers. Information needed for farm management is also more accessible and delivered faster through mobile device technology than ever before. Adoption of these types of technologies that don't depend on site-specific information to extract value has been rapid and steady. Others that require agronomic calibration or some level of data management such as remote sensing, soil management zone delineation, and using yield maps to characterize and understand field variability have been a much greater challenge to move into practice than many would have predicted two decades ago. The objective of this presentation is to discuss opportunities for PA to enhance K management and current industry and academic efforts to overcome existing barriers to adoption.

Socio-economic Characteristics and Resource Endowment of Smallholder Farmers Governs Potassium Fertilizer Use and Yield Variability in Telangana, India

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Abstract
Maize is an important crop of Telangana, grown in 8 out of the 10 districts of the state. Fertilizer nutrient use in Telangana was 1.34 million t, of which K_2O use accounted for only 6% of the total nutrient use. Widespread potassium depletion of agricultural soils is one of the most important bio-physical factors limiting maize production in the region. Lack of awareness among growers about the importance of K fertilizer use in maize, and farmer's socio-economic and resource endowment factors attributed to inadequate application of potassium. A study was initiated to understand the maize yield variability and K fertilizer use trends in the major maize growing districts of Telangana and its associated relationship with different socio-economic aspects of farmers. Grain yield of maize varied from 6.3-10.0, 2.5-7.0, 6.0-7.5, 1.2-6.3 t/ha with an average of 7.4, 4.9, 6.8 and 2.9 t/ha in the important maize growing districts of Karimnagar, Medak, Nizamabad and Mahabubnagar of Telangana. Yield variability in the study region was attributed to variability in the rainfall pattern, access to alternative irrigation sources, variable rates of fertilizer application and experience of farmers in maize growing. K use was highest in Karimnagar (127 kg/ha), followed by Medak (43 kg/ha), Nizamabad (36 kg/ha) and Mahabubnagar (0.7 kg/ha). Farmer's higher education and better understanding on the importance of K response in maize led to balanced K application in Karimnagar and Nizamabad. Farmers in Medak and Mahabubnagar neglected K application, which led to lower maize yields. In Karimnagar, maize yield was significantly and positively correlated with farm income, whereas, negatively and significantly correlated with non-farm income, indicating that investment from farm income helped in higher maize yields. In Mahabubnagar, negative correlation between yield and farmer age indicated that there is a need to encourage young farmers to become involved in farming for improving the productivity of maize. The above study identified the opportunity to rationalize K fertilizer recommendations using 4R principles based on farmer's resource endowment and socio-economic characteristics to improve productivity and profitability of growing maize in Telangana.

Keywords: Maize, Yield variability, K use trends, Resource endowment, Socio-economic characteristics

INTRODUCTION

Maize is an important field crop in the new state of Telangana in terms of acreage, production and utilization for food and feed purposes. The introduction of hybrid maize has increased the production potential of maize systems. However, the present productivity level of maize in the state is low due to several production constraints at the farm level. Widespread nutrient depletion of agricultural soils is one of the most important bio-physical factors limiting small scale maize production across Asia. Literature suggests that the ability of soil to supply nutrients naturally, as well as nutrient recovery for maize, are location specific (Witt et al., 2009). Therefore, enhancement of maize productivity can largely be achieved through proper supplementation of plant nutrition.

The emerging maize systems in India are characterized by improved agronomic, breeding and biotechnological advancements, while the nutrient use was limited by unbalanced plant nutrition with very high use of N coupled with less use of P and negligible use of K fertilizers and micronutrients (Jat et al., 2013). Potassium application to crops did not receive much attention in India till the 1980s because of the general belief that Indian soils were well supplied with K. However, potassium requirement of crops is in general identical to N, and 3-5 times higher than P. Majumdar et al (2012) reported that the average yield loss of maize in Indo-Gangetic plains due to skipping of K application was 700 kg ha^{-1}. The average K fertilizer use in India over the last 30 years has only been about one-seventh of N and about one-third of P. The fertilizer consumption scenario over the past decades showed that potash contributed to less than 10% of the total nutrient consumption in the country. Similarly, in the state of Telangana, the fertilizer nutrient use during 2013-14 was 1.34 M t, of which N, P_2O_5 and K_2O use accounted for 73, 21 and 6%, respectively (FAI, 2014). Improved K management in maize will have great potential for improving the overall productivity of maize systems in this region.

The 4R Nutrient Stewardship concept, and its implementation through site-specific potassium management (SSNM), helps to achieve agronomic and economic benefits while maintaining socially and environmentally sustainable crop production systems. However, to provide appropriate recommendations, a SSNM-based nutrient recommendation needs to be integrated with the classification of farmers as per their resource endowment. Grouping farmers within a domain in different resource endowment classes is an essential step in the realistic evaluation of the constraints and opportunities that exists within farm households for appropriate interventions (Banerjee et al., 2014). The current study investigates the K fertilizer use by farmers in maize and their associated socio-economic factors in determining the maize yield variability of the state.

METHODOLOGY

A joint collaboration was established between Professor Jayashankar Telangana State Agricultural University (PJTSAU) and the International Plant Nutrition Institute (IPNI) to initiate a study on agronomic, economic, social and environmental benefits of improved nutrient management practices in maize production systems under variable farm size, climate, soil fertility conditions and farmer resource endowment in Telangana. This paper considers a part of the study, which discusses the maize yield variability and K fertilizer use trends in four districts of Telangana and its associated relationship with different socio-economic aspects of farmers.

A rapid rural survey, to assess socio-economic and biophysical aspects of farmers, was conducted in four maize growing districts of Telangana. Based on the criteria of area under maize cultivation, prevailing yield levels, and access to water while growing crops (irrigated or rainfed situations), two established and two emerging maize growing districts were selected. Of the eight major maize growing districts in Telangana (Table 1), Karimnagar and Medak are chosen as the established districts while Nizamabad and Mahabubnagar are considered as the emerging districts. Karimnagar and Nizamabad falls under northern Telangana zone, with red earth soil type having a mix of loamy soils (Chalkas) and black cotton soils and with an annual rainfall of 900-1150 mm. Medak district comes under central Telangana zone while Mahabubnagar is in southern Telangana zone with normal rainfall of 800-1150 and 500-670 mm, respectively. The soil type in Medak was red earths with loamy texture (chalkas), red sandy soils and black cotton soils in pockets whereas the soil type in Mahabubnagar was predominantly red soils with chalkas.

Table 1. Area, Production and Productivity of maize in Telangana

District	Area (ha)	Production (t)	Productivity (kg/ha)
Adilabad	22020	68773	3123
Karimnagar	108706	568675	5231
Khammam	32057	172456	5380
Mahabubnagar	118589	55000	4729
Medak	142205	643031	4522
Nizamabad	94834	505743	5333
Ranga Reddy	42971	166701	3879
Warangal	80092	387607	4840
Total	641474	2567986	4630
Source: (http://www.telangana.gov.in)			

Three villages in each of the selected districts were chosen in consultation with the experts from the agricultural university and staff of the department of agriculture. Villages with high maize acreage under the identified maize growing seasons were selected for the survey. A total of 15 maize farmers in the villages were then selected for a detailed survey through systematic sampling. The number of maize farmers in each village (n) was divided by fifteen (n/15 = k), where k represented the frequency of sampling or the number of households between surveyed households. The farmers in each village were interviewed on socio-economic profile, farm profile, farm asset inventory, crop management practices, maize production related problems, soil resource use, and water resource use. From the survey, information on maize yield variability and the extent of P fertilizer use were determined in addition to identifying the major socio-economic factors responsible for higher maize yields in the study region.

Maize yield variability in Telangana

The survey indicated high maize yield variability among farmers in the established and emerging maize growing districts of Telangana (Figure 1). In the established maize growing districts, grain yield varied from 6.25-10.0 t/ha with a mean yield of 7.4 t/ha in Karimnagar. In Medak district, the grain yield ranged from 2.5-7.0 t/ha with an average yield of 4.91 t/ha. The higher yield in Karimnagar may be attributed to a high average rainfall (1025 mm) as compared to 975 mm in Medak district. Also, the rainfall productivity (kg yield per mm of rainfall) of Karimnagar (7.2) is higher than Medak (5.0), and all the surveyed farmers in Karimnagar have access to deep bore well and farm ponds, whereas, only 46% of farmers in Medak district have access to bore well as an alternative source of irrigation to maize crop. From the survey, it was revealed that an average maize farmer in Karimnagar practicing farming for 23 years have the experience of growing maize for almost the same period (average of 21.5 years). In Medak, even though most of the farmers have farming experience of more than 23 years, they have the experience of growing maize only for the last 10 years (Figure 2). The longer experience of Karimnagar farmers may have helped them fine tune agronomic practices that attributed to higher maize yield over the farmers in Medak district.

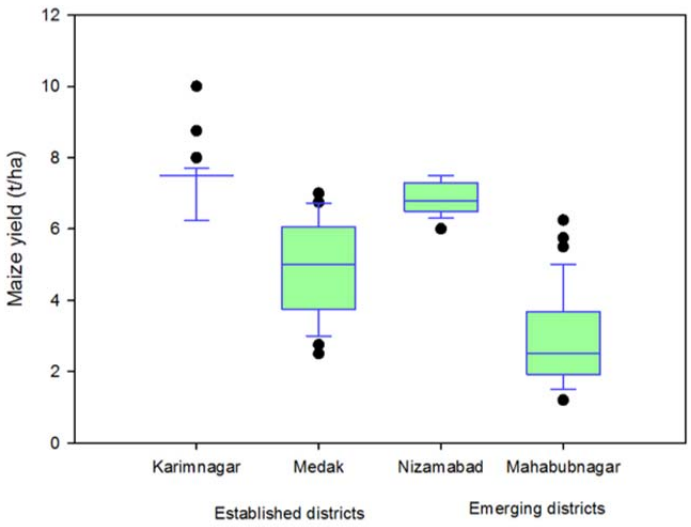

Figure 1. Yield variability in the established and emerging maize growing districts of Telangana

Boxes represent data within the first and third quartiles (interquartile range). The line inside the box denotes the mean. Lines extending beyond the interquartile range denote the 10th to 90th percentile of the data. Statistical outliers are plotted as individual points outside these lines

In the emerging maize growing districts of Telangana, maize yield in Nizamabad averaged 6.83 t/ha and ranged from 6.0 to 7.5 t/ha, indicating a narrow variability among the maize-growing farmers in the district (Figure 1). Maize yield in Mahabubnagar averaged 2.91 t/ha and ranged from 1.2 to 6.25 t/ha, registering the lowest maize yield among the four districts considered under the study. The survey indicated that the respondent farmers have the experience of growing maize only during the last five years even though they have been growing crops over the last 23 years (Figure 2). The survey also indicated that farmers in this district grow maize only during kharif season, completely dependent on rainfall, and keeping the land fallow during the rest of the year. Mahabubnagar is the second largest district in Telangana growing maize next to Medak (Table 1) and based on the survey data, it was observed that farmers have the experience of growing maize in the last five years even though they have the farming experience of more than 20 years (Figure 2). From this observation, it may be inferred that the majority of area expansion under maize has happened in the recent past indicating maize as the potential option of crop diversification during the kharif season where crop is grown predominantly under the rainfed situations.

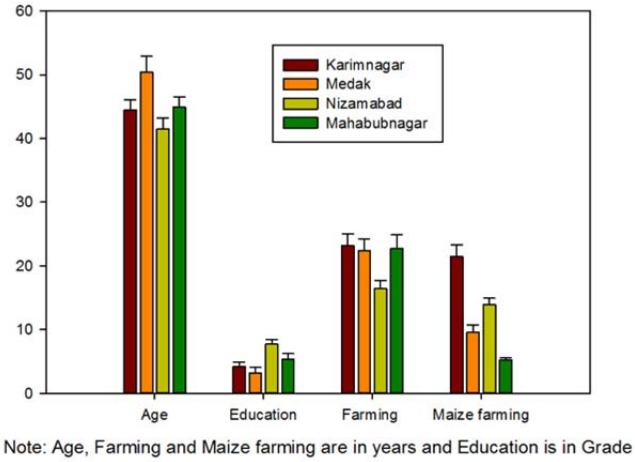

Figure 2. Characteristics of maize growing farmers in Telangana

Fertilizer K use trends in Telangana

The total nutrient use (Table 2) in the maize growing districts of Telangana was highest in Karimnagar (404 kg/ha), followed by Medak (402 kg/ha), Nizamabad (343 kg/ha) and Mahabubnagar (308 kg/ha). Whereas, the partial factory productivity, an indicator of productivity of maize crop in comparison to its nutrient input, was highest in Nizamabad (19.9) followed by Karimnagar (18.3), Medak (12.2) and Mahabubnagar (9.4), respectively. This gives an indication that farmers in Nizamabad and Karimnagar followed a generally better fertilizer application strategy, which is probably associated with the experience of maize farming. Figure 3 also illustrated that the K fertilizer use was 32, 11, 11 and 1% over the total nutrient use in Karimnagar, Medak, Nizamabad and Mahabubnagar district, respectively. Farmers in Karimnagar growing maize during the last 22 years had a better understanding of the importance of K response in maize and thus applied adequate K_2O rates to an extent of 127 kg/ha (Figure 3). Similarly, farmers of Nizamabad, owing to higher education (average of Grade 8) and long experience of maize farming (average of 14 years), understood the importance of balanced fertilization and restricted the nutrient use to a narrow range of 208-260, 64-80 and 32-40 kg/ha of N, P_2O_5 and K_2O, respectively (Table 2). Maize growing farmers in Medak and Mahabubnagar district applied imbalanced rates of N (140-488 and 75-620 kg/ha, respectively) and P_2O_5 (75-473 and 0-230 kg/ha, respectively) and neglected the application of K_2O (0-150 and 0-30 kg/ha, respectively), which resulted in unbalanced application of nutrients and led to lower maize productivity of 4.91 and 2.91 t/ha (Figure 1), respectively.

Table 2. Fertilizer nutrient use trends in maize growing districts of Telangana

District	N		P_2O_5		K_2O		Total
	Range	Mean	Range	Mean	Range	Mean	
Karimnagar	80-286	201	0-150	76	30-300	127	404
Medak	140-488	228	75-473	131	0-150	42.5	402
Nizamabad	208-260	234	64-80	73	32-40	36	343
Mahabubnagar	75-620	207	0-230	100	0-30	0.7	308

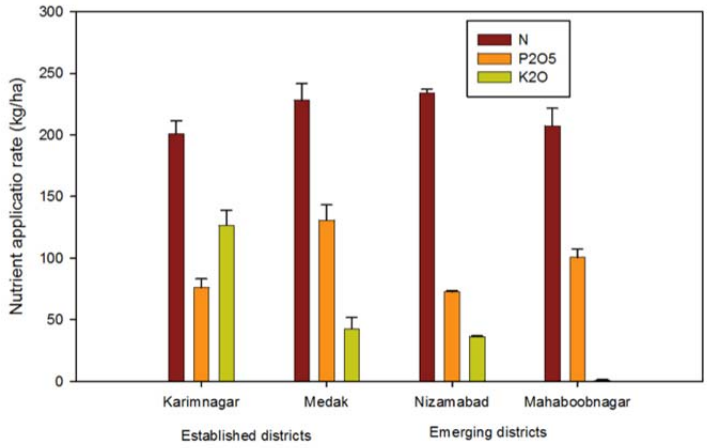

Figure 3. N, P_2O_5 and K_2O fertilizer use trends in maize growing districts of Telangana

Relationship between maize yield and the socio-economic aspects of the farmer

In Karimnagar, the yield of maize was significantly and positively correlated with the age of farmers and farm income, whereas, negatively and significantly correlated with the non-farm income (Table 3). This probably confirms that experience of farmers and investment from farm income helped in achieving higher maize yields in Karimnagar. Negative correlation between maize yield and non-farm income suggested that farm families were more dependent on non-farm income and probably showed lesser attention to agronomic practices, thus adversely affecting the maize yields. However, maize grain yield was negatively and significantly correlated with the age of the farmers in Nizamabad and Mahabubnagar. The average age of farmers in Nizamabad was 41(ranged from 24-70) and the average yield of maize (Figure 1) was the second largest (6.8 t/ha, next to Karimnagar) among the surveyed districts. This indicated that the young farmers in the district contributed to higher maize yield in Nizamabad, which was categorized as the emerging maize growing district. In Mahabubnagar, the average age of the farmer was 45 and the average maize yield was 2.9 t/ha. The negative correlation between yield and farmer age probably indicated that the older farmers were associated with maize growing and there is a need to encourage young farmers to become involve in farming for improving the productivity of maize in Mahabubnagar.

In Nizamabad, farm income, total income and farm size were negatively and significantly correlated with maize yield (Table 3). This indicated that the small farmers with low farm or total income produced higher maize yields, whereas big farmers with high income obtained lower maize yields. This trend suggested that achieving high maize yields is a top priority for small farmers for their sustenance, and interventions should aim at efficient utilization of available resources to maintain high, profitable maize yield. Bigger farmers with higher incomes have opportunities to improve maize yield through higher investment and better yield targeting. In Karimnagar and Mahabubnagar, farmer's income was positively and significantly correlated with maize yield suggesting higher investment in maize production (Table 3).

Table 3. Relationship of maize yield and K fertilizer use with different socio-economic factors of farmers in maize growing districts of Telangana

District	Parameter	Relationship	Age	Education	Years of farming	Farm Income	Non-farm Income	Total Income	Farm Size
Karimnagar	Maize Yield	r value	0.28	-0.28		0.76	-0.64		
		P-value	0.06	0.02	ns	0.04	0.05	ns	ns
	K_2O	r value						0.39	
		P-value	ns	ns	ns	Ns	ns	0.04	ns
Medak	Maize Yield	r value		0.31					0.43
		P-value	ns	0.01	ns	Ns	ns	ns	0.02
	K_2O	r value		0.23			-0.21		-0.22
		P-value	ns	0.02	ns	Ns	0.03	ns	0.01
Nizamabad	Maize Yield	r value	-0.8			-0.58		-0.693	-0.84
		P-value	0.04	ns	ns	0.04	ns	0.04	0.03
	K_2O	r value	-0.8		-0.49	0.42			0.49
		P-value	0.04	ns	0.01	0.01	ns	ns	0.05
Mahabubnagar	Maize Yield	r value	-0.3			0.38	0.35	0.368	0.25
		P-value	0.04	ns	ns	0.01	0.01	0.012	0.01
	K_2O	r value							
		P-value	ns	ns	ns	ns	ns	ns	ns

The pair (s) of variables with positive correlation coefficients and P values below 0.05 tend to increase together. For the pairs with negative correlation coefficients and P values below 0.05, one variable tends to decrease while the other increases. For pairs with P values greater than 0.05, there is no significant relationship between the two variables. ns indicate non-significant

Relationship between K_2O use and the socio-economic aspects of the farmer

The extent of potash use when compared with the age of the farmer revealed a significantly negative relationship in the district Nizamabad, indicating that the level of awareness on the use of K fertilizer was higher with the younger farmers in comparison to the older farmers. These findings when combined with a significantly positive relationship between K use and education levels in the district Medak revealed that irrespective of age of the farmer, better education of farmers helped in practicing right rates of K fertilizer application. Similarly, farm income and farm size showed a significant and positive relationship with the amount of K use in the district Nizamabad (Table 3). Gerendas et al., (2016) studied why the Indian farmers are not using balanced and adequate quantity of K fertilizers and reported that lack of awareness, poor knowledge and limited financial resources attributed to low K fertilizer use by the farmers. The study also highlighted the fact that farmers perceived potassium as a quality enhancing nutrient rather than the yield building nutrient and the awareness level of farmers are higher for zinc than potassium. The negative and significant correlation between the K fertilizer use and years of farming in Nizamabad district indicated that farmers' less experience in maize farming resulted in limited understanding on the benefits of adequate K fertilizer use and restricted farmers from adequate application of K to maize. Interventions to improve awareness among the farmers about 4Rs of K fertilizer use in the maize growing districts of Telangana may improve farm profitability. The results also highlighted the need for extensive and sustained market development efforts to improve K consumption in the state of Telangana.

SUMMARY

The above study helped in understanding the maize yield variability and the K fertilizer use trends in the two established and the two emerging maize growing districts of Telangana. The relationship between the maize yield and the socio-economic aspects of farmers was also well established. There is an opportunity

to rationalize K fertilizer recommendations based on 4R principles and farmer socio-economics to improve the productivity and profitability of maize production in the newly formed state of Telangana.

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Improving the Accuracy of Potassium Recommendations

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Abstract

From a scientist's perspective, the evidence-based recommendation is theoretically proven by sufficient supporting research and is explicit in terms of the precision and accuracy for a given inference space. From a user's perspective, a desirable recommendation is credible and customizable for local agronomic conditions and farm enterprise objectives inclusive of risk tolerance and varying time horizons. Further, users increasingly expect to inform the recommendation with their own data, which they may consider proprietary and of direct economic value to them. The common interest within the somewhat disparate goals of scientist and user is for data-driven solutions. However, the limited funds and current priorities of most public research agendas make it unlikely that all the scientific unknowns regarding K management will be adequately and expeditiously addressed via empirical, public sector research. Artificial intelligence (AI) and machine learning offer the opportunity to create a novel, public-private collaboration for a framework to deliver improved accuracy and utility in K recommendations. The strategy has the potential to (i) leverage the scientific research to date by harnessing private data to increase the inference space of scientific research without compromising individual privacies, (ii) rapidly surface most influential diagnostics for profitable K management and (iii) create a model for open-source "self-improving" nutrient management recommendations as a public good or service. Here we review the data that could be harnessed and the barriers and challenges to citizen science and to assembling and maintaining the disparate data sources required to support the framework. We discuss the K cycle and its uncertainties in the context of decision trees and other approaches to supervised machine learning but also consider the opportunities that may be provided by unsupervised approaches. With no known environmental and associated regulatory contexts to consider and a host of known limitations to current recommendations, K is the ideal nutrient through which to explore AI's use in nutrient management planning.

Connecting Frontier Science to Frontier Practice: How do we Increase the Impact of Scientific Findings on Soil and Crop Management of Potassium in the Field?

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Abstract
R. K. Bergethon is quoted as saying that it is not good to know more unless we do more with what we already know. Clearly, there is much we have to learn about prediction of potassium (K) needs of cropping systems. But, there is much we already know. Our primary challenge today is to better utilize existing knowledge of K in cropping systems when offering management guidance to farmers and to deliver that guidance in credible, usable forms appropriate for the farmer's technology environment. The science exists to develop plausible solutions to many of the problems associated with K management today, but it has not been integrated into decision support systems appropriate for farmer adoption. To do so will require trans-disciplinary collaboration across the research, extension, analytical laboratory, fertilizer production, and local service provider communities with farmer engagement along the way. Rigorous, systematic synthesis of relevant literature and evaluation of existing field and laboratory technologies will be essential. This conference is intended to contribute to that effort. To have traction today, solutions will require a solid transparent data foundation, to guide question development, meet the empirical needs of models, and to validate performance and efficacy of the proposed solutions. Adoption of solutions and filling knowledge gaps for K management both suffer from the insidious nature of K deficiency. Seldom does K deficiency result in catastrophic failure of the crop as is frequently the case with nitrogen deficiency or pest outbreaks. The result is an underappreciation for the severity of the problem. This intensifies the challenge of both solution implementation and of funding to develop solutions and fill knowledge gaps. Stakeholder cooperation is necessary to shine a light on the need for education, research and technology transfer to better connect the frontiers of K science to the frontiers of K practice.

DRIVERS FOR CHANGE

This conference illustrates the substantial growth that has occurred in our basic knowledge of the mechanisms of K cycling in soils, its function in plants and animals, and the potential implications of this new knowledge on K management. The major challenge before us now is to put this knowledge to use in the cropping systems of the world. R. K. Bergethon is quoted as saying that it is not good to know more unless we do more with what we already know (Bullock et al. 2007). Doing more with K knowledge requires that change takes place in the process of on-farm decision making and in the services supporting that process. Farmers must then be convinced to incorporate those changes into their operation.

Change does not always come easy in agriculture and varies markedly across interventions.

- **GMO Adoption**: One of the most rapidly adopted technologies in agriculture has been genetically modified organisms (GMOs; USDA 2016). For example, the fraction of planted area in herbicide tolerant soybeans in the US went from <10% to 75% in just 6 years. Insect resistance (Bt) corn planted acreage in the US went from <10% to 75% in 16 years. These were non-disruptive changes for farmers relative to equipment, knowledge and time, and generally made management easier and more effective.
- **Guidance Systems**: Another rapidly adopted practice has been use of guidance systems. A survey of Midwest US input and service providers in 2015 reported that the market area using GPS guidance with autosteer went from <5% to 64% (predicted) in 13 years (Erickson & Widmar 2015). The same survey reported adoption of auto control/auto steer by input and service providers going from <10%

to 75% in 9 years. Again, these were non-disruptive changes for both farmers and their suppliers but they did require an investment in additional equipment.

- **No-till**: Adoption of no-till is another story entirely. In the major corn/soybean growing region of the US, even after several decades of availability of the needed technologies, no-till or strip till occupies only about 33% of the corn, soybean, wheat and cotton area (Wade et al. 2015). Across North America and for the entire world, 15% and 9% respectively, of arable cropland is estimated to be in conservation agriculture (Kassam et al. 2014). The adoption rate has been much slower than the other two examples. Several reasons exist for slower adoption of changes in tillage systems, but a major factor is the disruptive nature of the change. It alters numerous management practices, requires new knowledge and skills, and can involve a transition period with negative impacts on productivity.

These examples illustrate that non-disruptive management practice changes can be adopted rapidly, partially due to the perception of limited risk. In the case of GMO adoption, farmers perceived that risks of weed pressure and insect damage could be significantly reduced simply by changing what seed was placed in the planter, although that seed did come at a higher cost. Guidance systems were more disruptive, but farmers perceived that the benefits (more efficient use of crop inputs, improved field operation logistics, and freeing drivers to do other tasks during auto-guidance) outweighed the costs (greater cost and greater technical expertise to install and operate equipment and software). Adoption of no-till has been much lower, particularly in cooler and wetter parts of the Corn Belt, where documented reductions in yield with no-till adoption point to significant risk, especially considering the significant equipment investments. In the more arid western U.S., no-till adoption has been greater, since moisture conservation provided significant benefits that outweighed the costs.

The level of risk or uncertainty is a significant factor in adoption rates. Yoon & George (2013) assert that a lack of adoption is not necessarily a technical issue nor an inability to learn. Rather, it often is the behaviour of individual farmers in the face of risk, in particular, market failure. For scientifically sound improvements to take hold, they must occur with the engagement and cooperation of researchers, extension, laboratories, the fertilizer industry, and local service providers, all focused on providing solutions to existing K management problems and helping manage the risk of needed changes. Commodity traders and processors may in some cases play important roles in market related risk management.

DECISION UNCERTAINTIES

Farmers base their crop management decisions on:

(1) **Their own experience and that of their neighbors.** However, due to the limited extent or range of their own experience they have difficulties relating a particular practice or experience to a particular set of conditions. Thus farmers are often not sure if an exceptionally good or bad outcome is due to chance effects such as a favorable weather and soil combination or whether it was due to a given combination of management practices (for example increased K applications).

(2) **Recommendations from scientists, extension agents and other "experts".** These advisers instruct farmers on how to grow their crops based on information derived from both controlled experiments carried out in similar conditions or in the same recommendation domain and / or based on their own experience (Norman and Collinson, 1985).

(1) and (2) can lead to:

(i) **Rejection of technology by farmers** that was selected by researchers which does not do well under real farm conditions.

(ii) **Rejection of technology by experts** because it did not perform well in trials, but might have done well under commercial conditions.

(iii) **Adoption of successful technology** (Francis and Hildebrand, 1989).

Furthermore, recommendation domains may be poorly defined, or the precise conditions of a block or field may not coincide with a specific recommendation domain. All decisions are affected by uncertainty

and in a practical sense, the value of information that science provides is defined by the improvement of decisions that it enables. This is information that farmers value highly, because it takes out key uncertainty from decisions. The challenge is to identify what uncertainties obstruct better use of existing K knowledge by farmers.

Rowe (1994) characterizes decision uncertainties generally according to four dimensions:

1) **Metric.** 'How big is it?' A common focus for scientists but clearly a major concern to growers who often have only a vague idea of average conditions and even less idea of deviations away from the average. As an example, soil testing, on-farm omission plots, and tissue testing have been used to quantify how big the need for K is in different areas (Dahnke 1990) and this dimension can vary substantially across a field (Mallarino 1996) or a landscape (O'Green et al. 2008) as well as with depth (Holanda et al. 1988; Jobbágy & Jackson 2004);
2) **Temporal.** 'How does it fluctuate?' For instance, phyto-available K in soil varies with soil moisture fluctuations throughout the season (Franzen 2011), but more broadly, so do market risks, with input and land costs and commodity prices having significant changes over time.
3) **Structural.** Are all necessary factors included in the decision? This is commonly of less concern to scientists, many of whom will seek clarity of result over relevance to a broad range of constituents. However, crop advisers will have to factor many aspects of farmer decision-making into a K recommendation for it to be implemented. Failure to address all major aspects of a problem can be fatal for the practical decision-maker.
4) **Translational.** How is the decision framed? How influential are values and beliefs to the perception of the outcome?

A particular challenge in K management is the insidious nature of most K deficiencies. With nitrogen (N), serious management problems are often catastrophic where it is painfully obvious that the crop is suffering and requires attention. In extreme cases, K deficiency can also be catastrophic where clear deficiency symptoms appear along with stunted growth. However, K deficiencies are often less pronounced, without clear symptoms, causing such problems to go undetected and providing less incentive for a change in practices to address the cause of the problem – termed 'hidden huger' in past literature. This insidious nature will make building awareness of K management problems an essential component of the process for connecting frontier science to frontier practice. Such awareness is essential for accurate risk assessment.

STEPS IN DEFINING SCIENCE-BASED SOLUTIONS TO K MANAGEMENT PROBLEMS

At its broadest level, science supports change through prepositional and prescriptive science (Mokyr 2002). Prepositional science provides fundamental insight about 'how the world is': the role of K in plant physiological functions, the release of K by soil minerals, etc. Prescriptive science provides 'technological recipes' that use fundamental knowledge to achieve goals: recommendations that have the 4Rs as their goal, applying K in the right form, at the right rate, in the right place, and at the right time. Hence, scientific insight is not limited to fundamental explanations of how the world works. Equally, the value of science to agriculture is not limited to fundamental insights of how agriculture 'works' (although long-term progress certainly depends on it).

Prepositional science informs prescriptive science, and the success or failure of prescriptive science informs prepositional science. Prepositional science has revealed factors that prescriptive science will need to incorporate in the future:

- **Prediction (likely through modeling) of flux throughout the soil profile.** This includes quantification of immediately plant-available K but also the interaction between K forms, soil water content and root distribution. Quantification of the contribution from mineral dissolution may be more important than we have assumed in the past and the impact of interlayer K release

or fixation must be accounted for if system K balance and changes in measured soil K levels are to be interpretable.

- **Prediction of crop demand for K and the quantity removed in crop harvest.** Successful management of K requires that potential K flux is sufficient to meet crop demand in total for the season and throughout the growth cycle. Species and varieties can vary markedly in both K uptake and in the concentration in harvested plant components and they show variability across sites and years. Reasonable site-specific estimates are important components for defining supplemental K needed to fill the gap between potential flux and anticipated demand and for determination of sustainability metrics. In addition, quantifying the pool of non-harvested plant K is helpful in understanding the biocycling of K and the resulting redistribution consequential for the following crop and for balance considerations. Some of these estimates can be made using precision agriculture technologies such as yield monitors and various proximal and remote sensing strategies
- **K "holding capacity".** In soils with low cation exchange capacity, it can be critically important in rate, timing and placement decisions to avoid leaching losses or seedling injury. At some point recommendation systems need to evaluate this potential problem.

Supplemental K needs and other K management guidelines then need to be defined based on integration of the above factors into a recommendation framework. Doing so will require prediction of recovery efficiency of added K in as site-specific of an approach as is possible and practical. The framework should also provide insights into interpretation of mass balance calculations. Due to the numerous potential fates of applied K other than in harvested plant components or traditional soil test extractable forms, management decisions and confidence could be improved by providing such insights. A strategy for developing a K recommendation framework that incorporates the factors mentioned above was developed in a frontiers of K science workshop that was part of the 2015 International Symposium on Soil and Plant Analysis (International Plant Nutrition Institute 2015; Figure 1).

As discussed above, for a more comprehensive approach to K management to become adopted, it must consider the drivers for change and decision uncertainties. Identifying non-disruptive interventions would likely accelerate adoption in this context. Once a basic framework is developed that identifies essential components, parameters and output, the appropriate user interface can be developed using best available surrogates for missing information. That interface could range from models requiring substantial analytical input and associated data to those that can operate with very limited analytical data from the specific site in question. An example of the latter is Nutrient Expert (Pampolino et al. 2012), which was created for small-holder systems in the developing world and uses carefully refined questions that farmers can answer based on their own observations and historical knowledge of the field.

STAKEHOLDERS AND THEIR ROLES

As this conference has demonstrated, much of the science exists to develop plausible solutions to many of the problems associated with K management today. However, it has not been integrated into a framework from which decision support systems can be developed to guide source, rate, time and place decisions and practices. Doing so is no small undertaking as it will require trans-disciplinary collaboration of researchers and extension specialists across numerous scientific disciplines, cooperation from analytical laboratories and other data providers, the involvement of fertilizer producers, and a willing local product and service provider community that will engage growers in the adoption process and in many cases with the discovery process as well.

A partial list of critical stakeholders and their potential roles follows.

- **Farmers or growers:** They are of course the end user and implementers of the products developed. They are also often the first to identify problems with current practices and can help set priorities for research and development. To an increasing degree today, they can also be participants in generating data in the discovery process via "citizen science" approaches.
- **Research scientists**: The K science relevant to developing a framework for 4R Nutrient Stewardship is in need of rigorous synthesis around the questions addressed at this conference. This conference and the resulting book should be a major step forward in that synthesis, however, additional reviews will likely be needed with expanded data sharing and evaluation of existing field and laboratory technologies. The complexities of the problems being addressed will likely require modeling approaches to be employed and will lead to identification of remaining knowledge gaps.
- **Laboratory services**: Analytical laboratories have a critical role to play in providing the soil and plant analysis required for more complete characterization of soil properties critical in defining potential K flux and K holding capacity. Assessing these additional properties in a cost-effective and timely manner could be a challenge but essential for progress in K management. It may well involve additional research commitments in laboratory or field procedures including sampling protocols and sensing technologies.
- **Data services**: Precipitation, temperature and other climatic factors have a major influence on crop growth and K demand and also greatly impact numerous soil processes related to K flux. And, it is highly likely that the only cost-effective means of assessing some critical soil properties will be via digital soil classification maps. Services that can supply these data and likely others will have important roles to play.
- **Extension**: Extension, in both private and public sectors, will have a critical role in guiding knowledge synthesis and transfer, development of a framework and associated decision support systems or tools and in evaluation of those products. Extension is also needed to help build coalitions between research, laboratory, and data communities to keep all parties communicating and moving forward.
- **Fertilizer industry**: Timely, affordable, access to appropriate K fertilizers is taken for granted in much of the world but can certainly be a limiting factor in some regions. It does little good if needs can be predicted but product to meet those needs is inaccessible.
- **Local service providers:** Last mile delivery and testing of technology and information via adaptive management with farmers or growers to fine tune it for local conditions is an important step. Local service providers are likely to also be part of the development process.
- **Traders:** Trading operates on supply and demand and determines the range in prices that a farmer can receive for his/her crop products. In addition, the degree of temporal changes in these prices is a form of risk that determines, in part, a farmer's willingness to make a management change.
- **Processors:** Processors emphasize consistency in crop quality as well as crop quantity. Processors often have great influence or control over which management practices are acceptable.

FILLING THE KNOWLEDGE GAPS

This conference has demonstrated that much more is known about K in soils and cropping systems than is currently utilized in K management. At the same time, it has identified knowledge gaps important to developing a functional framework for 4R K stewardship. Filling those gaps, considering the limited resources available and the tendency for the gaps to be located in the boundary regions between traditional disciplines, will require efficient collaboration across disciplines and among the stakeholders described in the previous section. Data sharing and communication among these stakeholders as parallel

but linked efforts proceed will be extremely valuable. A central part of 4R K stewardship is the dynamic feedback mechanism. Cycles of action and evaluation exist at each level of the stakeholder group. The opportunity to use precision agriculture technologies to collect high-resolution, geo-referenced data on nutrient prescriptions, applications, and removal greatly enhances the evaluation process and results in increased transparency and accountability of practices among stakeholder groups.

A highly relevant concept was recently presented by Cushnahan and colleagues (Cushnahan et al. 2016; Figure 2). They compared classical science, where data are generated late in a linear process, to an alternative approach to science where data are generated early in an iterative, cyclical process. The authors argued that this alternative approach, which facilitates use of "unexpected science" encountered along the way, is more appropriate in the data rich environment that exists in agriculture today. The use of precision technologies on farms and plantations and by researchers has greatly increased the volume of available data that could be employed in filling K knowledge gaps. Sharing relevant data among stakeholders employing this cyclical process of discovery could accelerate acquisition of new knowledge while reducing the total cost of arriving at an implementable solution.

Filling knowledge gaps and simultaneously connecting what we know from the frontiers of K science with innovative practitioners, farmers, and growers on the frontiers of practice will require focus on solutions to real problems faced by the end-user. Daniel Sarewitz, in a recent commentary on contemporary science in general, wrote that the most valuable science institutions will be closely linked to the people and places whose urgent problems need to be resolved … that they will link research agendas to the quest for improved solutions, often technological ones, rather than to understanding for its own sake (Sarewitz 2016). It would be wise for all engaged in the frontiers of K science to remain connected to those who grow crops for a living and the specific K related solutions they require.

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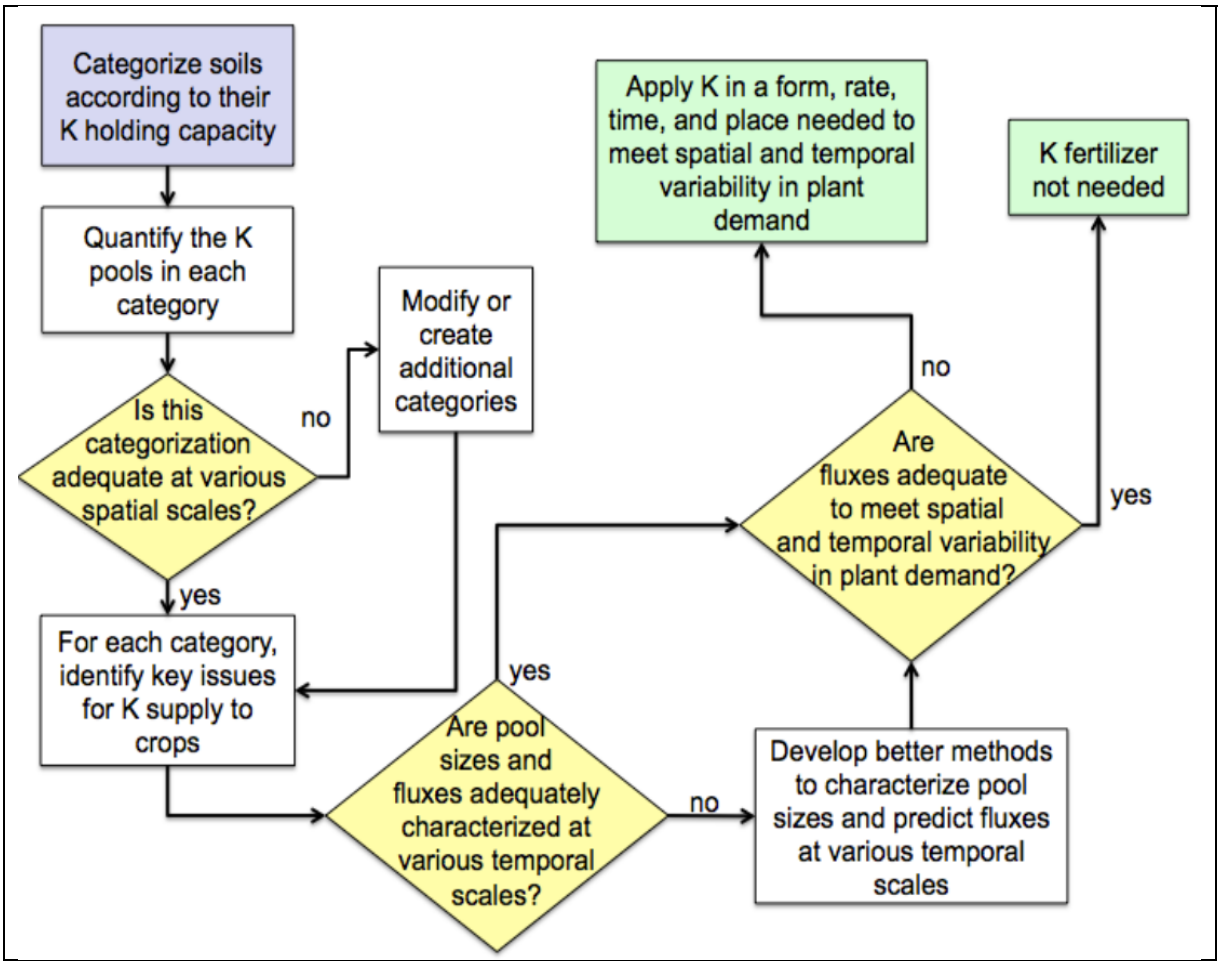

Figure 1. Decision tree for an overall strategy for improving soil K assessments and K recommendations (International Plant Nutrition Institute 2015).

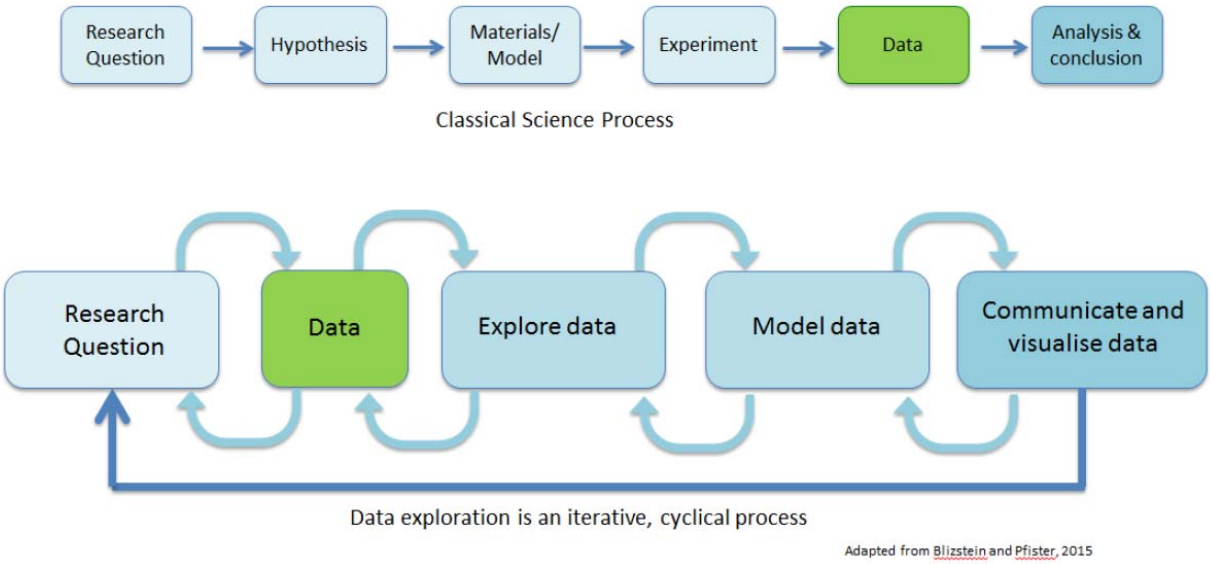

Figure 2. Disrupting the science process (Cushnahan et al. 2016).

Impact of K on Input Use Efficiencies: Nitrogen and Water

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Abstract
In a world of scarce resources efficient use of key inputs is vital to economic and environmental sustainability of agriculture. Two inputs with tremendous impact on crop yield and the environment are nitrogen (N) fertilizer and water. There are numerous interactions between potassium (K) nutrition and both water and N use in plants that alter nutrient use efficiency (NUE) and water use efficiency (WUE). Our presentation will first define these concepts, then explore the direction and magnitude of these interactions and characterize their underlying physiological basis. This latter knowledge may allow more precise management of K-N-water in future cropping systems. Included in our analysis are interactions with: species and cultivars within species; N fertilizer rate and form; K rate and form; irrigation; severity of drought stress; environment including temporal and spatial variation; developmental differences; root structure and function; soils; and other variables known to influence NUE and WUE. Understanding how K impacts NUE and WUE will guide K-management decisions as high yield and production efficiency continue to merge into a unified, common goal of modern food production systems.

Suitable Sources of Potassium Fertilizer for Fertigation of Northern Highbush Blueberry

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Abstract
Many blueberry growers are switching from broadcasting granular fertilizers to using fertigation through a drip irrigation system. Fertigation increases growth and production without increasing the need for more fertilizer. The objective of the present study was to evaluate different liquid sources of K fertilizers for fertigation in northern highbush blueberry (Vaccinium corymbosym L.). The study was conducted in a greenhouse using potted plants of 'Duke' blueberry. Treatments included a combination of the two soil types [optimum (4.9) and high pH (6.2)], two liquid K sources [(potassium sulfate and potassium thiosulfate (KTS)], five K rates (0, 0.05, 0.10, 0.15, and 0.20 g·L-1), and five liquid N sources [urea, ammonium sulfate, ammonium thiosulfate (ATS), urea ammonium nitrate (UAN), and urea-triazone (slow-release N); 0.10 g·L-1 N each). The plants were fertigated three times per week with each combination of K and N fertilizer, plus a modified Johnson's solution to avoid limitations of other nutrients. Fertigation with KTS and/or ATS reduced soil pH by at least a unit within 1–3 weeks in both of the soils. On average, the concentration of K in the soil solution increased by 25% with potassium sulfate and by 39% with KTS, and was highest when KTS was applied with urea or ammonium sulfate. The concentration of Ca and Mg also increased with the K fertilizers and was greater with KTS. Overall, KTS appears to be a good source of K for fertigation in blueberry and is recommended for use with urea on soils with optimum pH (4.5–5.5) and with ammonium sulfate on soils with high pH.

Impact of Long Term Nutrient Management on Dynamics of Potassium in 40 Years Old Soybean-wheat System on Alfisols of Ranchi

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Abstract
Potassium (K) is one of the plant nutrients which is required by crop in large quantity. In India, application of K is either missing in fertilizer schedule or applied in little quantity. Removal of K by crops in quantity larger than the K addition by farmers and imbalanced use of NPK fertilizers contribute to large-scale K mining leading to a negative balance of K to the tune of 10-11 million tons. This highlights the need to re-examine the current fertilizer K recommendations for different cropping systems on different soils. There are number of reports using the release rate of non-exchangeable K (NEK) to evaluate the capacity of soil to supply K to plants, but the study on dynamics and release of K under different nutrient management practices followed for a long time is limited. Keeping this in view, soil samples were collected from the long term fertilizer experiment (LTFE) at Ranchi centre to (i) study the effect of continuous application of fertilizer and manure on the forms of K and (ii) measure kinetics of NEK release as affected by long-term cropping, fertilization, and manuring. The experiment was started with rainy season (July – October) of 1972 at the research farm of Birsa Agriculture University, Kanka, Ranchi and the cropping system followed is soybean-wheat. The topographical details of experimental site are: 23.17ºN latitude and 85.19ºE longitude, 625 m altitude above mean sea level. The soil of experimental site is Red loam (Sandy clay loam texture) and taxonomically classified under the Order Alfisol, suborder- Ustalf, Subgroup- Hyperthermic mixed Typic Paleustalf. Out of ten treatments of LTFE, six treatments were selected for the study. Treatments include - Control, 100% N, 100% NP, 100% NPK, 100% NPK + FYM and 150% NPK. Soil samples were collected from these six treatments after completion of 40 cropping cycles and analysis were done using standard procedures. Kinetics of NEK release was studied by successive extraction with 0.01 M $CaCl_2$. Results of the study showed that, soil maintained less water soluble K due to continuous removal of this form by crop and downward movement by rain water. Lowest value for exchangeable K was recorded in 100% NP (50.7 mg/kg) followed by control (61.5 mg/kg) and 100% N (64.7 mg/kg) treatments with absence of K supply in fertilizer schedule for a long period and resulted decline in exchangeable K. From release study it was noted that cumulative NEK release recorded was largest in NPK+FYM treatment followed by 150% NPK. Two mathematical models tested for their suitability to describe the kinetics of NEK release. The first order equation described reaction rates better compared to parabolic diffusion curve, evidenced by highest R^2 values (0.991) and lowest standard error (6.72). This in turn tells that K release in the soil was mainly by cation exchange accompanied by film diffusion. Low values for release - rate constants (b) observed for soils indicated the restricted supply of potassium to exchangeable pool of soil ultimately leading to the depletion of K in the soil.

Keywords: Forms of potassium, cumulative NEK release, first order equation, release-rate constant

There is an Urgent Need to Include Potassium in the Fertilizer Program of Ethiopia to Enhance and Sustain Crop Production

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Abstract

Even if potassium was considered to be non-limiting nutrient in Ethiopia soils based on research conclusion reached five decades ago, emerging research evidences obtained since ten years back have disproved this conclusion. Apparently, results of experiments conducted for five years (2007-2011) to determine effects K application on yield and yield components of potato, wheat and barley grown on acidic soils of Chencha and Hagreselam areas, Southern Ethiopia (SE) revealed that all the three crops have significantly responded to K fertilization. Potassium has increased yields of these crops by more than 100 % relative control and NP fertilizers. Most recent research results also show that K as a limiting nutrient is occurring in many locations and with many crops in which no such limitations have been reported previously. To this effect, result of experiment conducted to determine effect of K maize at Hadero, SE revealed that K applied at 75 kg ha^{-1} increased grain yield significantly by 47 % over control. However, yield gain from K was much higher when it was applied along with NP. Accordingly, K + NP increased grain yield by 186 and 40.6 % over control and NP fertilizers respectively showing importance of K in balanced fertilization. Similarly, K fertilizer increased grain yield of tef by 237 % over control in Mudula, SE. Moreover, significant response of Ensete crop to K was obtained in Dale, SE. It is concluded that there are wide spread responses of crops to K application in many locations in Ethiopia suggesting low level soil K. Yet famers aren't using it. Thus, it is recommended that there is an urgent need to include K in fertilizer program of Ethiopia. This in turn requires convincing policy makers and all relevant stakeholders through mass demonstrations of K effects on crops in many locations at once.

Effect of Potassium Sulfate on Water Deficit Tolerance in Some Crops

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Abstract
One of agricultural extension ways is crop management in water deficit regions, which not only decreased crop production, but also decreased crops production area. For studying the role of potassium sulfate on yield and some physiologic attributes' changes of potato, corn and sunflower in water deficit conditions, three experiments were conducted in Islamic Azad University, Tabriz branch in 2014-2015 as RCBD based split plot. Water deficit range was from normal until 30% plant water need based on evaporation from pan A and potassium sulfate from 0 to 225 kg/ha. Water deficit led to lower water potential in plants and closed stomata that decreased leaf area and yield in potato, corn and sunflower more than 52.95% 81.01% and 36.92%, respectively. However, applying potassium sulfate increased these crops yield more than 29.44, 68.6, and 27.5%, respectively in compare to control. This was related to increasing photosynthesis by optimizing stomata efficiency with setting stomata number in leaf abaxial and adaxial, leaf relative water and chlorophyll content. Therefore, applying potassium sulfate to soil (generally in water deficit conditions) can regulate physiologic functions and improve plant growth and production by increasing plant efficiency from 20 to 70% that can extension crops to arid and semi arid region.

Keywords: Potassium sulfate, water deficit, crop extension, potato, corn and sunflower

INTRODUCTION

Drought is one of the most important factors that limits crops growth in all over the world, and is the most common environmental stress, which has limited nearly 45 percents of global cultivated areas (Burton *et al*., 1988). Potassium deficit has the most adverse effect in dry condition. Drought causes most problems in sufficient uptake of potassium by crops, because most amounts of potassium uptakes via the thin layers around the soil particles and they are going to thinner in drought condition. Higher potassium concentration in soil solute helps facilitate deliverance to roots. This subject represents importance of high application of potassium in dry areas (Anonymous, 1998). Plant reaction to potassium can be direct or indirect. Transpiration decreasing, increasing water uptake and/or inner resistance to drought are some of the direct reactions. Indirect reaction occurs when potassium application has no value to plant-water relation, but increases yield as an instance of nutritional cause (Goksoy *et al*., 2004). On the base of Johnson and Krauss (2003) estimation, diurnal uptake of five Kg potassium per hectare by plant, needs nearly 120 µM of this element concentration in soil solution, this requirement increases in dry soils to about 4 times as 490 µM in order to diurnal same uptake.

Pre sowing application of potassium can increase soybean yield in drought condition. Application method is effective on the crop yield, so that foliar application of potassium may increase yield after potassium deficit (Wang et al., 2004). Potassium increases plant root growth in drought condition by decreasing osmotic potential and increasing turgor pressure in winter wheat. In water deficit condition, potassium increases leaf relative water content (RWC) and cell membrane stability in corn (White, 2003). In this paper, the role of potassium was evaluated on water deficit tolerance of three important crops (potato, corn and sunflower).

MATERIALS AND METHODS

This study was conducted on potato (cv. Agria), corn (cv. JETA) and sunflower (cv. Euroflur) in three separate investigations in Islamic Azad University, Tabriz branch Agricultural Research Station in 2008-2010 as a RCBD based split plot design. On the base of soil test, soil textural class in research field was sandy loam. Other soil characteristics were as pH: 8.1-8.2, available potassium: 182-210 ppm, available phosphorous: 5-6 ppm, total nitrogen: 0.06-0.11% which indicated nitrogen deficit in the soil. Water application levels in potato were as irrigation after 35 (S_0), 70 (S_1), 105 (S_2), 140 (S_3) and 175 (S_4) mm evaporation from class A pan, and in both of corn and sunflower were as irrigation after 50 (D_0), 90 (D_1), 130 (D_2) and 170 (D_3) mm evaporation from class A pan. In study on potato, potassium application were: 0 (k_0), 75(k_1), 150 (k_2) and 225(k_3) kg potassium sulfate in hectare, these levels were changed as 0 (F_0), 50 (F_1), 100 (F_2), 150 (F_3) and 200 (F_4) kg/ha in corn and sunflower. In all of the three, water and potassium application levels were arranged in main and sub plots, respectively. Potassium sulfate was applied as pre sowing in soil. In these researches, leaf area and chlorophyll content index were measured via leaf area meter (ADM- 100) and chlorophyll meter (CM-200), respectively. Adaxial and Abaxial stomata numbers were counted in view zone of microscopic with 40x magnification in objective glass. Leaf relative water content (RWC) was measured from the third top leaf of canopy in the flowering time through fallowing equation: $RWC= [(W_f-W_d)/(W_s-W_d)]\times100$. Where: W_f, W_d and W_s are fresh, dry and saturated weights of leaf, respectively (Pier and Berkowitz, 1987). Stomata resistance was measured and recorded by poremeter (AP4). Potato tuber yield and corn and sunflower grain yield were measured as ton per hectare (t/ha). Statistical analysis was done by MSATAC software and means were compared by Least Significant Difference Test (LSD) in the 5% probability level.

RESULTS AND DISCUSSION:

Result of these studies showed that potato leaf chlorophyll content increased with irrigation intervals enhancement. In compared with S_0, leaf chlorophyll content in S_1, S_2, S_3 and S_4 increased 38.28, 72.03, 81.49 and 92.37%, respectively (Table 1). Drought stress enhancement decreased cell volume as result of prevention of cell dimension increase, and consequently concentrate cell sap. These three factors increased leaf chlorophyll content (Marschner, 1995). But this attribute was decreased in corn and sunflower by irrigation intervals enhancement. Greatest leaf chlorophyll content index was observed in D_0 as 54.49 in corn and 44.10 in sunflower, and its least was in D_3 as 31.9 and 34.46 in corn and sunflower, respectively (Table 2). Egilla et al., (2005) reported that leaf chlorophyll content of *Onobrychis radiata* and *Onobruchis viciifolia* was decreased in drought stress. Leaf chlorophyll content decreasing in drought stress in comparing with non-stress condition is possibly due to acceleration of leaf chlorosis and senescence.

Potassium applying increased leaf chlorophyll content in corn and sunflower. Maximum leaf chlorophyll content occurred in 200 kg/ha potassium sulfate as 54.43 and 42.51 in corn and sunflower, respectively, and its least was in non application of potassium sulfate as 32.23 in corn and 34.65 in sunflower. In compared with 0 kg/ha potassium sulfate, application of 50, 100, 150 and 200 kg/ha of potassium sulfate showed an ascendant increase in corn leaf chlorophyll content index as 10.15, 23.02, 31.93 and 39.27%, respectively, and 5, 12, 15 and 19 % in sunflower (Table 3).

Potassium application increased leaf chlorophyll content through encourages of nitrate reductase activity and nitrate reduction in crops. In other hand, potassium as a main ion in company with nitrate, participate in long distance translocation inner the xylem. It also has a role in substance reservation into vacuole and increases leaf chlorophyll content with nitrate reduction in leaves (Havlin and Westfall, 2005).
Drought decreased leaf area in this study. Decreasing leaf area by drought was prevented considerably with increasing potassium application, so the least potato leaf area was observed in S_4K_1 and its greatest was in S_3K_1. This subject represented that maximum and minimum of leaf area decreased 67.11% and increased 503.04%, respectively in compared with S_0K_0 (Table 1). Highest leaf area in corn and sunflower was occurred in D_0 as 0.66 and 0.21 m^2, respectively, and its least was in D_3 as 0.355 m^2 in

corn and 0.08 m^2 in sunflower. Corn leaf area in D_0 was 23.1, 38.83 and 46.35% and sunflower leaf area was 22, 36 and 170% more than D_1, D_2 and D_3, respectively (Table 2).

Potassium sulfate application enhancement as 0 to 200 kg/ha increased leaf area in these two crops. Maximum leaf area was 0.66 m^2 in corn and 0.18 m^2 in sunflower in 200 kg/ha potassium sulfate and its least were 0.34 and 0.10 m^2 in corn and sunflower in 0 kg/ha potassium sulfate, respectively. In compared with non application of potato, corn and sunflower, corn and sunflower leaf area increased 94.44 and 72% by application of 200 kg/ha potassium sulfate, respectively (Table 3). Wiebold and Scharf (2006) reported that, as a result of potassium application, corn leaf area in drought was even more than normal condition.

As the same time with potassium sulfate application, number of abaxial and adaxial stomata number was increased with irrigation intervals enhancement. Minimum abaxial stomata number of potato was in S_1K_0 as 45.30 and its maximum was in S_4K_3 as 82.22, as well as, least adaxial stomata number of the crop was 9 in S_0k_3 and its maximum was 23.31 in S_3k_1 (Table 1). In the corn, maximum adaxial and abaxial stomata number in D_3 were 17.65 and 25.43, respectively, and their minimum occurred in irrigation after 50 mm evaporation from the pan as 14.43 and 18.73, respectively (Table 2). Maximum adaxial and abaxial stomata number of sunflower were in 150 kg/ha potassium sulfate as 25 and 31, respectively, and their least occurred in 0 kg/ha potassium sulfate as 18 and 21, respectively (Table 3). Therefore, in these two crops stomata number enhancement in abaxial surface is more than adaxial one. Occurrence of this state may be a strategy to catch more atmospheric CO_2 or increase CER in drought condition, in fact, the crops increase stomata number in abaxial surface to ignore passive closure of stomata (Hinton, 2001).

Maximum adaxial and abaxial stomata number of corn was 18.6 and 26.6 in 200 kg/ha potassium sulfate, respectively, and their minimum were 13.51 and 18.16 in 0 kg/ha potassium sulfate. This enhancement in sunflower was observed as 18 to 23 in adaxial and 24 to 29 in abaxial stomata number (Table 3).

With increasing water deficient intensity, stomata length and width were decreased in both of corn and sunflower. Greatest adaxial stomata length and width were observed in D_0 as 2.149 and 1.127 µm, respectively, and their least were 0.686 and 0.794 µm in D_3 (Table 2). Potassium application increased adaxial and abaxial stomata length and width. Maximum adaxial stomata length and width were in 200 kg/ha potassium sulfate as 2.127 and 1.06, respectively, and their least were 1.707 and 0.811 µm in 0 kg/ha potassium sulfate. Consumption of 50, 100, 150 and 200 kg/ha potassium sulfate resulted to increasing 8.43, 12.77, 16.98 and 24.6% in adaxial stomata length and 12.23, 17.26, 22.4 and 30.73% in its width, respectively (Table 3). Changing in adaxial stomata dimensions was as same as abaxial ones, so that greatest abaxial stoma length and width of corn were 2.055 and 1.187 µm in D_0 and their least were in D_3, respectively (Table 2). Maximum abaxial stomata length and width were observed in application of 200 kg/ha potassium sulfate as 1.978 and 1.167 µm, respectively, and their least were 1.559 and 0.676 in non application of the fertilizer (Table 3). In attention to main role of potassium in changing stomata cells turgor pressure, potassium concentration enhancement in these cells results to water entrance from subsidiary cells to guard cells. This subject causes turgor pressure increase in guard cells and consequently stoma will be open and its dimension is going to increase (Marschner, 1995).

Adaxial stomata length of sunflower in non application of potassium sulfate changed with drought development from D_0 to D_3 as 1.350, 1.200, 1.047 and 0.64, respectively. These observations were 1.607 to 0.98 in application of 200 kg/ha potassium sulfate. Thus, potassium application in drought condition has prevented intensive diminish of stomata length. With increasing water deficit stress from D_0 to D_3, abaxial stomata length was decreased significantly in all of potassium application levels. So that, abaxial stomata length in 0, 50, 100, 150 and 200 kg/ha potassium sulfate in compared with same application of potassium in D_0 was decreased as 75%, 57%, 60%, 56% and 52%, respectively. Greatest adaxial and abaxial stomata width were observed in D_0 as 0.83 and 0.79 µm, respectively, and their least were 0.47 and 0.48 µm in D_3. Maximum adaxial and abaxial stomata width of sunflower were in application of 200

kg/ha potassium sulfate as 0.7 and 0.73 µm and their minimum were 0.59 and 0.55 in non application of the fertilizer, respectively (Table 3).

In order to prevent transpiration as a result of stomata number increasing, stomata number enhancement is accompanied with stomata dimensions decreasing in water deficit stress. Effect of stomata dimensions diminish on water exit is more than CO_2 entrance. Water exit is occurred from stomata circumferential and CO_2 enters from stomata area. Because main part of gas exchange is through abaxial stomata (Devaux *et al*., 2003).

In all of three studied crops, RWC was decreased, as its minimum in potato was 44.87 in S_4k_0 and its maximum was 70.85 in S_0k_2. This matter represents that minimum and maximum of this attribute were decreased as 28.02% and increased as 13.63%, respectively in compare with S_0k_0. In all of potassium application levels minimum rate of RWC was observed in S_4 as maximum water deficit stress, but decreasing of its intensity was diminished with potassium application (Table 1). Highest RWC in corn and sunflower were in D_0 as 63.31 % and 72.46 %, respectively, but their least were observed in D_3 as 53.68% in corn and 52.4% in sunflower (Table 2). Plant water uptake is decreased with drought stress enhancement which causes diminish in plant RWC (Gupta, 2005). Wastgate (1994) and Boyer (1998) found that water movement into leaf depends on water potential gradient between xylem and leaf, so that water potential decrease in xylem causes decrease in water potential gradient.

Maximum RWC in corn and sunflower were observed in F_4 as 65.71% and 62.53%, respectively, and their minimum were 53.18% and 52.54% in non application of potassium. Leaf RWC enhancement with increasing potassium application is justifiable with increasing root surface, promotion of water uptake ability, stomata movement adjustment, evaporation coefficient diminish and osmotic pressure enhancement (Leigh, 1989).

Potato tuber yield was decreased with increasing irrigation intervals, so that in compare with S_0 tuber yield in S_1, S_2, S_3 and S_4 was decreased 36.3, 13.96, 46.32 and 52.97%, respectively. Tuber yield increased with potassium application, so that, its maximum and minimum was observed in K_3 and k_0, respectively. Tuber yield was increased in k_1, k_2 and k_3 as 14.24, 23.32 and 29.44%, respectively in compared with k_0 (Table 1).

Highest corn and sunflower grain yield was in D_0 as 1522 and 577.4 kg, respectively, and its least was observed in D_3 as 288.1 and 364 kg (Table 2). This subject showed that corn yield is sensitive to water deficit stress more than sunflower. Corn grain yield was increased in 50, 100, 150 and 200 kg/ha potassium sulfate as 19.84, 34.64, 51.62 and 68.80%, respectively in compared with 0 kg/ha potassium sulfate, while this increase in sunflower was 8, 13, 20 and 27%, so that, potassium requirement of corn is more than sunflower (Table 3).

Table 1: Mean comparison of interaction between irrigation levels and potassium sulfate application in potato

Irrigation Level	Potassium Application	Leaf area (m^2/plant)	Adaxial stomata number	Abaxial stomata number	Leaf relative water content (%)
S_0=35	K_0	0.318	56.900	15.163	62.350
S_1=70	K_0	0.165	45.300	11.373	65.293
S_2=105	K_0=0 kg	0.144	52.723	15.000	62.090
S_3=140	K_0	0.089	75.000	20.050	60.243
S_4=175 mm	K_0	0.048	74.763	16.500	44.876
S_0	K_1	0.089	58.053	10.130	65.920
S_1	K_1	0.126	57.680	15.500	59.580
S_2	K_1=75 kg	0.172	57.503	14.783	59.203
S_3	K_1	0.156	66.130	23.213	62.570
S_4	K_1	0.871	68.620	16.500	45.180
S_0	K_2	0.111	57.710	10.500	70.850
S_1	K_2	0.206	46.413	10.500	62.763
S_2	K_2= 150	0.304	61.663	15.550	61.060
S_3	K_2	0.471	66.050	22.500	62.420
S_4	K_2	0.356	75.413	16.750	52.603
S_0	K_3	0.378	50.750	9.000	69.333
S_1	K_3	0.138	57.020	10.000	61.663
S_2	K_3=225	0.131	59.200	15.027	62.703
S_3	K_3	0.130	71.400	19.420	60.673
S_4	K_3	0.113	52.220	17.000	49.513
LSD 1%		*0.1179*	*11.35*	*3.268*	*5.323*

Table 2- Mean comparison of water deficit stress effect on corn and sunflower attributes

Irrigation levels	Chlorophyll content Index		Leaf Area ($m^2.plant^{-1}$)		RWC (%)		Grain Yield ($g.m^{-2}$)	
	Corn	sunflower	corn	sunflower	corn	sunflower	Corn	sunflower
50	54.49a	44.10a	0.6612a	0.215a	63.31a	72.46a	1522a	577.4a
90	40.87b	38.30b	0.5084b	0.166b	61.27a	67.87b	1196a	475.0b
130	35.84bc	36.71b	0.4044bc	0.136b	58.33ab	60.30c	576.1b	410.2c
170	31.9c	34.46c	0.3547c	0.087c	53.68b	52.4d	288.7b	364.0c

Table 2: Continued

Irrigation levels	Adaxial stomata Length		Abaxial stomata width		Adaxial stomata No.		Abaxial stomata No.		Abaxial stomata Length		Adaxial stomata width	
	corn	sunflower	corn	sunflower	corn	sunflower	Corn	sunflower	Corn	sunflower	Corn	sunflower
50	2.055a	1.354a	1.127a	0.832a	18.73c	21.92c	14.43b	18.15c	2.149a	1.434a	1.09a	0.791a
90	1.93a	1.2b	1.020a	0.715b	20.39bc	24.97b	15.68b	20.25b	2.027a	1.258b	0.987b	0.662b
130	1.686b	1.06b	0.838b	0.602c	23.26ab	27.82b	17.19a	22.05b	1.823b	1.112b	0.778c	0.555c
170	1.546b	0.845c	0.795b	0.479d	25.43a	31.91a	17.65a	24.26a	1.686b	0.66c	0.744c	0.475c

In each column, means with same letter do not differ significantly at LSD 5%.

Table 3- Mean comparison of Potassium sulfate effect on corn and sunflower attributes

K_2SO_4 (kg.ha^{-1})	Chlorophyll content Index		Leaf Area (m^2.plant^{-1})		RWC (%)		Grain Yield (g.m^{-2})	
	corn	sunflower	corn	sunflower	corn	sunflower	Corn	sunflower
0	31.23d	34.65d	0.342d	0.11c	53.18d	52.54d	663.5d	400.4c
50	34.76cd	36.19cd	0.421c	0.137bc	56.53c	55.32c	795.2c	432.9b
100	40.57bc	37.82c	0.463c	0.159ab	59.16b	58.21b	893.4c	455.9b
150	45.88ab	40.78b	0.520b	0.162ab	61.18b	60.11b	1006b	484.3a
200	51.43a	42.51a	0.665a	0.187a	65.71a	62.53a	1120a	509.7a

Table 3: Continued

K_2SO_4	Adaxial stomata Length		Abaxial stomata width		Adaxial stomata No.		Abaxial stomata No.		Abaxial stomata Length		Adaxial stomata width	
(kg.ha^{-1})	corn	sunflower	corn	sunflower	corn	sunflower	Corn	sunflower	Corn	sunflower	Corn	sunflower
0	1.56d	1.025c	0.811c	0.593e	18.16e	24.13c	13.51c	18.63d	1.71d	1.058c	0.717c	0.553d
50	1.72c	1.075bc	0.910b	0.619d	19.87d	25.28bc	15.23b	20.40c	1.85c	0.935d	0.841bc	0.583cd
100	1.84b	1.113b	0.951b	0.647c	21.74c	26.30b	16.30b	21.33bc	1.93bc	1.135b	0.930b	0.613c
150	1.93a	1.155b	0.993ab	0.696b	23.38b	28.30a	17.55a	22.23ab	1.99b	1.183b	0.985b	0.653b
200	1.98a	1.21a	1.060a	0.731a	26.60a	29.27a	18.6a	23.30a	2.13a	1,268a	1.029a	0.700a

In each column, means with same letter do not differ significantly at LSD 5%.

DISCUSSION

It is most possible that available water decrease for crops is one of the main causes for yield diminishes in arid and semiarid years which are same with 130 (D_2) and 170 (D_3) mm evaporation from class A pan conditions in this study. In addition, the results of this study showed that application of 50, 100, 150 and 200 Kg/ha potassium sulfate increased crops yield in compared with non application of this fertilizer. In fact, yield enhancement was the result of yield components increase. Totally, it is concluded that potassium application results in drought tolerance enhancement in many of crops in water deficit condition and practically moderates adverse effect of water deficit on yield diminish. To deal with drought, potassium application can be a strategy for growers in conditions with different drought stresses.

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Response of Fine Roots to Potassium and Throughfall Exclusion in a Eucalyptus Grandis Plantation in a Tropical Region

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Abstract
In tropical regions, climate change will cause longer dry periods and/or lower amounts of rain in the rainy season. Potassium (K) can have a positive effect on water use efficiency by plants. Several morphological and physiological traits are modified by K availability and water supply regimes. However, there is a lack of information about the interaction of K and soil water availability in the ecophysiological behaviour of plants, especially about roots. Most previous studies in tropical woody ecosystems did not sample the deepest roots. In the present study, a dispositive was used for excluding 37% of rainfall (-W) in a low fertility soil cultured with a *Eucalyptus grandis* plantation of five years, with and without K fertilization (+K and -K). Our hypotheses were: i) improving K nutrition increases fine root biomass and area, ii) a decrease of 37% rainfall decreases fine root biomass and area, but increases roots depth and, iii) the interaction of +K with -W increases fine root biomass, area and depth. The experimental design was in randomized blocks four treatments (-K+W; +K+W; -K-W and +K-W) and three blocks. Fine roots (diameter < 2mm) were studied from the soil surface to the water table (17-19m). Living fine roots, from each soil sample, were scanned, and root length and area were estimated using the WinRHIZO software. Roots were dried at 65°C for determining dry biomass. Soil volumetric water content was measured with TDR probes along the soil profile. The results indicate that there were no significantly differences of fine root biomass and specific root length between treatments. Nevertheless, potassium fertilization increased the root area index (RAI, m^2 m^{-2} soil) from 0 to 1 m. That means that K increased the absorptive root area, even with 37% of rainfall exclusion.

Wood Ash Application: Effects on Nutrient Uptake of Maize and Lima Bean in an Intercrop

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Abstract

This study investigated the effects of wood ash application on the nutrient uptake of maize and lima bean in an intercrop during the late and early seasons of 2014 and 2015, at Akure in the rainforest zone of Nigeria. The treatments were 100% sole maize, 100% sole lima beans, 75% maize + 25% lima beans, 50% maize + 50% lima beans, and 25% maize + 75% lima beans. Wood ash was applied at 2.4kg-^{1} per plot while control plots were unamended. Soil physical and chemical properties were determined before planting and after harvesting. Chemical analysis of the wood ash used was also determined. Leaves of both maize and lima beans were taken to laboratory for chlorophyll and mineral constituents analysis before the fruit formation. It was observed that sole maize plot treated with ash had the highest potassium uptake 0 .50% over the unmaended sole maize plot. Potassium uptake levels were found to be reduced in all the intercropped (maize and lima bean) plots when compared with sole maize plots.

Response of Transgenic Cotton to Potassium, Right Rate and Right Time of Application

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Abstract
Cotton is an important commercial and fiber crop of India. After release of transgenic cotton (Bt cotton) in India during 2002-03, the area under cotton cultivation consequently increased. Presently about 15 million small farmers grow transgenic cotton in 11.7 million ha, made India the global leaders in transgenic cotton area. However, low production with 390 lakh bales (Third in global ranking) and declining productivity (565 kg ha^{-1} lint as against global productivity of 759 kg ha^{-1} lint) is an alarming concern. Potassium nutrition in transgenic cotton plays an important role in enhancing the productivity by increasing resistance to the pests and diseases and improving water use efficiency. It also helps in improving fiber properties like fiber strength, fiber length, fineness and ginning out turn. A study at the University of Agricultural Sciences, Dharwad, India during the monsoon season in vertisols assessed the effect of different levels of potassium and omission on cotton yield, K nutrient uptake, fiber properties, economics and determined the right rate and time of potassium application.

Results indicated omission of potassium (K) from the scheduled nutrient recommendation resulted in 16% yield reduction (yield loss by 0.41 t ha^{-1}) and 25% reduction in net returns, highlighting the importance of applying K_2O @ 75 kg ha^{-1} to transgenic cotton. Application of K along with nitrogen in four equal splits, once at planting and the remaining at 30, 60, and 90 days after planting resulted in higher seed cotton yield (4.3 t ha^{-1}) and higher K uptake (156 kg ha^{-1}) over the other options of timing. Drip irrigation at 0.8 Etc along with fertigation of 75% recommended dose of nitrogen and potassium (112:75:56 kg ha^{-1} $N:P_2O_5:K_2O$) in six equal splits at 15 days interval and basal soil application of entire phosphorous enhanced the seed cotton yield and net returns over single row planting and furrow irrigation with nutrient application of 50% N + 100% P_2O_5 and K_2O as basal at the time of sowing. Hence, right timing of K application at early boll set and after first bloom through application of right K rates proved vital for higher yields of transgenic cotton.

Efficiency of Potassic Fertilization with KCl Coated by Humic Acids

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Abstract

Potassic fertilization with potassium chloride (KCl) may result in large potassium (K) losses by leaching in sandy soils. Agriculture expansion to meet food demand will depend on the exploration of sandy soils, where K losses may be high, depending on the fertilizer and way of application. The objective of this work was to evaluate the efficiency of KCl coated with humic acids (coated KCl) or conventional KCl (KCl), as affected by soil K level on soybean grain yield. Experiments were performed in field with soybean, in low, medium and high soil K levels. The soil is a Rhodic Hapludox with 670 g kg^{-1} of sand and 210 g kg^{-1} of clay. The treatments were K sources, KCl and coated KCl, applied in a single rate or split rate, and a control treatment. The experiments were conducted in Botucatu, Sao Paulo State, Brazil. The use of KCl resulted in higher levels of non-exchangeable K in the soil than the use of coated KCl, due to the fast KCl solubilization. The use of coated KCl in single rate resulted in higher soybean grain yield than the use of KCl in the low soil K level, due to the better K release synchronism as the plant developed, avoiding possible losses by leaching and accumulation of non-exchangeable K in the soil. In the medium and high soil K level there was higher K content in soybean leaves when coated KCl was applied than the conventional KCl, however there was no response to K fertilizer in grain yield. The coated KCl is an adequate source of K for soybean in sandy soils, to be used in a single application at planting. Application of conventional KCl has to be split.

Potassium Rates and Timing Influence Phenology, Growth and Yield of Maize (Zea mays) with and without Cattle Dung Application under Moisture Stress

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Abstract

Two field experiments were conducted to study the response of maize (*Zea mays* L., cv. Azam) to potassium (K) levels (30, 60, 90 kg ha^{-1}), K application time (T_1 = full at sowing, T_2 = full at knee height, and T_3 = 50% each at sowing and knee height). One experiment was carried out in the field where 5 t ha^{-1} cattle dung was applied, while the field under second experiment received no cattle dung (0 t ha^{-1}). The research was carried out under moisture stress condition at the Agronomy Research Farm of The University of Agriculture Peshawar during summer 2014. The experiments under both with and without cattle manure field were laid out in randomized complete block design using three replications. One control plot where no K was applied was used in each replication in both experiments. The results revealed that the K treated plots (rest) under both fields (with and without cattle dung) had delayed maize phenology, improved growth (taller plants, higher flag leaf area, leaf area index), produced more yield components (longer ear lengths, more grains row^{-1} and ear^{-1}, and heavy grains) and grain yield (4307 kg ha^{-1}) and shelling percentage than control (K not applied). On the average, the experiment under cattle dung had better growth, produced more yield components, grain yield (4507 kg ha^{-1}) and shelling percentage than the experiment that received no cattle dung. The mean values of both experiments confirmed that increasing the rate of K had delayed phenological development, improved growth, and produced higher yield components, grain yield (4612 kg ha^{-1}) and shelling percentage (90 kg K ha^{-1} > 60 kg K ha^{-1} > 30 kg K ha^{-1}). Likewise, maize phenology was delayed, flag leaf area, leaf area index, yield components, grain yield (4407 kg ha^{-1}) and shelling percentage increased significantly when K was applied in two equal splits (two equal splits > full at sowing > full at knee height). It was concluded from this study that application of K at the rate of 90 kg ha^{-1} in two equal splits (50% at sowing and 50% at knee height) along with cattle dung (5 t ha^{-1}) could improve crop growth, increased crop productivity and growers income under limited irrigation condition.

Potassium Management for Improving Productivity of Winter and Summer Oil-seed Crops under Semiarid Conditions

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Abstract

Potassium (K) and phosphorus (P) applications improve growth, increase yield and yield components of sunflower (*Helianthus annuus* L.) on K and P deficient soils in Northwest Pakistan. A field experiment was conducted using sunflower cv. Hysun-33 at the Agricultural Research Farm of the University of Agriculture Peshawar, Pakistan, during summer 2006. The experimental design was a randomized complete block in split plot arrangements, with six levels of K (0, 25, 50, 75, 100, and 125 kg K ha^{-1}) as main plots and four levels of P (0, 45, 90, and 135 kg P ha^{-1}) as sub-plots with three replications. Sunflower yield and yield components responded positively to K and P fertilization but the magnitude of response varied with the levels of K and P. Days to flowering and maturity, grains per head, 1000-grains weight, shelling percentage, and grain yield increased tremendously in the K and P-fertilized plots as compared to the control with no K and P applied. The combined application of 100 kg K and 45 kg P ha^{-1} significantly increased yield components, grain yield, harvest index, and shelling percentage of sunflower, suggesting that 100 kg K ha^{-1} in combination with 45 kg P ha^{-1} could maximize productivity of sunflower.

Improper sulfur (S) and potassium (K) fertilizer management, particularly with continued soil nutrient mining, is one of the major factors contributing to low seed yield of canola in northwestern Pakistan. A field experiment was conducted in 2007−2008 on a S and K deficient clay loam soil at the Research Farm of the University of Agriculture Peshawar, Pakistan, with an objective to determine seed yield and yield components response of Brassica oilseed rape versus mustard to S and K application. Twenty treatments in a randomized complete block design were consisted of two oilseed rape (*B. napus* canola) and mustard (*B. juncea* canola) genotypes at three rates each of S (15, 30, and 45 kg S ha^{-1}) and K (30, 60, and 90 kg K ha^{-1}) fertilizers plus one control (no S and K applied). Seed yield and yield components increased significantly with K and S fertilization as compared to the zero-S/zero-K control. Both genotypes responded positively for seed yield and yield components to K and S fertilization, but the magnitude of response varied with levels of S and K, as well as combined K + S applications. It is concluded that a combination of 60 kg K + 30 kg S ha^{-1} would improve seed yield and yield components of rape and mustard in the study area and contribute significantly to increased production. Growing *B. napus* was better than *B. juncea* in the study area, because *B. napus* produced significantly higher seed yield and yield components than *B. juncea*, indicating that yield components are the most important criteria for selection of Brassica genotypes for higher seed yield.

Combined Effects of Elevated Carbon Dioxide, Potassium Deficiency and Terminal Drought on Grain Yield and Quality of Bread Wheat

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Abstract

Potassium (K), being an essential macro nutrient, is of prime importance for crop production. However, in most of the agricultural soils K balance is in a declining trend and has already reached to negative values in some countries. The negative K balance will essentially lead to K deficiency resulting in reduced crop yield and quality. In addition to adequate nutrient supply, climate plays a major role in successful crop production. Increased atmospheric carbon dioxide (CO_2) and reduced precipitation are predicted to be the major climatic challenges that would affect wheat yield and quality in the future. This study aimed to assess combined effects of elevated CO_2, K deficiency and terminal drought on grain yield and quality of bread wheat.

Bread wheat (*Triticum aestivum*, cv Tahirova) plants were cultured in soil with adequate or low K supply in pots under ambient (400 ± 10) or elevated (700 ± 10) CO_2 in two identical growth chambers. Drought stress was applied at the onset of flowering. Plants were harvested at full maturity to determine yield, yield components and grain K and protein concentration.

Potassium deficiency and terminal drought significantly reduced grain yield under all conditions of atmospheric CO_2. Overall, K deficiency and drought reduced grain yield by 69.5 and 18 % respectively, whereas elevated CO_2 increased it by 25 %. The reduction in grain yield was a function of reduced number of tillers and spikes per plant, grain weight, and harvest index. Grain K concentration was increased in K deficient plants as a consequence of “concentration effect”, however grain K content (µg K $seed^{-1}$) and gain K uptake (mg $plant^{-1}$) were significantly reduced. Elevated CO_2 reduced grain K concentration whereas drought had some positive effect on it. Elevated CO_2 significantly reduced grain protein concentration and content. It is concluded that K deficiency has worst effect on grain yield as compared to quality of bread wheat, however elevated CO_2 compromises the quality of produce. Elevated CO_2 ameliorates the effect of terminal drought only under adequate K supply, but not under K deficiency.

Studies on Nutrient Expert® Based Nutrient Management Under Zero Tillage and Conventional Tillage

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Abstract

The need for precise and responsive management of Nitrogen and potassic fertilizer in wheat is compelling for both economic and environmental reasons. Besides the importance of nitrogen, potassium also helps in stomatal functioning, improving protein synthesis, photosynthesis, carbohydrates and fats, increasing enzyme activity and translocation of photosynthates. Even then balanced application of potassium is often ignored by farmers. The small and marginal farmers of West Bengal, India presently face acute shortage of labour and sharp hike in labour wages. In this situation, adoption of Zero tillage cultivation of wheat can not only ensure timely sowing but can also raise the profitability of the production system. The "Nutrient Expert" a Decision support tool developed by IPNI (International Plant Nutrition Institute) & CIMMYT is an easy to use, interactive and computer based decision support tool that can rapidly provide nutrient recommendations for individual farmers' field. The precise application of nutrients under different tillage techniques through the use of these tools can raise the profitability of the production system and may reduce environmental pollution.

A field experiment was conducted under sandy loam acidic soil, low in Nitrogen, medium in Phosphorus and Potassium. There were two techniques of tillage- Zero tillage, conventional tillage and two levels of nutrient management – : Farmer's practice and Nutrient expert based fertilizer recommendation. The experiment in Factorial Randomised Block Design was replicated in the fields of ten marginal farmers of Burdwan district of West Bengal, India with a popular wheat variety PBW 343.

The growth parameter as well as yield components and yield were significantly affected by fertilizer and tillage. Application of nutrient on the basis of recommendation obtained from "Nutrient expert" gave highest yield and yield parameter values. The AE, RE, PE of N and K was also highest in Nutrient expert treated plot.

Nutrient management has played a crucial role in achieving self sufficiency in food grain production. The need for precise and responsive management of N fertilizer in Wheat is compelling for both economic and environmental reasons. Static fertilizer recommendations based on average response lead to excessive fertilization in some years and inadequate fertilizers in years with high N losses. The uncertainty in optimum N rate poses risks for profit loses which is exacerbated by the assymetric profit response of wheat to N rates. The associated higher cost of under fertilization relative to over fertilization drives farmers to apply imbalanced rates. This uncertainty can be addressed by providing more accurate location and time specific recommendations that increase accuracy and reduce uncertainty (Clune et al., 2013). Potassium also has an important role in stomatal functioning and internal ionic concentration of the plant tissues. Its role is also found in improving protein synthesis, photosynthesis, carbohydrates and fats, increasing enzyme activity and translocation of photosynthates. Potassium plays an influential role in the process of nitrate reduction within the plant. Plants require nutrient for osmotic regulation and enzyme functions. The nutrient is highly mobile within plant tissues which promote the transport of starch and sugars. Wheat also require potassium, since this nutrient is crucial to metabolic functions such as the movement of sugars from the leaves to the sink. It is involved in regulating the amount of water in the plant; in the absence of sufficient potassium then the crop do not use water efficiently. Also adequate

potassium levels in the plant help it to withstand water stress during periods of drought. Potassium plays a vital role in maintaining the turgidity of plant cells to obtain maximum leaf extension and stem elongation due to its turgor maintenance capacity. This helps to achieve rapid ground cover to maximize the sunlight interceptation and which will leads to accelerate the growth rate rapidly in the critical periods of the growing season.

The “Nutrient Expert” a Decision support tool developed by IPNI (International Plant Nutrition Institute) & CIMMYT is an easy to use, interactive and computer based decision support tool that can rapidly provide nutrient recommendations for individual farmers’ field in the presence or absence of soil testing data. The precise application of nutrients through the use of these tools can raise the profitability of the production system and may reduce environmental pollution. Very little work has been done to use the improved tools for nutrient management in the lateritic soil of West Bengal. In this context, an experiment was carried out to study the precision nutrient management through use of “Nutrient Expert” in Wheat under gangetic soil of West Bengal, India. Zero-tillage cultivation is a farming practice that reduces costs while maintaining harvests and protecting the environment. Innovative partnerships among researchers, farmers, and other actors in the agricultural value chain have enabled the adoption of zero-tillage to sow rice in the Indo-Gangetic Plains, increasing farmers' incomes, fostering more sustainable use of soil and water, and providing a platform for cropping diversification and the introduction of other resource-conserving practices. The small and marginal farmers of West Bengal, India presently face acute shortage of labour and sharp hike in labour wages. In this situation, adoption of Zero tillage cultivation of wheat can not only ensure timely sowing but can also raise the profitability of the production system.

Keywords: Nutrient expert, Site specific nutrient management, Wheat, Yield, Zero tillage

MATERIALS AND METHODS

A field experiment was conducted in the farmer’s field of Ausgram I Block, Burdwan, West Bengal, India under sandy loam soil with soil pH of 5.4, which is low in Nitrogen (154 kg N/ha), medium in Phosphorus (24 kg/ha) and Potassium (110 kg/ha). There were two techniques of tillage-T1: Zero tillage, T2: conventional tillage and two levels of nutrient management – N1: Farmer’s practice and N2: Nutrient expert based fertilizer recommendation. The experiment was replicated five times in the field of marginal farmers of Burdwan district of West Bengal. The study was conducted with a popular wheat variety PBW 343. The experimental design was Factorial Randomised Block Design.

RESULT AND DISSCUSSION

Table 1: Effect of precise nutrient management on the growth and yield of wheat

Treatment	Plant height (cm)	Dry matter at harvest (gm /plant)	LAI	Grain yield ha(ton)	Straw yield (ton)
Zero tillage	76.5	437.8	3.12	3.76	4.96
Conventional Tillage	77.1	479.2	2.80	3.37	4.29
SEm(±)	**1.35**	**9.87**	**0.09**	**0.09**	**0.13**
CD(P=0.05)	**(NS)**	**28.58**	**0.25**	**0.26**	**0.38**
Nutrient Expert	84.6	503.8	3.24	3.81	4.67
Farmers' Practice	69.3	413.2	2.68	3.32	4.58
SEm(±)	**1.6**	**12.7**	**0.06**	**0.07**	**0.03**
CD(P=0.05)	**4.7**	**38.1**	**0.17**	**0.23**	**0.10**

Table 2: Effect of precise nutrient management on the yield attributes of wheat

Treatment details	Yield attributes						
	Effective tillers/m^2	Grains/ Earhead	Spikelets/ Earhead	Ear Weight (gm)	Ear Length (cm)	Test weight (g)	Harvest Index
Zero tillage	287	39	17	2.1	14.8	42.6	43.1
Conventional Tillage	265	34	15	1.9	14.2	41.2	43.9
SEm(±)	**7.47**	**0.65**	**0.28**	**0.05**	**0.35**	**0.51**	**0.76**
CD(P=0.05)	**22.01**	**1.90**	**0.81**	**0.14**	**1.02**	**NS**	**NS**
Nutrient Expert	291	38	18	2.2	15.2	42.5	44.9
Farmers' Practice	261	35	14	1.8	14.1	41.3	42.0
SEm(±)	**8.5**	**0.81**	**0.33**	**0.07**	**0.32**	**0.62**	**0.81**
CD(P=0.05)	**25.5**	**2.43**	**0.99**	**0.21**	**0.96**	**NS**	**2.43**

There were temporal differences in various agronomic parameters. The values for growth parameter like plant height, dry matter, LAI, yield components like number of effective tillers per sq. m, no of spikelets

per earhead, no of grains per spikelet, harvest index were observed. It was the found that the growth parameter as well as yield component and yield were significantly affected by different level of fertilizer and different types of tillage. The result indicated that different schedules of fertilizer expressed significant effect on plant height, dry matter, LAI,Wheat grain yield and straw yield at harvest. It was found that the application of nutrient on the basis of recommendation obtained from the decision support system like "Nutrient expert" gave highest yield and yield parameter values. The AE and RE of N and K was also highest in Nutrient expert treated plot and it was significantly higher than all other treatments. The PE was also highest in Nutrient expert treated plot. Similar response in Maize was also reported by Kumar *et al*, 2013.

CONCLUSION

This indicates that production and use efficiency of nutrients can be increased with the use of nutrient expert tool and SSNM

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Effect of Potassium Rich Sea Weed Extracts on Performance of Potato in the Red and Lateritic Soil of West Bengal

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Abstract

Potato (*Solanum tuberosum* L.) is a wholesome food crop and is used as a staple food in several developed countries. Globally, it ranks fourth in importance among food crops i.e., after rice, wheat and maize.

Sea weeds are marine algae, saltwater dwelling, and simple organisms which have wide range of beneficial effects including increased crop yields, increased uptake of inorganic constituents from the soil, more resistance to stress conditions and reduction in storage losses of fruit. Investigations revealed that seaweed species were observed to be a potential source of fertilizer especially potassium

A field experiment was conducted in the red and lateritic soil of West Bengal, during *Rabi* season of 2012-13 at the farmer's field in Chella Kamarpara, Birbhum, West Bengal. The experiment consisted of fifteen treatment combinations comprising of five concentrations of liquid extracts of two sea weed species namely *Kappaphycus* (K) and *Gracilaria* (G) at different levels of fertilizer which were replicated thrice and was laid out in randomized block design (RBD). The Recommended dose of fertilizer (RDF) was 200:150:150 kg/ha of N: P_2O_5:K_2O. The highest values for growth attributes, yield attributes, yield and nutrient analysis were recorded with the spraying of seaweed extract at different stages. The highest tuber yield was recorded with applications of 15% *Kappaphycus* + 100 % recommended dose of fertilizer (RDF), followed by 15% *Gracilaria* + 100 % RDF resulting in an increase by 27.88% and 27.09%, respectively compared to the water applied plots. Improved uptake of mainly potassium (K) was also observed with seaweed extract applications. Application of seaweed extract along with 100% recommended dose through fertilizers also paid higher gross and net returns, return per rupees invested from potato cultivation. So, use of seaweed extract proved beneficial in terms of improved growth, yield, potassium nutrition and economics of potato cultivation in red and lateritic soil of West Bengal.

Assessment of Potassium Deficiencies in Agricultural Systems in Uruguay

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Abstract
A well-defined local recommendation guideline for K fertilization is demanded by farmers and technicians, particularly for Uruguay, where the agriculture is strictly dependent on imported fertilizers. Typically, the main crops planted in Uruguay are barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*) as winter crops, and corn (*Zea mays L.),* and soybean [*Glycine max* (L.). Merr.] as summer crops. The objectives of this study were to correlate grain crop yields to soil-test K (STK) (CH_3COONH_4 test) from soil samples taken from the Ap horizon. Experiments were established at 110 site-years from 2004 to 2015 in commercial production fields: 14 for corn, 15 for barley, 56 for soybean, and 25 for wheat, under no-tillage systems. The source of K was KCl in all experiments. The STK ranged from 0.12 to 1.22 cmol K kg^{-1} and relative yields (yield without K application/yield with K application) were of 8% to 110%. Crops responded positively to K application in 58% of the cases in soils testing < 0.20 cmol K kg^{-1}, 43% of the cases when testing from 0.21 to 0.30 cmol kg^{-1}, 34% at soils from 0.30 to 0.40 cmol kg^{-1}, and 29% in soils from 0.40 to 0.50 cmol kg^{-1}. Only at three of 35 sites with soil testing above 0.51 cmol K kg^{-1} (9%) response to KCl application was observed. Potassium increased yields more frequently at corn and to a lesser extent at soybean. Critical levels were closer to the 0.34 cmol kg^{-1} level previously established. Future research discriminating soil texture, non-exchangeable K, and mineralogy is needed.

INTRODUCTION

Increasing crop productivity is strongly influenced for an adequate nutrient management, which requires of well-defined recommendation guidelines. This is particularly important for Uruguay, where agriculture -the major economic activity- is strictly dependent on imported fertilizers. While nitrogen (N) and phosphorus (P) have been included in the fertilization and research programs since the decade of 1950, soil K has been considerate sufficient for most crops and, as a result, the development of an experimental base for this nutrient has been neglected. Recently, however, K was identified as one of the main constraints for crop production (Barbazán, Ferrando & Zamalvide, 2007; Bordoli, Barbazán & Rocha 2012). Additionally, a decline of K levels has been detected in some of the most fertile soils of the traditional crop area (Morón & Quincke 2010), after more than 100 years of continued farming without K replenishment. Therefore, there is a need of to develop rational guidelines for K fertilizer application.

Wheat and barley have been traditionally the major national crops, but during the last 10 years, the soybean turned out as the most frequently planted crop. Additionally, since the late 1980's, all these crops have been grown under no- till systems (NT), which in conjunction with the use of new varieties and more efficient and modern equipment, among other factors, allowed increasing the agricultural area in about 300% during the last decade (DIEA 2014). Those new management practices and the climatic conditions of the temperate region where Uruguay is located, allow farmers to grow 1.5 crops per year, which, moreover, are produced under a short-term land leasing regime.

Published information showing the effects of K fertilization on different crops, soil tillage systems, and soil type is abundant in the world (Mallarino & Blackmer 1994, Mallarino, Webb & Blackmer 1991a, 1991b, Slaton et al. 2010), but in Uruguay, this information is scarce.

One of the best predictor of K fertilization needs is the soil-test K (STK) in soil sampling taken at0-15 or 0-20 cm depth at planting date.

The objectives of this study were to correlate grain crop yields to STK from soil samples taken from the Ap horizon. The results of this study would be useful for the establishment of rational recommendations of K fertilizations based on STK in the country, where the total amount of the K fertilizer applied is increasing and the area for agricultural expansion is limited.

MATERIALS AND METHODS

Field K response trials were established at 110 site-years between 2007 and 2014 (Table 1). The trials were located in commercial fields and represented soils used typically under agriculture at Uruguay. Most of the sites had been under continuous NT management for at least 15 years before treatment application, and never received significant K fertilization during the whole agricultural production period. A randomized complete block design with three replications was used for all site-years. The treatments were at least two rates, ranging from 0 to 200 kg K ha^{-1}), as potassium chloride (KCl), surface- broadcast-applied by hand before or immediately after planting. Except K fertilization, the rest of the crop management practices were those normally recommended at each site. Composite soil samples (15 cores, 2-cm diameter each) were collected randomly before treatment application from the first 20 cm depth. Soil was dried at 40°C, ground, and passed through a 2-mm sieve. Each soil sample was characterized for selected chemical properties, soil organic matter by the Walkley Black method (Nelson & Sommers 1982), and soil pH by potentiometry, using a 1:2.5 soil:water ratio (Table 1). Exchangeable Ca, Mg, K, and Na were extracted by 1 mol L^{-1} NH_4OAc.

Crop grain was harvested by hand from the center of each plot and threshed using a stationary thresher. Yields were corrected to 155 g kg^{-1} moisture for corn, 140 g kg^{-1} for wheat and barley, and 130 g kg^{-1} for soybean.

Analysis of variance for treatments effects on grain yield were conducted separately for each site-year according the General Lineal Models (GLM) procedure of SAS (SAS Inst., Cary, NC.). Soil test K critical concentrations (CC) were calculated with the statistical Cate-Nelson method (Cate & Nelson 1971).

RESULTS AND DISCUSSION

Soil K test ranged from 0.12 to 1.22 cmol K kg^{-1} across the 110 site-years, with a mean of 0.44 cmol K kg^{-1} (Table 1) and a median value of 0.36 cmol K kg^{-1}.

Grain yields increased significantly ($P< 0.10$) by K application at 32 of the 110 sites. Crops responded positively to K application in 58% of the cases in soils testing < 0.20 cmol K kg^{-1}, 43% of the cases when testing from 0.21 to 0.30 cmol kg^{-1}, 34% at soils from 0.30 to 0.40 cmol kg^{-1}, and 29% in soils from 0.40 to 0.50 cmol kg^{-1} (Fig. 1). Two sites with barley and one with corn responded positively when STK was > 0.51cmol kg^{-1}.

The yield of barley, corn, soybean, and wheat receiving no K fertilizer and grown on soils that responded positively to K application averaged 2582, 3367, 2127, and 2626 kg ha^{-1}, respectively, with a relative yield respect to the highest yield in each site, of 72%, 64%, 71%, and 80%, respectively. For sites that did not respond significantly to K application, the average yield of the control treatments was 3224, 4970, 2315, and 4884 kg ha^{-1} for barley, corn, soybean, and wheat, respectively. The crops that most frequently responded to the application of K were corn (40%) and barley (39%), followed by wheat (24%) and finally by soybean (11%). The maximum losses of yield due to K deficiency were observed in a site with corn (92%) and in a site with soybean (54%).

Critical concentrations calculated by the Cate and Nelson statistical procedure were similar to the previous values of 0.3-0.4 cmol K kg^{-1} established by Barbazán et al. (2011) (Fig. 2). The relationship between grain yield response and soil-test values shows large variability indicating that further research discriminating soil texture, non-exchangeable K, and mineralogy is needed.

CONCLUSIONS

Potassium fertilization increased the yield of all the main crops grown in the typical soils of Uruguay. For all crops, the critical concentration was similar to previously established. However, further investigation to evaluate possible discrimination by soil texture, non-exchangeable K levels, and mineralogy is needed.

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Table 1. General soil properties of the Ap horizon for barley, wheat, corn, and soybean farms in Uruguay.

Crop	n		pH	SOM	Ca	Mg	K	Na
			(2.5:1 H_2O)	g kg^{-1}	--------- cmol kg^{-1} ---------			
barley	14	Mean	5.99	33.6	17.72	2.09	0.49	0.35
		Min.	4.74	13.7	2.00	0.57	0.18	0.24
		Max.	7.40	54.2	33.81	4.27	1.02	0.62
wheat	26	Mean	5.80	35.3	16.00	2.27	0.47	0.34
		Min.	4.60	19.0	4.46	1.13	0.19	0.11
		Max.	7.30	45.0	34.43	5.30	1.20	0.69
corn	14	Mean	5.90	40.1	19.01	2.61	0.48	0.44
		Min.	5.05	18.0	6.15	0.88	0.15	0.30
		Max.	7.30	54.2	31.31	4.27	1.22	0.70
soybean	56	Mean	5.51	41.1	13.98	2.15	0.42	0.39
		Min.	4.60	19.0	2.29	0.66	0.12	0.18
		Max.	7.00	63.0	35.40	4.60	1.01	0.79
All crops	110	Mean	5.69	39.2	15.81	2.28	0.44	0.38
		Min.	4.60	13.7	2.00	0.57	0.12	0.11
		Max.	7.40	63.0	35.40	5.30	1.22	0.79

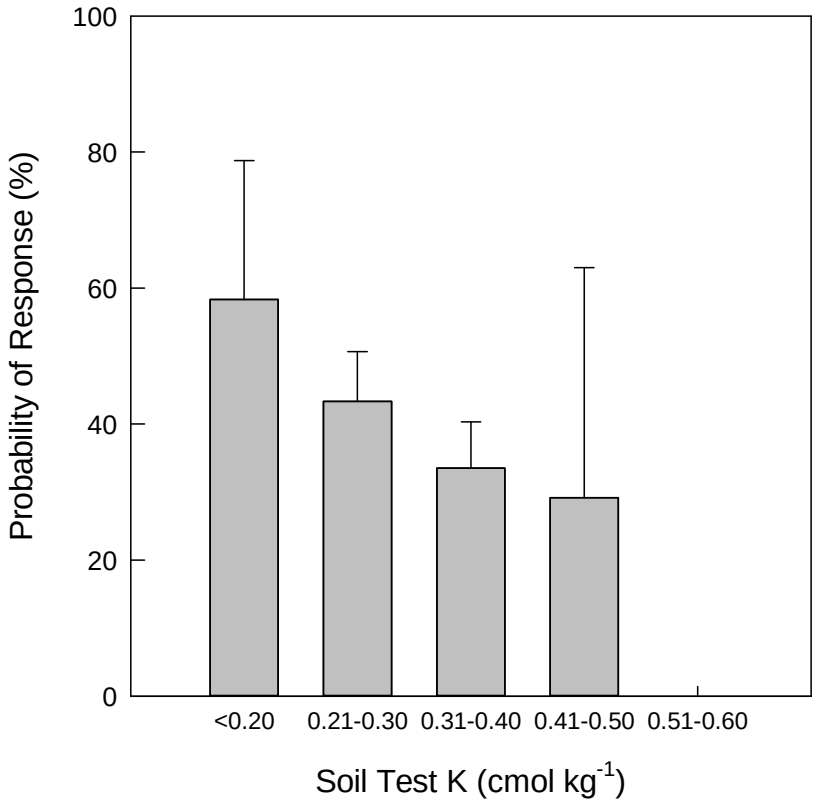

Figure 1. Relationship between response probability and soil test K.

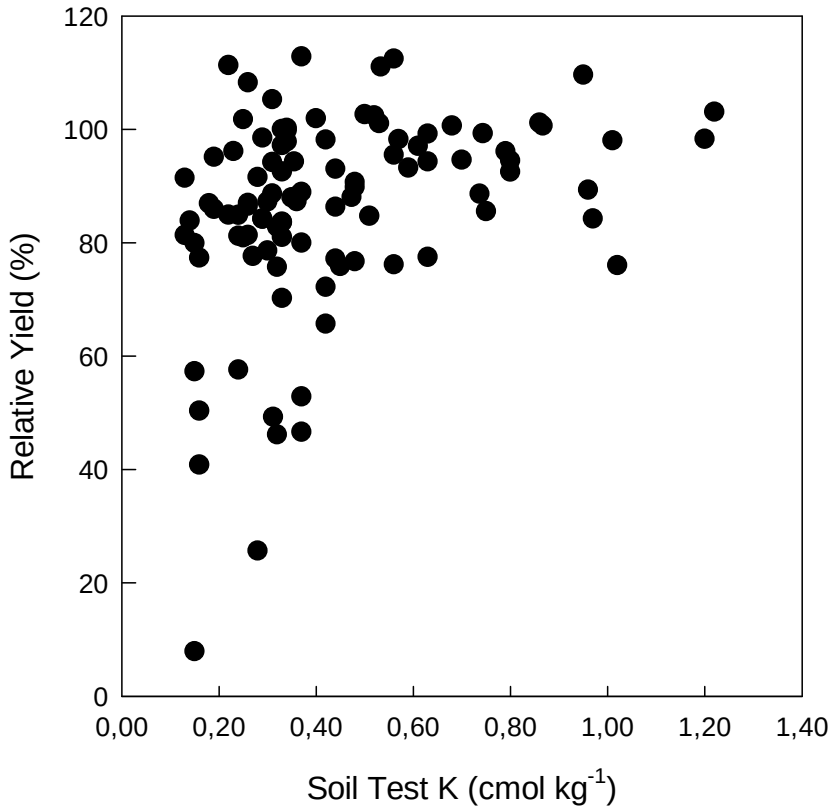

Figure 2. Relationship between relative yield for all crops and soil test K.

Alternative Source of Potassium Fertilization in Bean Crops

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Abstract
The common bean (*Phaseolus vulgaris* L.) is a very important crop in national agricultural scenario, as part of the daily diet of people in different regions of Brazil. The use of an alternative source of potassium fertilization on bean as a substitute for potassium chloride, a fertilizer that is widely used in this culture, is an important factor to reduce the high costs due to the fact that potassium chloride is an input imported in large scale in Brazilian agriculture. The objective of this study was to evaluate the use of phonolite rock, which is a crushed rock, as a substitute for potassium chloride in planting fertilization for bean crop. The experimental design was randomized block design with 5 blocks, each block consisting of 4 plots totalizing 20 plots in four treatments. The treatments were 20 kg $K_2O.ha^{-1}$ using potassium chloride, 40 kg $K_2O.ha^{-1}$ - using potassium chloride, 20 kg $K_2O.ha^{-1}$ - using phonolite rock and 40 kg $K_2O.ha^{-1}$ - using phonolite rock. For this experiment was evaluated the production of seeds, number of pods per plant and average number of seeds per pod, collecting plants in the area of each plot, which was composed of the three central rows of each plot (area of one square meter). The use of phonolite rock, as an alternative to potassium fertilization in bean crop, yielded similar results in relation to potassium chloride in all parameters evaluated, therefore, an alternative source of potassium fertilization viable to be used in agricultural crops.

Keywords: *Phonolite rock, Phaseolus vulgaris, bean crops, alternative fertilizers.*

Potassium Solubilization in Phonolite Rock by Diazotrophic Bacteria

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Abstract
Some strains of nitrogen fixing bacteria, besides fixing the N_2, can produce phytohormones, controlling pathogens, solubilizing minerals containing phosphorus (P) and potassium (K), contributing to plant growth. However, there is a need to evaluate the potential of these bacteria to solubilize other minerals containing elements of economic importance such as potassium (K), an essential nutrient for plants, imported in large scale in Brazil, representing approximately 90 % of the total used in agriculture. Therefore, the aim of this study was to evaluate potassium solubilization (K) of phonolite rock by strains of associative nitrogen fixing bacteria supplied with two different carbon sources. These bacteria were isolated from four culture media (VMY JNFb, LGI and NFB) semi-solid and semi-selective for the genus: Burkholderia - VMY Herbaspirillum -JNFb, Amazon Azospirillum - LGI and Azospirillum spp. - NFb. Twelve bacterial strains were cultured for seven days at 25°C in liquid conditions "Aleksandrov" supplemented with phonolite rock powder. The experiment was carried in a completely randomized factorial, 13 x 2 (12 bacterial strains and a control without inoculation) and two carbon sources (glucose and sucrose) with four replications. After the growth, the supernatant was separated by centrifugation and analyzed for the final pH value and the content of K. All diazotrophic bacterial strains contributed to increase the release of K when compared to the control treatment. The strain UNIFENAS 100-94 solubilized 130 mg L^{-1} K in the presence of the two carbon sources, indicating the potential use of these diazotrophic bacterial strains for K solubilizing from rock minerals.

Keywords: *Phonolite rock*, bio-solubilization, carbon source, rock powder

Nitrogen and Potassium Fertilizer Sources in Wheat Crop

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Abstract
The supply and the appropriate proportions of nutrients are essential to the yield and quality of wheat cultivation. Among various nutritional processes involved, nitrogen and potassium are responsible for the production and quality in wheat crop. One of the rocks studied as a potential source of K is phonolite volcanic rock, found in the area of Poços de Caldas, Minas Gerais, Brazil, with 8.0% of the total K_2O. The small concentration of K_2O present in the soluble phonolite rock is due to the predominance of some mineral constituents, where K is retained by covalent bonds in the mineral structure, providing low K concentrations for soil solution. Certain combinations of doses of N and K fertilization influence nutrition, growth and development of plants. Potassium is not part of chemical structure of the plant compounds, but has important regulatory functions, for example, the activation of at least 50 enzymes. The aim of this study was to evaluate different sources of nitrogen and potassium fertilizers with high and low levels of solubilization during the crop development. The experiment was conducted in DBC design, factorial 2 x 2, 5 blocks, totalizing 20 plots. Each plot represents 120 plants and only plants that developed 60 cm far from the centerline were evaluated. The data was submitted to the Scott – Knott test ($p < 0.05$). The evaluated characteristics were dry matter and weight of panicle, stem and plants. The results showed that the association of nitrogen and potassium fertilizers sources of similar solubility was the most indicated to the wheat crop development.

Keywords: potassium fertilization, nitrogen fertilization, wheat, phonolite rock

Phonolite Rock Fertilization as an Alternative Source of Potassium in Sorghum Crop

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Abstract
In recent years the sorghum crop (Sorghum bicolor) has been highlighted regarding to the expansion, mainly in the succession of plantings summer crops. The increase in planting sorghum has shown the necessity for further studies on the mineral nutrition of the crop, particularly the potassium (K), which is the second most nutrient absorbed by the majority of plant species and can be found in all plants tissues. The phonolite, is a rock with about 9% of K2O, and has emerged as an alternative source of potassium, being considered as a slow-release fertilizer that also provides other nutrients essential for plant growth, such as Ca, Mg, Mn and Fe. The objectives of this study were to evaluate the productivity and the residual effect in the soil, when using the phonolite as an alternative source of potassium in the sorghum crop. The experiment was conducted at UNIFENAS, Alfenas – MG, the treatments used was the dose of 60 Kg.ha-1 K2O, using three sources of potassium: potassium chloride (KCl), potassium sulfate and magnesium (K-Mag), phonolite rock and the control treatment. The green mass parameters, dry weight, height and stem diameter were analyzed. After the crop harvest, soil samples were taken to determine the amount of residual potassium in the soil. The results presented that the use of phonolite rock as an alternative source of potassium is not a viable source to promote the development of sorghum, the different sources of potassium fertilizers in the soil are able to produce similar residual effect and the soluble sources of potassium (potassium chloride and K-Mag) can provide greater dry matter production in forage sorghum.

Keywords: Phonolite rock, sorghum bicolor, potassium fertilizer, alternative fertilizers

Recalibration of Soil Potassium Test for Corn in North Dakota, U.S.A. and Effect of Sampling Time

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Abstract
Potassium (K) fertilizer recommendations for corn (*Zea mays*, L.) are commonly guided by yield response calibrations to soil test potassium (STK). The standard method for STK assessment in the North Central region of the United States employs neutral 1.0 M NH_4OAc on air-dry or oven-dry soil; however, sample drying and date of soil sampling have been shown to affect the amount of extractable K. Furthermore, yield responses to K fertilization may be inconsistent on low and high STK soils. Potassium rate trials were established in southeastern North Dakota during 2015 and 2016 with objectives to evaluate soil K testing methods and their relationship with corn yield response to K fertilization and to assess temporal soil K variation. Soil test methods evaluated were NH_4OAc on air-dry and field-moist soil, sodium tetraphenylboron, and an ion-exchange resin. Soil test K was affected by the date of soil sampling at most sites. NH_4OAc extractable-K from air-dry soil was the best predictor of relative yield response ($r^2 = 0.54$), although it only predicted significant yield responses at less than half of sites. A mineralogical analysis for K-bearing minerals and clay species showed that yield response was positively albeit minimally related to K-feldspar, muscovite, smectite, and illite content. An adequate determination procedure for plant-available K in North Dakota soils remains to be identified.

INTRODUCTION

Fertilizer recommendations are commonly guided by yield response calibrations to soil test levels. The current potassium (K) fertilizer recommendations for corn (*Zea mays*, L.) in North Dakota are based on limited research conducted in the late 1970s and early 1980s; this was a time when native soil K fertility was sufficient for most crop K requirements with the exception of particularly sandy soils (Zubriski & Moraghan 1983). In 1980, 3% of soil tests in North Dakota indicated medium or lower STK levels (<130 mg kg^{-1}) (Nelson 1980). The recent change to intensive corn and soybean (*Glycine max*, Merr.) production systems from chiefly spring wheat (*Triticum aestivum*, L.) rotations, particularly in eastern North Dakota, without maintenance K fertilization has resulted in more low STK values being reported. In 2010, 17% of soil tests in North Dakota had STK levels below the critical level of 160 mg kg^{-1} (Fixen et al. 2010). Given lower STK values becoming more common, a recent spike in K fertilizer price after decades of price stability, and higher corn yields due to improved genetics and agronomic practices, a reassessment of the soil K test and K fertilizer recommendations in North Dakota has been prompted.

The standard soil K test method for soils in the North Central region of the United States employs a neutral ammonium acetate (1.0 M NH_4OAc at pH 7.0) on air-dried or 40 °C oven-dried soil (Warnacke & Brown 2012). This method has come under scrutiny because soil sample drying (Barbagelata & Mallarino 2012; Luebs et al. 1956) and time of soil sampling (Childs & Jencks 1967; Franzen 2011; Liebhardt & Teel 1977; Vitko et al. 2009) have been shown to affect STK results. Moreover, yield responses to K fertilizer application may be inconsistent on both low and high STK soils (Rakkar et al. 2015). Recognition of these factors complicates the interpretation of STK results for fertilizer recommendations. Alternative methods for plant-available K assessment have been proposed to address the shortfalls of the standard soil K method such as NH_4OAc on moist soil (Barbagelata & Mallarino 2012), sodium tetraphenylboron (Cox et al. 1999), and ion-exchange resins (Rahmatullah & Mengel 2000; Skogley & Haby 1981).

The objective of this study was to revise the K fertilizer recommendation for modern corn production in North Dakota through: (i) evaluation of the NH_4OAc extraction method on air-dry and field-moist soil as well as novel soil tests including $NaBPh_4$ and an ion-exchange resin, (ii) assessment of STK relationship with yield response, and (iii) assessment of STK changes during the growing season.

METHODS AND MATERIALS

Field Study

On-farm K rate trials were established in southeastern North Dakota at thirteen locations in 2015 and six locations in 2016. The experiments were organized using a randomized complete block design with four replications and six K rate treatments on corn and one non-fertilized fallow treatment to assess soil K changes without plant uptake. The K treatments were 0, 34, 67, 101, 135, and 168 kg ha^{-1} K_2O applied as fertilizer-grade potassium chloride (0-0-60) granules hand-broadcasted prior to planting. The experiment unit size was 3.0 m by 9.1 m. Fertilizer treatments were incorporated shallowly (5-8 cm) by farmer-cooperators, except on no-till sites. Farmer-cooperators planted corn and applied herbicides and other inputs on experiment areas when they conducted those activities on the rest of the field. Initial soil samples were collected from non-fertilized check and fallow plots from 0- to 15-cm and 15- to 30-cm depths and thereafter collected biweekly until harvest from the 0- to 15-cm depth only. Six soil cores were taken from each plot. After physiologic maturity, corn grain was hand-harvested as whole corn ears from one interior 9.1-m row, shelled, weighed for grain yield, and measured for grain moisture and test weight. Grain yield was corrected to 145 g kg^{-1} grain moisture.

Soil Analysis

Soil samples were hand-homogenized and split into two subsamples. One subsample was air-dried following the procedure suggested for the North Central region (Gelderman & Mallarino 2012), ground to pass through a 2-mm sieve, and analyzed for NH_4OAc-extractable K (Warnacke & Brown 2012). A 2-g air-dry soil sample was extracted with 20 mL 1.0 M NH_4OAc at pH 7.0 and shaken for 5 minutes in 50-mL Erlenmeyer flasks. The extract was filtered through Whatman No. 2 filter paper (GE Healthcare Bio-Sciences, Pittsburgh, Pennsylvania, USA) and analyzed for extractable K by atomic absorption spectroscopy (AAS). The other subsample kept at field-moisture was stored in a plastic re-closeable bag and refrigerated until analysis. The field-moist sample was prepared following the direct sieving procedure described by Gelderman and Mallarino (2012). Field-moist soil was passed through a 2-mm sieve, and soil water content was determined by drying a 6 g moist subsample to air-dryness and constant weight. A 2-g air-dry equivalent mass of field-moist soil was weighted and extracted with 20 mL 1.0 M NH_4OAc at pH 7.0, thereafter, following the same analysis procedure described for the air-dry K method.

The sodium tetraphenylboron extraction method (Cox et al. 1999) was used to determine the most reactive and total nonexchangeable K fractions using 5-minute and 7-day extraction times, respectively. Resin-extractable K was determined using a mixed-bed, cation- and anion-exchange resin capsule (UNIBEST Inc., Walla Walla, Washington, USA). A 30-g air-dry equivalent mass of 2-mm sieved, field-moist soil was incubated with a resin capsule and 30 mL deionized water for 7 days at constant 20 °C. After the incubation period, the resin capsule was washed with deionized water to remove attached soil and leached with 50 mL 2M HCl using a manual slow-drip leaching apparatus (UNIBEST Inc., Walla Walla, Washington, USA). The resin leachate was analyzed for resin-extractable K using AAS. The cation exchange capacity was estimated (ECEC) by summation of extractable Ca, Mg, K, Na, and neutralizable acidity (Warnacke & Brown 2012). Semi-quantitative mineral identification and clay speciation was conducted by Activation Laboratories Ltd. (Ancaster, Ontario, Canada) on a composite field-moist soil sample from each site. Soil texture was determined by the hydrometer method (Gee & Or 2002).

Data Analysis

Data was analyzed using SAS 9.4 (SAS Institute, Inc.) to determine if yield responses to K fertilizer were significant using *proc GLM*. Relative grain yield was calculated by dividing the average yield of the 0 kg ha^{-1} K_2O treatment by the maximum average treatment yield at each experiment site. Relative grain yield and STK were regressed to fit a modified Mitscherlich model (Ware et al. 1982) using *proc NLIN*. Relative yield data from LN15, LS15, V15, and VC16 were excluded from regression analysis because of non-K nutrient deficiencies, poor plant population, or no-till cultivation. Soil K data was analyzed as a randomized complete block design with split-plot in time arrangement using *proc MIXED* to determine if changes in soil K were significant and regressed to fit sinusoidal models over time using *proc NLIN*. Mineralogical analyses were related to soil test and yield response data using *proc FACTOR* with squared multiple correlation prior communality estimates and orthogonal rotation.

RESULTS AND DISCUSSION

Effect of Soil Sample Drying on Soil Potassium

The initial STK levels at each site ranged from 69 to 444 mg kg^{-1} air-dry soil K (DK). On average, DK was 1.267 times higher than field-moist soil K (MK) ($p<0.01$, $n = 1365$, range: 0.69 – 2.75), showing that sample drying overestimated the amount of exchangeable K from field-moist condition. The ratio of DK/MK regressed against MK showed that the relative amount of K released upon drying was greater for low K soils (Figure 1). Distinct trends for individual soils or groups of soils could be identified within the data cloud indicating that other soil or site characteristics influenced STK upon drying, resulting in four groups of sites with compatible drying curves (Figure 2). However, the groups themselves could not be related with any particular soil textural or mineralogical feature. The average DK/MK ratio for each site was most strongly correlated to the smectite/illite ratio of the clay fraction (Figure 3). Soils with a higher proportion of smectite in their clay fraction released more K upon drying. Conversely, this suggests that K in illitic soils was less influenced by soil moisture status. Soil texture and soil moisture status exhibited no strong relationship with sample drying effect.

Effect of Sampling Time on Soil Potassium

Soil test K measured throughout the growing season from late May to early September (2015) or late September (2016) revealed that STK did change from spring to fall. The effect of sampling time on DK and MK was statistically significant ($p<0.05$) at 18 of 19 sites (data not shown). Generally, STK of cropped plots was highest in late May or June and reaching its lowest level in late summer before slightly increasing in fall, agreeing with the cyclical STK observations of Peck and Sullivan (1995) in Illinois. The seasonal decrease in STK was influenced by plant K uptake and seasonal soil moisture status. Soil test K trends in fallow plots were of lesser magnitude but more variable in trend direction, sometimes remaining stable or increasing. The study region received limited rainfall in late summer and early fall of 2015, which exacerbated the effect of K fixation on reducing STK in late summer. In 2016, the study region was dry during spring and early summer, followed by scattered rains in late summer that differentially affected STK change for those sites.

Regression analysis of cropped plots showed that the relationship between STK and sampling time could be modelled by a sinusoidal function. Sinusoidal relationships between DK and sampling time were significant ($p<0.10$, r^2 range: 0.83-0.99) at five of 13 sites in 2015 and at five of six sites in 2016. Significant sinusoidal relationships ($p<0.10$, r^2 range: 0.68-0.99) between MK and sampling time were established for 12 of 13 sites in 2015 and three of six sites in 2016. The 12 sites from 2015 were successfully summarized into one function that indicated the periodicity of the sinusoidal relationship in STK change was consistent across low and high MK sites (Figure 4). Although the individual 2016 sites exhibited strong sinusoidal relationships, the sites were unable to be summarized into one function because of the late season rainfall variability across the study region. Across both years, the fallow plots exhibited significant sinusoidal relationships ($p<0.10$) at only three sites for DK and six sites for MK, showing that the role of K and water uptake by corn was an important factor in establishing the sinusoidal

pattern (data not shown). The seasonal difference in STK from spring to fall for individual sites ranged from 19-82 mg kg^{-1} DK and 15-83 mg kg^{-1} MK, which would be great enough to change existing STK interpretation classes at most sites simply depending on a spring versus fall soil sampling time.

Yield Response to K Fertilization

The wide range of STK in the K trials encompassed the current 160 mg kg^{-1} DK critical level, which should have lent itself useful prediction of a yield response to K fertilization. In contrast, corn yield increased to K fertilization at only six of 12 sites with DK below the 160 mg kg^{-1} critical level (Table 1). Moreover, one site with DK above the 160 mg kg^{-1} critical level (VC16) had a yield increase. The established critical level for the DK test predicted yield response less than half of the time (Table 2). Two sites (F115 and GD16) had yield decreases at the high 167 kg ha^{-1} K_2O rate (Table 1).

Modified Mitscherlich models of relative yield regressed against DK and MK (Figure 5) showed that DK was a better predictor of yield response to K fertilization than MK, which contrasted the observations of Barbagelata and Mallarino (2012) in Iowa. The coefficient of determination for the DK model (r^2=0.54) showed that even the best regressor DK was not a strong predictor of yield response. These poor relationships between NH_4OAc extraction methods (i.e., exchangeable K) and relative yield response suggest that other factors contribute to plant-available K supply.

Sodium tetraphenylboron-extractable K (TBK) for the 5-minute and 168-hour extractions had no significant relationships with relative yield (Figure 6). The $NaBPh_4$ extraction with its ability to extract a portion of nonexchangeable K did not provide a better estimate of plant-available K than NH_4OAc-extractable K. Schindler et al. (2002) observed that $NaBPh_4$ had no advantage over NH_4OAc to estimate corn K uptake in montmorillonitic soils due to the diminished capacity of smectitic clays to fix K. This observation would apply to the smectite-dominated mineralogy of most sites in this study.

Resin-extractable K was best modelled by a linear function yet had no significant relationship with relative yield (Figure 7). Resin-extractable K was positively correlated with DK (r^2=0.46, $p<0.01$, n=19), MK (r^2=0.50, $p<0.01$, n=19), and K saturation of ECEC (r^2=0.80, $p<0.01$, n=19), but it was negatively correlated with estimated cation exchange capacity (r^2=0.25, $p<0.01$, n=19). This suggests that other cations competed for exchange sites on the resin in high ECEC soils, which would reduce its ability to extract exchangeable and nonexchangeable K forms alike in these soils.

Mineralogical analysis indicated that some sites contained appreciable amounts of K-feldspar, muscovite, and/or illite. Potassium-feldspars and nonexchangeable K may serve as a large source of plant-available K if plant demand is high (Parker et al. 1989; Sadusky et al. 1987), which may explain the lack of yield response on high K-feldspar soils. A factor analysis of STK and mineral components showed that yield response was positively albeit minimally related to DK, K-feldspar, muscovite, smectite, and illite content (Figure 8). No mineralogical component exhibited a distinct relationship with yield response. Potassium release from mineral K or nonexchangeable K forms may provide enough K to satisfy plant K requirements in low STK, non-responsive soils; however, the amount of K release remains to be elucidated.

SUMMARY

The standard soil K test in the North Central region employs a neutral 1.0 M ammonium acetate extraction on air-dry or oven dry soil; however, the method has come under scrutiny because sample drying and time of soil sampling have been shown to affect the amount of extractable K. Soil sample drying was shown to significantly increase NH_4OAc-extractable K from its field-moist condition by a factor of 1.267 on average; yet, the ratio of DK/MK varied with MK, and the smectite/illite ratio of the clay fraction appeared to influence the degree of K release upon drying. The time of soil sampling did

affect soil test K levels during the growing season, being highest in spring and lowest values in late summer. At most sites, the change in soil K was described by a sinusoidal function over time.
The current soil test critical level of 160 mg kg^{-1} DK predicted corn grain yield response to K fertilizer less than half of the time. Relative yield response were best related to DK; yet, the relationship was not adequate for confident K fertilizer recommendations. Sodium tetraphenylboron and resin extraction methods, which have the ability to assess a portion of nonexchangeable K, had no significant relationships to yield response. Potassium-feldspar, muscovite, and illite amounts were positively albeit minimally related to yield response. An adequate determination procedure for plant-available K in North Dakota soils for the guidance of K fertilizer recommendations remains to be identified.

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TABLES AND FIGURES

Table 1. Corn grain yield response to K fertilization.

Site	Grain yield						p>F
	Fertilizer K rate (kg ha^{-1} K_2O)						
	0	34	67	101	135	168	
	---------- kg ha^{-1} ----------						
AB15	9667	9667	9604	9541	10357	10483	0.91
AR15	9541	10357	10294	10671	10420	10483	0.60
B15	13747	13433	13684	13119	13370	13558	0.91
C15	12868	12052	13244	14186	13621	12931	0.28
D15	12993	13307	12680	12742	12491	12428	0.82
F115	12052 ab†	12554 a	12366 a	13182 a	12554 a	10922 b	0.03
F215‡	11361 c	11926 bc	12303 abc	11550 bc	13119 a	12554 ab	0.06
LN15	10294	10043	9855	10043	10922	10483	0.64
LS15	10608	9667	9604	10357	10106	10545	0.35
M15	10232 c	10545 bc	10734 bc	10734 bc	11550 ab	12177 a	0.04
P15	11801	11675	11550	12115	12052	12177	0.86
V15	6654	6591	6591	6403	6654	7532	0.60
W15	11487 bcd	11048 a	11361 cd	11989 abc	12366 a	12115 ab	0.01
AK16	12118	11619	12576	11751	13031	11164	0.13
CF16	13568	14224	13659	13813	15443	15106	0.15
GD16	10399 b	10913 b	10930 b	11661 a	11983 a	10564 b	<0.01
LB16	10057 b	11926 a	12003 a	13066 a	11885 a	12430 a	<0.01
MO16	15117	14549	15126	14614	14476	14308	0.80
VC16	8967 c	10839 a	10279 ab	9332 bc	9356 bc	10778 a	0.01

† Within rows, treatment means followed by the same letter are not significantly different according to LSD (0.05).
‡ Significance modified to LSD (0.10).

Table 2. Frequency of yield response prediction by dry soil K test.

	Soil K test class (mg kg^{-1})†				
	VL‡ 0-40	L 41-80	M 81-120	H 121-160	VH 161+
Number of sites in soil test class	0	3	6	5	5
Number of sites with significant yield response	---	2	2	2	1
Probability of significant yield response	---	67%	33%	40%	20%
Probability of expected response above/below current 160 mg kg^{-1} critical level			50%		80%

† Soil K test classes for NH_4OAc-extractable K on air-dry soil from North Dakota soil fertility recommendations for corn (Franzen 2014).
‡ VL, very low; L, low; M, medium; H, high; VH, very high.

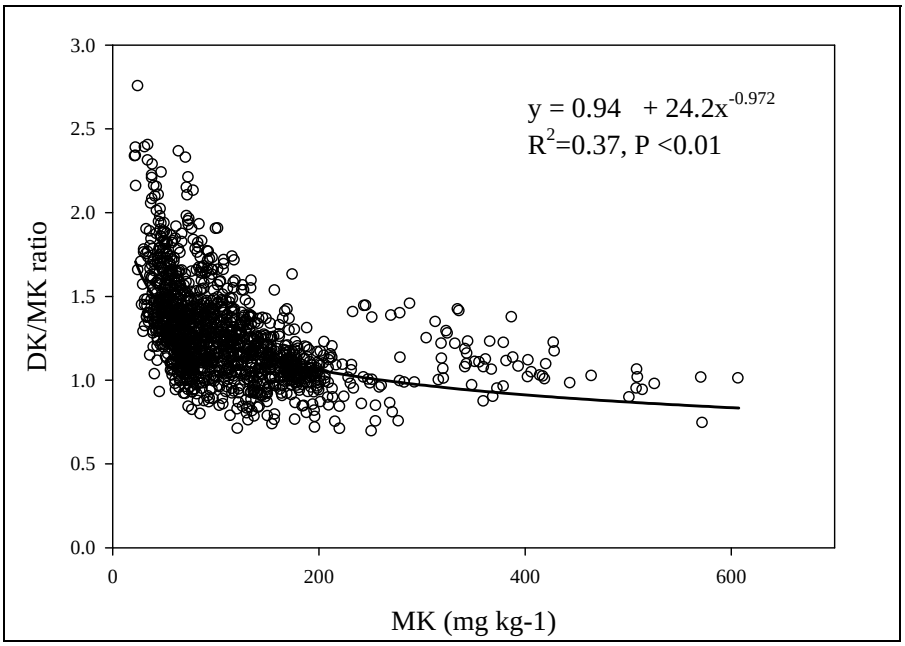

Figure 1. Relationship between the ratio of air-dry soil K (DK) and field-moist soil K (MK) regressed against field-moist soil K (MK).

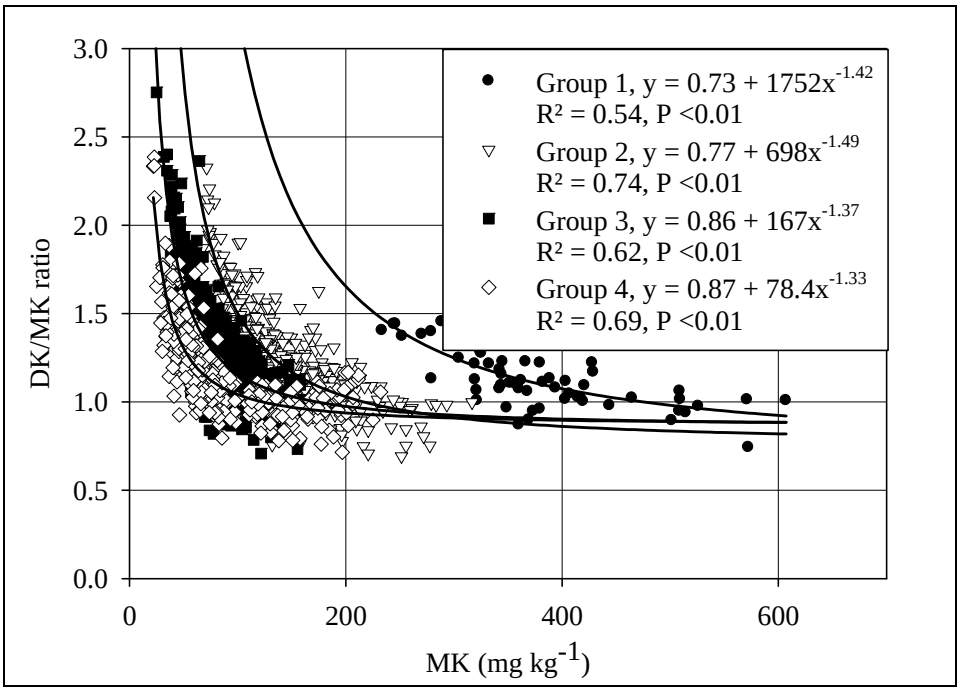

Figure 2. Relationship between the ratio of air-dry soil K (DK) and field-moist soil K (MK) regressed against field-moist soil K (MK) for four groups of visually-separated soil drying curves.

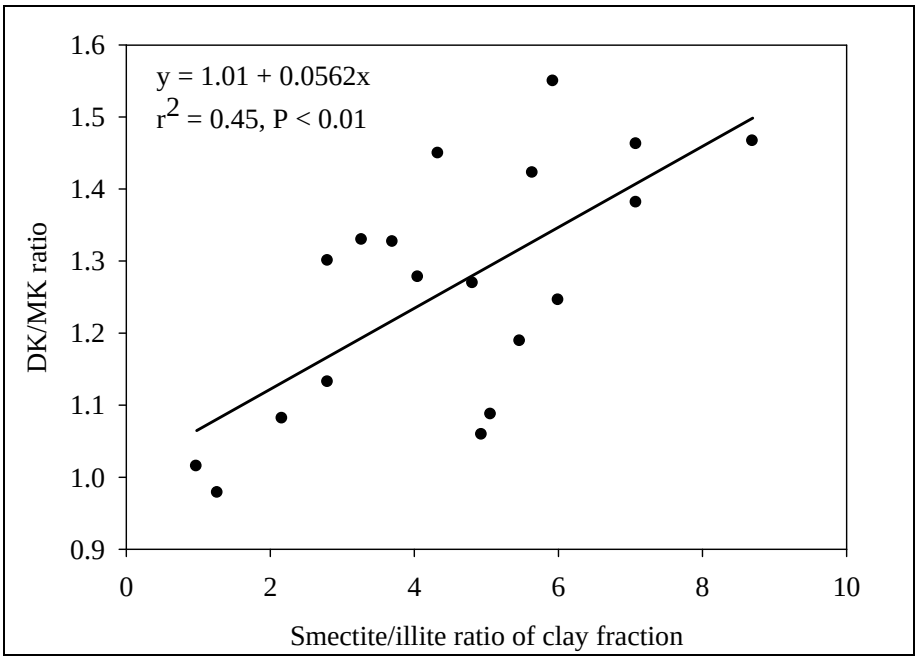

Figure 3. Relationship between the ratio of air-dry soil K (DK) and field-moist soil K (MK) regressed against the smectite-to-illite ratio of the clay fraction.

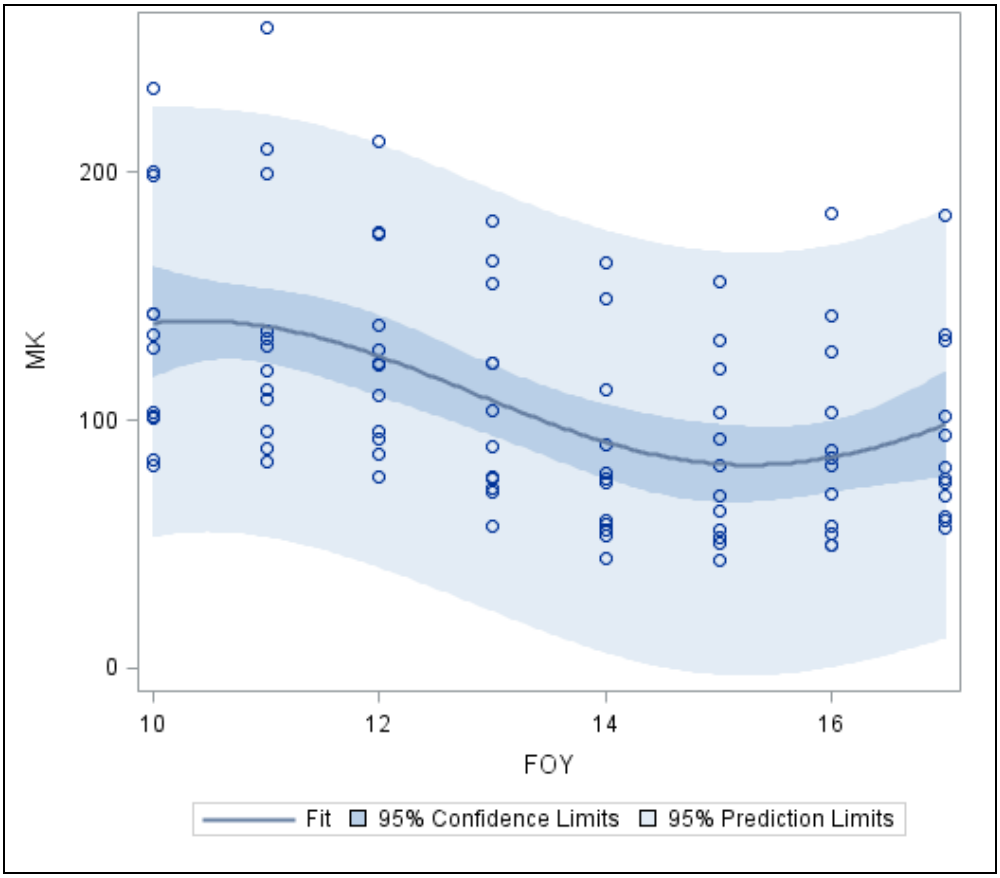

Figure 4. Field-moist soil K (MK) and sampling time (fortnight of year, FOY) fit to a sinusoidal regression model (MK = 111+29.1*sin (0.6425*FOY+1.185), $r^2 = 0.21$, $P < 0.01$) for 12 of 13 combined cropped, unfertilized treatments from 2015.

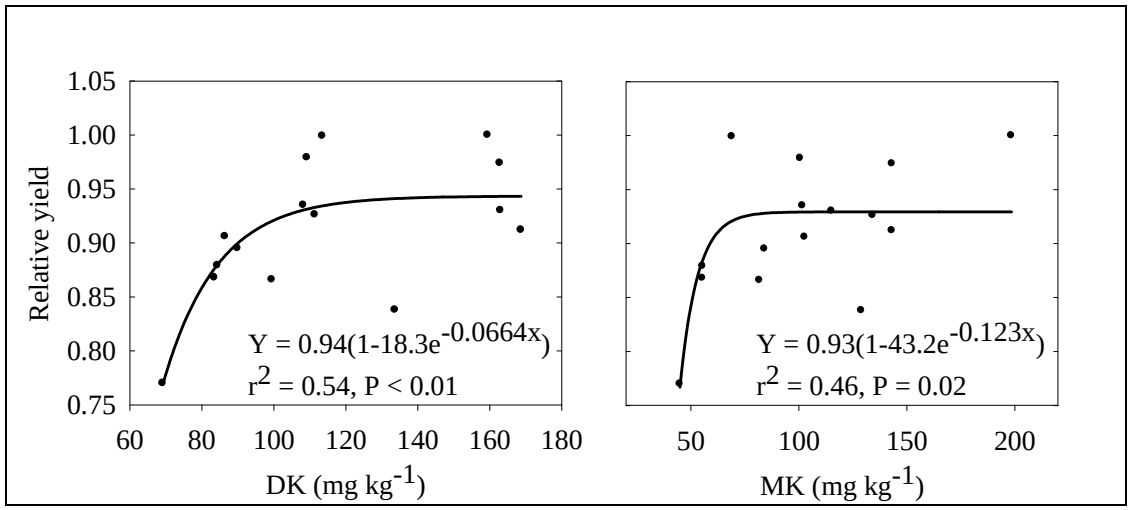

Figure 5. Relative grain yield of unfertilized treatment to maximum yield compared with NH_4OAc-extractable K from air-dry soil (DK) and field-moist soil (MK).

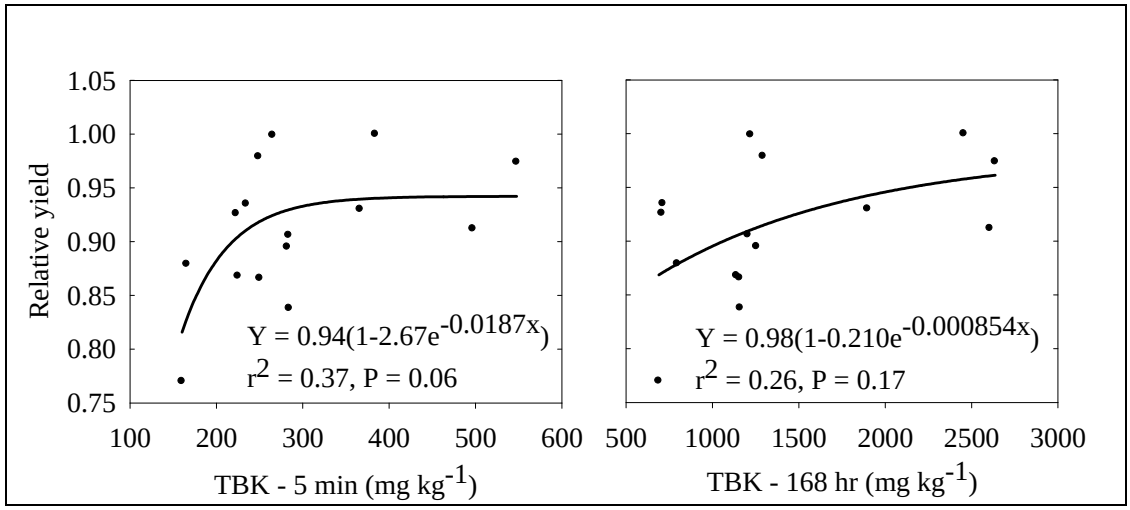

Figure 6. Relative grain yield of unfertilized treatment to maximum yield compared with tetraphenylboron K (TBK) for 5 minute and 168 hour extractions.

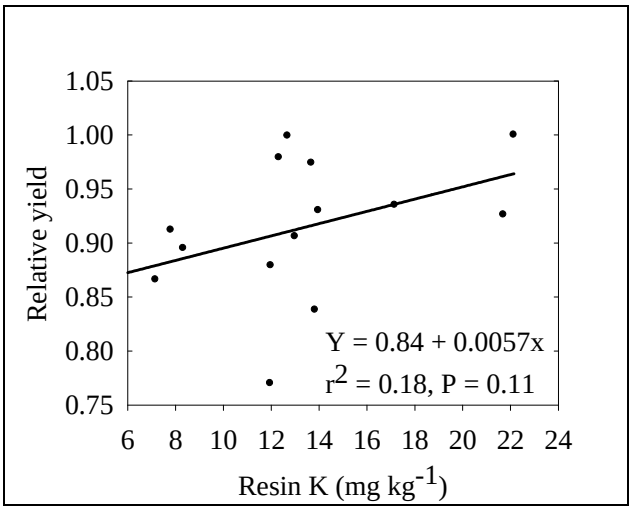

Figure 7. Relative grain yield of unfertilized treatment to maximum yield compared with resin-extractable K.

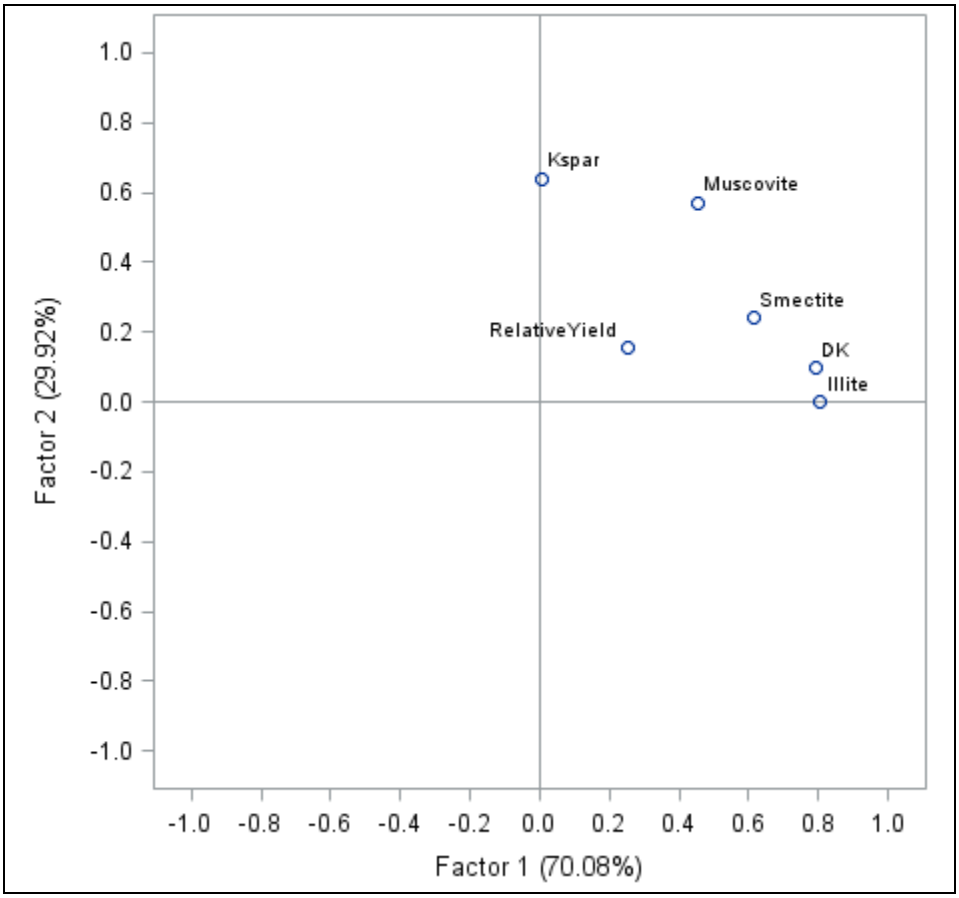

Figure 8. Varimax-rotated factor solution of air-dry soil NH_4OAc-extractable K (DK) and mineral components related to relative yield response to K fertilization. Mineral components expressed as fraction of whole soil.

Potassium Management Strategies for Higher Productivity of Rice (*Oriza sativa* L.)

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Abstract

Although Green Revolution had tremendous impact on nitrogen fertilizer use in Asia, it had much less impact on the use of phosphorous and potassium fertilizers Ranjha *et al.* (2001). Rice is one such crop which consumes considerable amount of potassium due to lack of distinct recommendations and methods we are left with lower potassium use efficiency. In order to standardize the potassium fertilization methods a field experiment was conducted and salient findings are discussed in this paper.

MATERIAL AND METHODS

A field experiment was conducted for two consecutive seasons of 2014 and 2015 at Agriculture and Horticulture Research Station, Honnavile, University of Agricultural and Horticultural Sciences, Navile, Shivamogga. The experiment consists of different levels, time and varied concentration of foliar applications and was planned by adopting split – split plot design with three replications. All the crop management practices are adopted as per the recommendations of the University (Anon., 2014), observations and statistical analysis was carried out by adopting standard methodology suggested.

RESULTS AND DISCUSSION

Data presented in the Table 1 indicated that, significantly higher grain (58.70 q/ha) and stover (63.20 q/ha) yields of paddy was obtained with application of potassium at 100 kg/ha. Significant improvement of grain yields of paddy in the said treatment was traced back to the significant improvement in yield attributing traits such as number of productive tillers per plant (20.00), panicle weight (16.10 g), panicle length (10.35 cm), number of grains per panicle (51.39) and test weight (20.20). Among the different time of application, 50 per cent of recommended potassium applied at basal coupled with remaining 50 per cent as top dressing recorded significantly higher grain and stover yields of paddy. It could be due to continuous availability of the potassium in the soil nutrient pool during major part of crop growth might have favored the crop growth and was also reflected through higher values of yield attributing characters of paddy (Table 1). Among the various foliar feeding treatments tried in the study, grain yields of paddy improved as the concentration of potassium increases up to 2 per cent K_2SO_4. Present findings are in the line of Ranjha et al. (2001). Excellence grain yields of paddy with foliar feeding of potassium with 2 per cent K_2SO_4 at 75 DAT was traced back to the superiority of yield attributing characteristics such as number of productive tillers per plant (19.95), panicle weight (16.10 g), panicle length (19.65 cm), number of grains per panicle (51.50) and test weight (10.95 g). It could be due to direct supply of higher amount of readily available potassium to the metabolic site might have favored the crop during flowering to grain filling stage. These finding are in agreement with the findings of Ebrahimi et al. (2012).

Table 1. Yield attributes and yield of paddy as influenced by different potassium management treatments (Pooled data of two season)

Treatment	Productive tillers (No.)	Panicle weight (g)	Panicle Length (cm)	Grains per panicle (No.)	Test Weight (g)	Grain Yield (q/ha)	Stover yield (q/ha)
Levels of K (M)							
M1	19.00	15.40	10.05	49.46	19.40	56.45	61.10
M2	19.50	15.75	10.15	50.51	19.75	57.50	62.30
M3	20.00	16.10	10.35	51.39	20.20	58.70	63.20
S.Em±	0.13	0.17	0.09	0.44	0.25	0.19	0.24
CD (0.05 %)	0.48	0.68	0.35	1.72	0.96	0.73	0.96
Time of application (S)							
S1	17.90	14.50	17.90	46.98	9.90	53.55	58.40
S2	21.30	17.05	20.75	54.41	11.75	62.05	66.20
S3	19.30	15.65	19.10	49.97	10.50	57.05	62.00
S.Em±	0.15	0.18	0.23	0.37	0.11	0.28	0.33
CD (0.05 %)	0.46	0.59	0.74	1.21	0.35	0.90	1.07
Foliar spray (F)							
F1	18.80	15.20	18.70	48.80	10.40	55.70	60.20
F2	19.70	15.85	19.45	51.01	10.80	57.95	62.80
F3	19.95	16.10	19.65	51.50	10.95	58.95	63.60
S.Em±	0.12	0.14	0.20	0.32	0.09	0.21	0.25
CD (0.05 %)	0.35	0.39	0.57	0.90	0.25	0.59	0.71

M_1-50 kg/ha M_2- 75 kg/ha M_3-100 kg/ha S_1-100% basal S_2- 50% basal S3-25% basal **F_1**-Foliar application of 0 % K_2SO_4 at 75 DAT F_2-Foliar application of 1 % K_2SO_4 at 75 DAT **F_3**-Foliar application of 2% K_2SO_4 at 75 DAT

CONCLUSION

Paddy crop fertilized with 100 kg/ha of potassium coupled with 50 % as basal and one foliar of 2% K_2SO_4 at 75 DAT found significantly superior by recording higher grain yield of paddy in command area of Southern Transitional Zone of Karnataka.

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Potassium Management in an *Alfisol* under a Long Term Fertilizer Experiment in Finger Millet–Maize Cropping System

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Abstract
Long term fertilization study to evaluate soil fertility, productivity of soil and crops was started in 1986 at Bengaluru on finger millet-maize cropping system. Selected treatments like 50% NPK, 100% NPK, 150% NPK, 100% NPK+lime, 100% NP, 100% N, 100% NPK+FYM, 100% NPK and control were considered to study the yield sustainability, potassium use efficiency and dynamics in soil.

The results revealed that application of super optimal dose of NPK (150%) resulted in higher grain yield of finger millet (47.44 q ha^{-1}) followed by NPK+FYM (41.75 q ha^{-1}). Integrated use of organics and inorganics recorded higher yield of maize (31.49 q ha^{-1}) followed by 150% NPK (29.50 q ha^{-1}). Application of 50% NPK recorded 26.54 q ha^{-1} and 16.96 q ha^{-1} finger millet and maize yield over the years suggesting insufficient fertilizer dose. Imbalanced fertilization (N and NP alone) drastically affected the yields with a profound effect of potassium on reduced yield of crops over the years. Higher sustainable yield index (SYI) of 0.633 was recorded in 150 % NPK followed by 100%NPK+lime and 100%NPK+FYM (0.586 and 0.557) for finger millet, whereas, in maize application of NPK+FYM recorded higher SYI (0.299) followed by 100% NPK+lime (0.271).

Higher potassium use efficiency (KUE) by finger millet was recorded in 100% NPK (148.51%) and 150%NPK (145.88%) whereas, in maize application of 100% NPK+lime resulted in higher potassium use efficiency (83.78%) followed by 100 % NPK (77.57%). Greater than 100 per cent KUE indicated very low uptake of K from soil by the crop. Different forms of potassium in soil showed a decreasing trend without K application. Potassium applied treatments recorded more water soluble and exchangeable potassium in soil. There was no consistent trend of non-exchangeable potassium in soil among various fertilizer applications. Application of FYM maintained all the fractions of potassium.

Key words: Potassium management, long term fertilizer experiment, finger millet, maize and cropping system

Fertilizer-dependent Efficiency of *Mesorhizobium* for Improving Growth, Potassium Uptake and Yield of Wheat (*Triticum aestivum* L.)

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Abstract
Acquisition of nutrients by plants is primarily dependent on root growth and bioavailability of nutrients in the rooting medium. Most of the beneficial bacteria enhance root growth, but their effectiveness could be influenced by the nutrient status around the roots. In this study, the inoculation of wheat durum seeds by *Mesorhizobium* strain is carried out in order to assess the positive impact of plant growth promoting rhizobacteria (PGPR, Plant Growth Promoting Rhizobacteria) on growth, potassium uptake and yield of wheat under simultaneously varying levels of the major nutrient N (at 0%, 25%, 50%, 75%, and 100% of recommended doses). The effectiveness of the bacterial inoculum is related to the characterization of multiple PGP activities such as the production indole acetic acid (IAA), hydrogen cyanide (HCN), siderophores, of phosphate solubilization, as well as the antifungal activity. Results of pot and field trials revealed that the efficacy of these strains for improving growth and yield of wheat reduced with the increasing rates of N added to the soil. In most of the cases, significant negative linear correlations were recorded between percentage increases in growth and yield parameters of wheat caused by inoculation and increasing levels of applied N fertilizers. It is highly likely that under low fertilizer application, the inoculation of wheat durum seeds by *Mesorhizobium* strain might have caused reduction in the synthesis of stress (nutrient)-induced inhibitory levels of ethylene in the roots through ACC hydrolysis into NH_3. The results showed also a synergetic effect of *Mesorhizobium* strain on potassium uptake in wheat plant. In fact, many microorganisms in the soil are able to solubilize “unavailable” form of K-bearing minerals, such as mica, illite and orthoclases, by excreting organic acids which either directly dissolves rock K or chelate silicon ions to bring the K into solution. The results of this study imply that these *Mesorhizobium* strains could be employed in combination with appropriate doses of fertilizers for better plant growth, better nutrient uptake and savings of fertilizers.

The Effect of Potassium Fertilization on Mineral Absorption and Yield of Durum Wheat on Sub-humid and Semi-arid Bioclimatic Stages of Tunisia

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Abstract
This study was conducted in 2015-2016 crop season, in two different bioclimatic stages: sub-humid and semi-arid climate of Tunisia represented respectively by the platform El Gnadil governorate of Beja and the platform Hkim from governorate of Jendouba. Durum Wheat, variety Maali was grown under different K fertilizer treatments (without K/ha and with 50 kg K/ha, 100 kg K/ha and foliar application at 50% at heading stage). The effect of potassium fertilization, with a fixed level of nitrogen and phosphorous fertilization, on the yield, yield compounds and mineral composition of durum wheat were investigated. Trials were set up in a randomized block design with three replications for each treatment. Results showed that the durum wheat grain yields and quality were significantly different between fertilizer treatments and when compared with the control. The effect of potassium fertilization was highlighted in the semi-arid site where yield increased by 21.01% for the treatment 100kg/ha and 28.57% for the foliar potassium application, compared to control K0. For sub-humid site, the yield only increased by 15% for the highest dose (100kg/ha). Analysis of the effect of potassium fertilization on the mineral composition showed that the content of K and Ca^{++} in the leaves and stems increase with increasing fertilization dose potassium. It was noted that this increase is significant only at the semi-arid region. For example, for calcium, it has increased, at this site from 0.48 mg/gMF to 1.11 mg/gMF in response to the addition of 100kg/ha and to 0.86 mg/gMF under foliar potassium application. According to this study, it can be assumed the important role of potassium fertilization in improving mineral absorption for durum wheat in semi-arid regions and this may explain the role of K in the maintenance of cell turgor, as osmoticum, in the limiting condition of water in these areas.

Keywords: Durum Wheat - Bioclimatic stages - Potassium fertilization – Yield - Mineral composition

Potassium - Silicon Interaction under Drought Condition

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Abstract
Agricultural production continues to be limited by a variety of biotic (e.g., pathogens, insects and weeds) and abiotic (e.g., drought, salinity, cold, frost and waterlogging) factors that can significantly reduce the quantity and quality of crop yield. Among the abiotic stresses drought is one of the major stress factors limiting crop production worldwide. Several studies have indicated an important role of K in the mitigation of drought stress. This is partially due to the role of K in controlling cell turgor and stomata closure but also to its role in stress signalling. Additionally, silicon (Si) has been reported to alleviate drought stress in several species like rice, wheat and soybean. Recently, it has been shown that Si ameliorated the growth of soybean seedlings in K-deficient medium by decreasing K deficiency-induced membrane lipid peroxidation and oxidative stress via the modulation of antioxidant enzymes. Moreover, in sorghum Si alleviated K deficiency symptoms by enhancing hydraulic conductivity and K accumulation in the xylem which ultimately improved the plant water status under K-deficient conditions. Moreover, Si has been reported to interfere with phytohormonal signalling, rendering it possible that beneficial effects of Si on K nutrition and drought tolerance may be indirect. Although there is ample evidence that K and Si can improve drought tolerance on their own, their combinatorial effect on drought stress tolerance has so far not yet been reported. In order to investigate how and to what extent K, Si or a combination of these will improve drought tolerance, we are performing different experiments in greenhouse employing barley, potato and tomato plants which are different in their need to K nutrition under low or high level of K or Si and drought stress.

Keywords: Potassium, Silicon and drought stress

Silent Decline in Soil Potassium May Influence Sustainable Production of Alfalfa

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Abstract
Alfalfa (*Medicago sativa* L.) is the most important perennial forage crop grown in the U.S. and many parts of the world. Alfalfa production is heavily reliant on soil nutrients. Continuous production of crops has resulted in depletion of most soil nutrient reserves. These nutrient deficits must be met through fertilization. For increased production of alfalfa, it is often recommended to use potassium (K) and phosphorus (P) fertilizers. In alfalfa production, K is a key element and removed in high quantities with hay harvesting. Many studies suggested that fertilizing alfalfa stands with K and P improved yield and increased stand longevity. However, whether fertilizing alfalfa with K in an un-limiting or limiting soil will result in any yield increase is elusive. Our knowledge on the effects of application of K to soils with adequate residual amounts and soils with declining K is still rudimentary. Recent reports suggest that median K levels have declined in many states of USA. This study was initiated to determine the effects of K, cultivar, and harvest time on growth, yield, nutritive value, and stand persistence of alfalfa. Treatments included two cultivars (low lignin vs. conventional) of alfalfa, four rates of K (0, 56, 112, and 168 kg K_2O ha^{-1}), and two harvest times (late bud to 10% bloom vs. 7-10 days after the first harvest). The study was laid out in a randomized complete block design with four replicates. Preliminary results showed no significant effect of K rates or cultivars on emergence and seedling counts of alfalfa. Also, no nutrient deficiency symptoms were noticed in the young seedlings of alfalfa. Continuous and long-term monitoring is needed to accurately determine the effects of K, cultivar, and harvest on alfalfa growth, yield, nutritive value, and stand longevity.

INTRODUCTION

Alfalfa (*Medicago sativa* L.) is an important perennial forage crop grown in the U.S. and many parts of the world. It is often exported from hay farms to domestic livestock operations, primarily beef and dairy, throughout the U.S. Also, alfalfa is exported to many countries around the world. The value of this crop is in excess of $10 billion dollars (USDA-NASS, 2014). The contribution of alfalfa to central and western states' economies is highly significant and fills an important rotational niche in these agricultural systems.

Being a deep rooted and N fixing legume, alfalfa scavenges nutrients remaining after the growth of less efficient, shallow rooted crops and then provides nitrogen (N) for following crops as the root systems decompose (Koenig, 2002). Alfalfa production is heavily reliant on soil nutrients. Continuous production of crops, including alfalfa, has resulted in depletion of most soil nutrient reserves (Lissbrant et al., 2009). These nutrient deficits must be met through fertilization, mostly using synthetic fertilizers. For increased production of alfalfa, it is often recommended to use K and P fertilizers (Barnett et al., 2011; Lissbrant et al., 2009). In alfalfa production, K is a key element and removed in high quantities with hay harvesting (CSSA, 2011; Tarkalson and Shapiro, 2005). Our present understanding of alfalfa response to fertilization, knowledge on the effects of the application of K to soils with adequate residual amounts and soils with declining K is still rudimentary.

Based on a recent report released by the International Plant Nutrition Institute (IPNI, 2016) concerning changes in soil test levels, median K levels have declined by 16, 37, and 17% between 2001 and 2015 in Colorado, Kansas, and Wyoming, respectively. When using 120 ppm of K as the critical level for deficiency, Wyoming has the greatest percent of soils testing low at 25% followed by Kansas at 15%, and Colorado at 8% (IPNI, 2016). As a result, K deficiency symptoms are commonly observed in alfalfa

grown on Wyoming soils. Since producers are profit- oriented and expect the highest possible return on investment with little risk, identifying threshold levels of K fertilization in alfalfa that give the highest farm profit is essential. The objective of this study was to determine the effects of K, cultivar, and harvest time on growth, yield, nutritive value, and stand persistence of alfalfa.

MATERIALS AND METHODS

The study was laid out in a randomized complete block design with four replicates at the University of Wyoming Sustainable Agriculture Research and Extension Center, near Lingle, Wyoming, USA ($42^o14'$N, $104^o30'$W; 1272 m elevation). There were three factors in the study namely cultivar of alfalfa, K rate, and harvest date. Cultivars included HI-GEST 360 (low lignin alfalfa) and AFX 457 (conventional alfalfa). There were four rates of K: 0 (control), 56, 112, and 168 kg K_2O ha^{-1}. The source of K was muriate of potash (50% K_2O). Harvesting treatments included harvest at optimum growth stage (late bud to 10% bloom) and 7-10 days after the first harvest. These three factors provided 16 treatment combinations (Table 1). A clean weed free land was prepared in early September of 2016 during which P was incorporated as a blanket dose of 84 kg P_20_5 ha^{-1} as triple super phosphate (TSP; 46% P_2O_5). Potassium fertilizer was applied and thereafter alfalfa seeds (22 kg pure live seeds ha^{-1}) were planted using a research grade Hege cone planter on September 8, 2016. Plots were then irrigated by an overhead sprinkler (lateral pivot) to optimum soil moisture. Initial data collection included emergence, seedling count, and visual estimate of nutrient deficiency symptoms. Harvesting treatment will be in effect from spring 2017 and onwards. Data was analyzed by ANOVA using Proc MIXED (SAS, 2013).

RESULTS AND DISCUSSION

The study is newly established and ongoing. Observation is being made and data is being collected continually. Initial observations suggest that the plant stand is well-established (Figure 1). Irrigation after seeding followed by some precipitations in September helped seeds to emerge quickly and seedlings to establish. Emergence record and seedling count were conducted on October 8, 2016, after one month of seeding. The preliminary results are presented in Table 1. Although treatments had no significant effect on early crop establishment, the mean emergence in the entire study was 55% and the values ranged from 35% (168 kg K_2O ha^{-1}; AFX 457; Late harvest) to 71% (168 kg K_2O ha^{-1}; HI-GEST 360; Late harvest). There was an average of 254 seedlings m^{-2}. The highest seedling count (361 seedlings m^{-2}) was observed in plots receiving 56 kg K_2O ha^{-1} (AFX 457; Late harvest). The number of seedlings m^{-2} seemed to be enough for a successful alfalfa stand establishment (Islam, 2013), which will be monitored in the following years. No visible nutrient deficiency symptoms, especially K deficiency, were observed. This was not unlikely with the young seedlings and early alfalfa stand.

CONCLUSION

Alfalfa stand was well-established with the influence of irrigation water and precipitations. No significant effect of K was observed among alfalfa cultivars. No nutrient deficiency symptoms were noticed in the young alfalfa seedlings. Continuous and long-term monitoring is needed to accurately determine the effects of K, cultivar, and harvest on alfalfa growth, yield, nutritive value, and stand longevity.

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TABLES AND FIGURES

Table 1. Emergence and seedling counts for different combinations of alfalfa cultivar, K rate, and harvest date. Data was recorded on October 8, 2016

Treatment description	Emergence	Number of seedlings
(K rate, kg K_2O ha^{-1}; cultivar; harvest date)	(%)	(seedlings m^{-2})
0 (AFX 457; Early harvest)	55	228
56 (AFX 457; Early harvest)	48	170
112 (AFX 457; Early harvest)	56	225
168 (AFX 457; Early harvest)	55	242
0 (HI-GEST 360; Early harvest)	53	284
56 (HI-GEST 360; Early harvest)	53	314
112 (HI-GEST 360; Early harvest)	58	256
168 (HI-GEST 360; Early harvest)	58	228
0 (AFX 457; Late harvest)	51	270
56 (AFX 457; Late harvest)	58	361
112 (AFX 457; Late harvest)	58	250
168 (AFX 457; Late harvest)	35	183
0 (HI-GEST 360; Late harvest)	53	225
56 (HI-GEST 360; Late harvest)	60	342
112 (HI-GEST 360; Late harvest)	58	225
168 (HI-GEST 360; Late harvest)	71	261
Mean	55	254
P-value	0.75	0.87

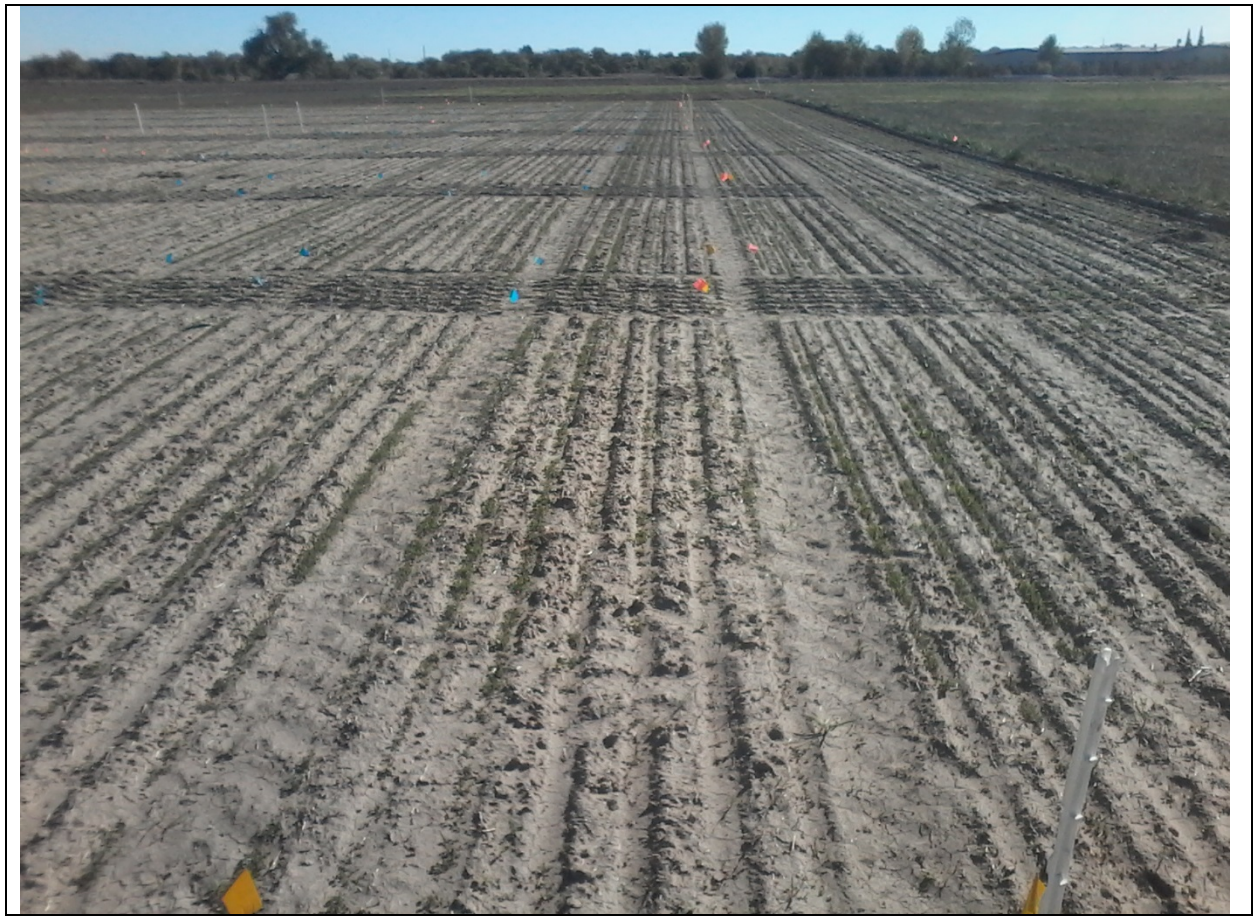

Figure 1. Alfalfa study plots at the University of Wyoming Sustainable Agriculture Research and Extension Center, near Lingle, Wyoming, USA. Picture was taken on October 8, 2016.

Influence of Potassium Supply Different Sources on the Pectin Concentration and Pectin Yield of Gooseberry (Ribes grassularia L.)

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Abstract
Only a part of gooseberries which are produced will be consumed directly as a fresh fruit. A significant amount of them will be processed for jams and compotes.

The gooseberry is relatively high in pectin content, the characteristic pectin contents varies between 1.0 and 2.5/3.0 weight %. The pectin is widely used for food processing (first of all in the confectionery products) as a gelling additive.

Despite the fact, that the synthetic production of pectin in the chemical reactors is already worked out, in the higher quality food processing the natural pectin originating from apple or gooseberry, is more preferred.

Pectin is a plant origin carbohydrate derivate (more precisely the polyuronide), containing a complex set of polysaccharides with different chain lengths. It is well known fact, that in the carbohydrate synthesis of the plants potassium (and magnesium also) has a primary importance. That is why for ensuring the adequate pectin synthesis, gooseberries requires a proper supply of potassium and magnesium, too.

Despite of high nutrient demand, gooseberry is mainly grown in the northeastern region of Hungary, mostly in acidic sandy soils, poor in nutrient supply. For these soils the very low potassium content is characteristic, it means, we have to pay an elevated attention for the potassium supply.

To clear the effects of potassium and magnesium supply on the pectin concentration and pectin yield, a randomized, four-repetition small plots (20 m^2 $parcel^{-1}$) experiment was established. There were delivered different doses of potassium fertilizers, both of chloride and sulfate form. The treatment set up using “Patentkali” was a variant in which the addition of Epsom salt and potassium sulfate is contained in the fertilizer, to test whether the treatment with magnesium in combination with the impact of the test parameters. In the experiment, a total of 32 plots were set up. To enhance the reliability of the results, the experiments were carried out in two consecutive years.

The pectin concentration in form of calcium pectate was determined in the berries of each plot. On the basis of pectin concentration and fruit fresh mass, the pectin yield was calculated. The data sets were evaluated by a one-way variance analysis. The experimental results will be demonstrated on the poster.

Influence of Potassium Levels on Yield and Yield Qualities of Lentil in Sinai

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Abstract
Two field experiment were carried out during winter seasons at 2014/2015 and 2015/2016 at production and research station of Maghara at north of Sinai government, Desert Research Center, Ministry of Agriculture, Egypt. Study the effect of foliar potassium rates and timing on varieties of lentils plants Seeds of five varieties (Sinai 1, Giza 9, Giza 370, Giza 4, Giza 29 and Giza 51). results showed that the foliar application of potassium lead to increase of all growth yield characters under increase of rate of potassium and all varieties. Potassium fertilizer had a significant effect on plant height, number of pods per plant, hundred seed weight, and seed yield, potassium (5 g/l) produced most plant height number of pods per plant, hundred seed weight, and seed yield than other treatments.

Keywords*:* potassium level, yield and yield qualities, lentil, Sinai

INTRODUCTION

Due to favorable climate and soil, lentil can be grown successfully in northern Sinai, Egypt. The average yield of lentil in Egypt is height as compared with other leading lentil growing countries of the world. To meet up the protein demand for the increasing population, lentil production needs to be increased.

Potassium (K), as a plant nutrient is becoming increasingly important and a good crop response to K is being reported from many parts of the world. Pulse crops showed yield benefits from potassium application. Improved potassium supply also enhances biological nitrogen fixation and protein content of pulse grains (Srinivasarao et al., 2003). The supply of potassium to leguminous crops is necessary especially at the flowering and pod setting stages (Zahran et al., 1998). An improved variety is the first and foremost requirement for initiation and accelerated production program of any crop. Variety plays an important role in producing high yield of lentil because different varieties responded differently for their genotypic characters. The present study was, therefore, undertaken to find out the effect of different rates of potassium on the yield of lentil.

MATERIALS AND METHODS

Lentils seeds plants were procured from agriculture research center followed to agriculture ministry and sowing in two field experiment were carried out during winter seasons at 2014/2015 and 2015/2016 at production and research station of Maghara at north of Sinai government, Desert Research Center, Ministry of Agriculture, Egypt. Seeds of five varieties (Sinai 1, Giza 9, Giza 370, Giza 4, Giza 29 and Giza 51) were sowing at 20/11/2014 and 18/11/2015 respectively, to study the effect of foliar potassium rates and timing on varieties of lentils plants.

The soil was well prepared were added at the rate of 8 kg/m^2 as well as calcium superphosphate (15.5% P_2O_5) at the rate of 150 k/feddan (hectare = 2.4 feddan) during the preparation of the soil. Seeds were sown in hills 10 cm apart on rows 60 cm in between and covered with a thin layer of the soil, then irrigated. Three weeks later, the developed plants were thinned to leave one plant per hill. All varieties were treatment at three times (50, 65 and 80 days after sowing) with three levels of potassium (00, 2.5 and 5.0 g/l) as form potassium sulfate (52%).

The plants were collected after 110 days from sowing to determine the growth and yield characters. Total Nitrogen content: Sample of 0.2 gm dry material were digested by sulphuric and perchloric acids using

Micro-Kjeldahl method (Jackson, 1967). Distillation was carried out with 40% NaOH, and ammonia was received in 4% boric acid solution. Protein content was determined by the Kjeldahl method for the calculation of all proteins which equal nitrogen content multiplied by 6.25 (A.O.A.C.,1990).

Potassium content: weight of 0.2 g dry matter from canola shoot was extracted Chaudhary et al, (1996) for one hour in a boiling-tube of distilled water in a boiling water bath, the extract was filtered. Sodium and potassium content in the aqueous extracts were measured with Flame Photometer. Meanwhile, chloride was determined by titration by 0.001 N AgNOa and using potassium dichromate as indicator. Phosphorous content: Phosphorous was determined calorimetrically at wave length 725 nm using chlorostannous-reduced molybdo phosphoric blue color method, in hydrochloric described system as described by Jackson (1978).

Characters studied included biological yield (ton/ha) and harvest index (%), determined according to method described by El Naim *et al* (2010).

Statistical analysis:
The experiment was conducted as split plot design having varieties in main plot and intervals in sub plot. Data were subjected to statistical analysis of variance according to Gomez and Gomez (1984), and L.S.D value for comparison.

RESULTS AND DISCUSSION
All data in tables 1a, b and c showed that the foliar application of potassium lead to increase of all yield characters as plant height (cm), dray weight (g/plant), number of pods/plant, weight of hundred seeds (g), harvest index, stover yield (t/ha), seed yield (t/ha) and biological yield (t/ha) under increase of rate of potassium and all varieties. Potassium fertilizer had a significant effect on plant height, number of pods per plant, hundred seed weight, and seed yield, potassium (5 g/l) produced most plant height number of pods per plant, hundred seed weight, and seed yield than other treatments (Table 1 a, b and c).

Jain & Tiwari (1997) reported that application of K in lentil produced maximum seed weight. Shabir (1982) also recorded that application of 5 g/l potassium significantly increased thousand seed weight. Hamayun & Chaudhary (2004) and Raghuwanshi et al., (1993), also observed similar results. K as 5g/l treatments showed better results than 2.5 g/l treatments. However, Jain & Tiwari (1997) reported that K application gave the highest number of seed per pod.

Table 1a: Effect of rates of potassium and varieties of lentils plants on yield and its components at 50 days after sowing.

Treatments		Plant height(cm)	Dray wt. gm/plant	No. of pods/plant	100seeds Weight/g	Harvest Index	Stover yield(t/ha)	Seed Yield(t/ha)	Biological Yield(t/ha)
Sinai 1	**0.0g/l**	32.096	4.0946	41.418	4.0238	50.98239	2.26678	2.35764	4.62442
	2.5 g/l	33.512	4.1182	47.554	4.1654	48.7318	2.57594	2.4485	5.02444
	5.0 g/l	35.164	4.2008	49.206	4.5666	47.41169	2.79306	2.51812	5.31118
Giza-9	**0.0g/l**	31.742	3.9294	27.2816	3.7406	47.41355	2.24318	2.02252	4.2657
	2.5 g/l	32.332	3.7406	28.556	3.8704	48.40019	2.54998	2.39186	4.94184
	5.0 g/l	32.922	2.655	29.618	3.9058	46.83458	2.76474	2.43552	5.20026
Giza370	**0.0g/l**	30.798	4.4486	40.12	3.9766	51.49485	2.22076	2.35764	4.5784
	2.5 g/l	32.096	4.0828	46.02	4.1182	49.24063	2.52402	2.4485	4.97252
	5.0 g/l	33.748	3.6462	47.672	4.5194	47.92275	2.73642	2.51812	5.25454
Giza-4	**0.0g/l**	30.444	3.8468	26.432	3.6934	47.91725	2.19834	2.02252	4.22086
	2.5 g/l	31.034	3.127	27.612	3.8232	48.90229	2.49924	2.39186	4.8911
	5.0 g/l	31.506	2.9854	28.674	3.8586	47.33945	2.70928	2.43552	5.1448
Giza 29	**0.0g/l**	29.618	4.1182	38.94	3.9412	51.47291	2.1771	2.30926	4.48636
	2.5 g/l	30.798	3.8232	44.722	4.071	49.2371	2.47328	2.39894	4.87222
	5.0 g/l	32.332	3.2804	46.256	4.4722	47.91476	2.68214	2.46738	5.14952
Giza-51	**0.0g/l**	29.146	4.0002	25.606	3.658	47.91786	2.15468	1.9824	4.13708
	2.5 g/l	29.736	4.071	26.786	3.7878	48.89217	2.44968	2.34348	4.79316
	5.0 g/l	30.326	3.7878	27.848	3.8232	47.31913	2.655	2.38478	5.03978
LSD V		4.67584	0.14456	7.49216	0.39416	13.64584	0.15184	0.8164	0.31304
LSD R		4.51984	0.14872	8.40736	0.00208	13.02184	0.57824	0.5044	0.90584
LSD V x R		3.26144	0.19552	6.27432	0.00312	12.08584	0.44304	0.7124	0.74984

Table 1b: Effect of rates of potassium and varieties of lentils plants on yield and its components at 65 days after sowing.

Treatments		Plant height(cm)	Dray wt. gm/plant	No. of pods/plant	100seeds Weight/g	Harvest Index	Stover yield(t/ha)	Seed Yield(t/ha)	Biological Yield(t/ha)
Sinai 1	0.0g/l	32.912	4.1987	42.471	4.1261	50.98239	2.32441	2.41758	4.74199
	2.5 g/l	34.364	4.2229	48.763	4.2713	48.7318	2.64143	2.51075	5.15218
	5.0 g/l	36.058	4.3076	50.457	4.6827	47.41169	2.86407	2.58214	5.44621
Giza-9	0.0g/l	32.549	4.0293	27.9752	3.8357	47.41355	2.30021	2.07394	4.37415
	2.5 g/l	33.154	3.8357	29.282	3.9688	48.40019	2.61481	2.45267	5.06748
	5.0 g/l	33.759	2.7225	30.371	4.0051	46.83458	2.83503	2.49744	5.33247
Giza370	0.0g/l	31.581	4.5617	41.14	4.0777	51.49485	2.27722	2.41758	4.6948
	2.5 g/l	32.912	4.1866	47.19	4.2229	49.24063	2.58819	2.51075	5.09894
	5.0 g/l	34.606	3.7389	48.884	4.6343	47.92275	2.80599	2.58214	5.38813
Giza-4	0.0g/l	31.218	3.9446	27.104	3.7873	47.91725	2.25423	2.07394	4.32817
	2.5 g/l	31.823	3.2065	28.314	3.9204	48.90229	2.56278	2.45267	5.01545
	5.0 g/l	32.307	3.0613	29.403	3.9567	47.33945	2.77816	2.49744	5.2756
Giza 29	0.0g/l	30.371	4.2229	39.93	4.0414	51.47291	2.23245	2.36797	4.60042
	2.5 g/l	31.581	3.9204	45.859	4.1745	49.2371	2.53616	2.45993	4.99609
	5.0 g/l	33.154	3.3638	47.432	4.5859	47.91476	2.75033	2.53011	5.28044
Giza-51	0.0g/l	29.887	4.1019	26.257	3.751	47.91786	2.20946	2.0328	4.24226
	2.5 g/l	30.492	4.1745	27.467	3.8841	48.89217	2.51196	2.40306	4.91502
	5.0 g/l	31.097	3.8841	28.556	3.9204	47.31913	2.7225	2.44541	5.16791
LSD V		4.7208	0.14595	7.5642	0.39795	13.77705	0.1533	0.82425	0.31605
LSD R		4.5633	0.15015	8.4882	0.0021	13.14705	0.5838	0.50925	0.91455
LSD V x R		3.2928	0.1974	6.33465	0.00315	12.20205	0.4473	0.71925	0.75705

Table 1c: Effect of rates of potassium and varieties of lentils plants on yield and its components at 80 days after sowing.

Treatments		Plant height(cm)	Dray wt. gm/plant	No. of pods/plant	100seeds Weight/g	Harvest Index	Stover yield(t/ha)	Seed Yield(t/ha)	Biological Yield(t/ha)
Sinai 1	0.0g/l	32.368	4.1293	41.769	4.0579	50.98239	2.28599	2.37762	4.66361
	2.5 g/l	33.796	4.1531	47.957	4.2007	48.7318	2.59777	2.46925	5.06702
	5.0 g/l	35.462	4.2364	49.623	4.6053	47.41169	2.81673	2.53946	5.35619
Giza-9	0.0g/l	32.011	3.9627	27.5128	3.7723	47.41355	2.26219	2.03966	4.30185
	2.5 g/l	32.606	3.7723	28.798	3.9032	48.40019	2.57159	2.41213	4.98372
	5.0 g/l	33.201	2.6775	29.869	3.9389	46.83458	2.78817	2.45616	5.24433
Giza370	0.0g/l	31.059	4.4863	40.46	4.0103	51.49485	2.23958	2.37762	4.6172
	2.5 g/l	32.368	4.1174	46.41	4.1531	49.24063	2.54541	2.46925	5.01466
	5.0 g/l	34.034	3.6771	48.076	4.5577	47.92275	2.75961	2.53946	5.29907
Giza-4	0.0g/l	30.702	3.8794	26.656	3.7247	47.91725	2.21697	2.03966	4.25663
	2.5 g/l	31.297	3.1535	27.846	3.8556	48.90229	2.52042	2.41213	4.93255
	5.0 g/l	31.773	3.0107	28.917	3.8913	47.33945	2.73224	2.45616	5.1884
Giza 29	0.0g/l	29.869	4.1531	39.27	3.9746	51.47291	2.19555	2.32883	4.52438
	2.5 g/l	31.059	3.8556	45.101	4.1055	49.2371	2.49424	2.41927	4.91351
	5.0 g/l	32.606	3.3082	46.648	4.5101	47.91476	2.70487	2.48829	5.19316
Giza-51	0.0g/l	29.393	4.0341	25.823	3.689	47.91786	2.17294	1.9992	4.17214
	2.5 g/l	29.988	4.1055	27.013	3.8199	48.89217	2.47044	2.36334	4.83378
	5.0 g/l	30.583	3.8199	28.084	3.8556	47.31913	2.6775	2.40499	5.08249
LSD V		4.684832	0.144838	7.506568	0.394918	13.67208	0.152132	0.81797	0.313642
LSD R		4.528532	0.149006	8.423528	0.002084	13.04688	0.579352	0.50537	0.907582
LSD V x R		3.267712	0.195896	6.286386	0.003126	12.10908	0.443892	0.71377	0.751282

In respect of interaction, the highest number of pods/ plant were observed in Sinai 1with 5 g/l K interaction in tables 1 a, b and c. Similar results were achieved by Tariq et al., (2001) in Mungbean. The highest of seeds yield, 100 grain weight, stover, biological yield were in variety Sinai 1. Azad et al. (1995) and Singh (1998) reported that seed yield of lentil increased with the increase of potassium levels.

Grain and Stover yield of all varieties were increased with the increase of potassium application up to 2.5 g/l. Therefore, fertilization of all the varieties with 5g/l appeared as the best rate of potassium in respect of grain and stover yield.

Tables 2 a, b and c indicated that the foliar application with potassium in form K_2SO_4 lead to increase most of grain content from protein %, nitrogen g/kg, potassium g/kg, phosphor g/kg, Zn m/kg, Cu m/kg, Fe m/kg and Mg m/kg in all varieties.

Increasing levels of K produced significant effect on nitrogen uptake by grain and straw of lentil. A similar trend was also reported by Brar et al. (2004). Effect of K application on P uptake by grain was found to be significant. The responses were observed up to the higher level of potassium application. As regards the Zn uptake by grain, application of potassium significantly increased the Zn uptake with increase in K levels. The increased grain content of minerals by K application, thereby activating more

absorption of nutrients from the leaves, resulted in higher uptake of nutrients Brar *et al.* (2004), and Lakshmamma *et al.* (1996) also reported similar results in groundnut.

Table 2 a: Effect of rates of potassium **and varieties of lentils plants on yield and its components at 50 days after sowing some minerals contents.**

Treatments		Protein %	Nitrogen g/kg	Potassium g/kg	Phosphor g/kg	Zn m/kg	Cu m/kg	Fe m/kg	Mg m/kg
Sinai 1	**0.0g/l**	4.1148	6.1452	5.4648	55.836	11.3292	58.6656	52.812	25.7175
	2.5 g/l	4.4064	6.4152	5.02848	57.132	12.15	61.398	56.484	27.54
	5.0 g/l	4.9788	6.8364	4.61376	60.804	13.1652	64.8108	61.0848	31.1175
Giza-9	**0.0g/l**	4.0068	6.0696	5.37732	55.728	11.232	58.4712	52.7256	25.0425
	2.5 g/l	4.2768	6.3612	4.9518	56.916	11.8476	61.2144	56.2356	26.73
	5.0 g/l	4.8492	6.7716	4.53708	59.184	12.6576	64.2492	60.3936	30.3075
Giza370	**0.0g/l**	3.9312	5.9616	5.28984	55.296	11.1456	58.3956	52.4448	24.57
	2.5 g/l	4.1364	6.2964	4.87512	56.7	11.6748	60.9876	59.1948	25.8525
	5.0 g/l	4.6548	6.7824	4.48308	58.86	12.3984	64.1088	60.264	29.0925
Giza-4	**0.0g/l**	4.0608	6.1236	5.43132	55.728	11.2752	58.3848	51.5268	25.38
	2.5 g/l	4.374	6.3936	5.0058	57.024	12.1176	61.128	55.1988	27.3375
	5.0 g/l	4.914	6.8364	4.59216	60.696	13.1328	64.5192	59.7996	30.7125
Giza 29	**0.0g/l**	4.0068	6.048	5.37732	55.08	11.1564	57.8016	51.0084	25.0425
	2.5 g/l	4.32	6.3288	4.9518	56.484	11.988	60.5124	54.6372	27
	5.0 g/l	4.86	6.7716	4.53708	60.048	12.9924	63.8712	59.1948	30.375
Giza-51	**0.0g/l**	3.9528	6.048	5.35572	55.62	11.1996	58.2012	51.408	24.705
	2.5 g/l	4.212	6.3288	4.9302	56.808	11.8152	60.9444	54.9504	26.325
	5.0 g/l	4.7844	6.7392	4.51548	59.724	12.6252	63.9792	59.1084	29.9025
LSD V		5.130222	0.014873	0.128828	0.254553	3.43684	2.29622	9.39995	9.95207
LSD D		5.180512	0.015301	0.115988	0.214214	2.30264	3.80492	8.00895	9.49197
LSD V x D		3.885812	0.020116	0.110531	0.214321	1.41454	1.52582	6.08295	8.26147

Table 2 b: Effect of rates of potassium and varieties of lentils plants on yield and its components at 65 days after sowing some minerals contents.

Treatments		Protein %	Nitrogen g/kg	Potassium g/kg	Phosphor g/kg	Zn m/kg	Cu m/kg	Fe m/kg	Mg m/kg
Sinai 1	**0.0g/l**	25.00313	4.0005	5.9745	5.313	54.285	11.0145	57.036	51.345
	2.5 g/l	26.775	4.284	6.237	4.8888	55.545	11.8125	59.6925	54.915
	5.0 g/l	30.25313	4.8405	6.6465	4.4856	59.115	12.7995	63.0105	59.388
Giza-9	**0.0g/l**	24.34688	3.8955	5.901	5.22795	54.18	10.92	56.847	51.261
	2.5 g/l	25.9875	4.158	6.1845	4.81425	55.335	11.5185	59.514	54.6735
	5.0 g/l	29.46563	4.7145	6.5835	4.41105	57.54	12.306	62.4645	58.716
Giza370	**0.0g/l**	23.8875	3.822	5.796	5.1429	53.76	10.836	56.7735	50.988
	2.5 g/l	25.13438	4.0215	6.1215	4.7397	55.125	11.3505	59.2935	57.5505
	5.0 g/l	28.28438	4.5255	6.594	4.35855	57.225	12.054	62.328	58.59
Giza-4	**0.0g/l**	24.675	3.948	5.9535	5.28045	54.18	10.962	56.763	50.0955
	2.5 g/l	26.57813	4.2525	6.216	4.86675	55.44	11.781	59.43	53.6655
	5.0 g/l	29.85938	4.7775	6.6465	4.4646	59.01	12.768	62.727	58.1385
Giza 29	**0.0g/l**	24.34688	3.8955	5.88	5.22795	53.55	10.8465	56.196	49.5915
	2.5 g/l	26.25	4.2	6.153	4.81425	54.915	11.655	58.8315	53.1195
	5.0 g/l	29.53125	4.725	6.5835	4.41105	58.38	12.6315	62.097	57.5505
Giza-51	**0.0g/l**	24.01875	3.843	5.88	5.20695	54.075	10.8885	56.5845	49.98
	2.5 g/l	25.59375	4.095	6.153	4.79325	55.23	11.487	59.2515	53.424
	5.0 g/l	29.07188	4.6515	6.552	4.39005	58.065	12.2745	62.202	57.4665
LSD V		5.226114	0.015151	0.131236	0.259311	3.50108	2.33914	9.57565	10.13809
LSD D		5.277344	0.015587	0.118156	0.218218	2.34568	3.87604	8.15865	9.66939
LSD V x D		3.958444	0.020492	0.112597	0.218327	1.44098	1.55434	6.19665	8.41589

Table 2 c: Effect of rates of potassium and varieties of lentils plants on yield and its components at 80 days after sowing some minerals contents.

Treatments		Protein %	Nitrogen g/kg	Potassium g/kg	Phosphor g/kg	Zn m/kg	Cu m/kg	Fe m/kg	Mg m/kg
Sinai 1	0.0g/l	4.0386	6.0314	5.3636	54.802	11.1194	57.5792	51.834	25.24125
	2.5 g/l	4.3248	6.2964	4.93536	56.074	11.925	60.261	55.438	27.03
	5.0 g/l	4.8866	6.7098	4.52832	59.678	12.9214	63.6106	59.9536	30.54125
Giza-9	0.0g/l	3.9326	5.9572	5.27774	54.696	11.024	57.3884	51.7492	24.57875
	2.5 g/l	4.1976	6.2434	4.8601	55.862	11.6282	60.0808	55.1942	26.235
	5.0 g/l	4.7594	6.6462	4.45306	58.088	12.4232	63.0594	59.2752	29.74625
Giza370	0.0g/l	3.8584	5.8512	5.19188	54.272	10.9392	57.3142	51.4736	24.115
	2.5 g/l	4.0598	6.1798	4.78484	55.65	11.4586	59.8582	58.0986	25.37375
	5.0 g/l	4.5686	6.6568	4.40006	57.77	12.1688	62.9216	59.148	28.55375
Giza-4	0.0g/l	3.9856	6.0102	5.33074	54.696	11.0664	57.3036	50.5726	24.91
	2.5 g/l	4.293	6.2752	4.9131	55.968	11.8932	59.996	54.1766	26.83125
	5.0 g/l	4.823	6.7098	4.50712	59.572	12.8896	63.3244	58.6922	30.14375
Giza 29	0.0g/l	3.9326	5.936	5.27774	54.06	10.9498	56.7312	50.0638	24.57875
	2.5 g/l	4.24	6.2116	4.8601	55.438	11.766	59.3918	53.6254	26.5
	5.0 g/l	4.77	6.6462	4.45306	58.936	12.7518	62.6884	58.0986	29.8125
Giza-51	0.0g/l	3.8796	5.936	5.25654	54.59	10.9922	57.1234	50.456	24.2475
	2.5 g/l	4.134	6.2116	4.8389	55.756	11.5964	59.8158	53.9328	25.8375
	5.0 g/l	4.6958	6.6144	4.43186	58.618	12.3914	62.7944	58.0138	29.34875
LSD V		5.178168	0.015012	0.130032	0.256932	3.46896	2.31768	9.4878	10.04508
LSD D		5.228928	0.015444	0.117072	0.216216	2.32416	3.84048	8.0838	9.58068
LSD V x D		3.922128	0.020304	0.111564	0.216324	1.42776	1.54008	6.1398	8.33868

Jain & Tiwari (1997) reported that application of K in lentil produced maximum seed weight. Shabir (1982) also recorded that application of 5 g/l potassium significantly increased thousand seed weight. Hamayun & Chaudhary (2004) and Raghuwanshi et al., (1993), also observed similar results. K as 5g/l treatments showed better results than 2.5 g/l treatments. However, Jain & Tiwari (1997) reported that K application gave the highest number of seed per pod.

In respect of interaction, the highest number of pods/ plant were observed in Sinai 1with 5 g/l K interaction in tables 1 a, b and c. Similar results were achieved by Tariq et al., (2001) in Mungbean. The highest of seeds yield, 100 grain weight, stover, biological yield were in variety Sinai 1. Azad et al. (1995) and Singh (1998) reported that seed yield of lentil increased with the increase of potassium levels. Grain and Stover yield of all varieties were increased with the increase of potassium application up to 2.5 g/l. Therefore, fertilization of all the varieties with 5g/l appeared as the best rate of potassium in respect of grain and stover yield.

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Yield and Quality of Cabbage (*Brassica oleracea*) Influenced by Potassium Nutrition in Eastern Region of India

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Abstract
Jharkhand an eastern state of India has tremendous potential to increase the vegetable production with exceptional quality parameters through adoption of balance fertilizer applications. Vegetable production is lacking Potassic fertilizer while majority of the Jharkhand soils are medium in K status. Crop quality improvement is gaining importance as it improves not only human health, also increased farm income and higher realization of market prices.

Experiment was conducted in different farmer's field to evaluate optimum dosages, time and methods of application of potassium on yield and biochemical properties of cabbage. during June, 2011 to 2014 under rain fed condition. Seven treatments were laid in RBD. An uniform dose of N and P was applied (N:P:100:60 kg ha^{-1}), K. was applied in different combination.

The N.P.K, of head was analyzed by Kjeldahl method's and by digestion in di-acid (HNO_3:$HClO_4$) adopting standard procedure (Jackson, 1973). Carbohydrate by Anthron method (Hedge & Hofrieter, 1962). Reducing sugar analyzed by di-nitro salicylic (DNS) acid method (Miller,1972), while volumetric method was used for ascorbic acid. Refract meter (0-30). was used for TSS. Folin Ciocalteu method was used for total poly-phenol of the head.

Application of potassium irrespective of the time and dose increased the yield of cabbage compared to farmer's practice. Maximum head yield (76.20 t/ha) with the highest B:C ratio (5.65) was obtained under 200% K (120 kg/ha) applied in two splits (50 % as basal and 50%, 25 days of transplanting of seedling). The quality parameters of cabbage like carbohydrate content (5.02 %), reducing sugar (4.01 %), non-reducing sugar (1.01 %), phenol (74.86 mg/100 g), TSS (5.33 ^{0} Brix), ascorbic acid content (57.14 mg/100 g), protein content (12.38 %) and fiber content (3.17 %) also remained higher under the same treatment.

Potassium Increases Tolerance of Wheat to Frost

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Abstract

Increased K supply from soil and fertiliser have been reported to protect crops such as potato from foliar frost damage. However, there is no evidence of increased frost tolerance from K fertiliser application in wheat where frost damage is most commonly associated with decreased grain set. Frost is increasingly common in the Southwest of West Australia and now considered a major risk factor for wheat production. In this region, 7-50 % of soils are low in K but K fertiliser rates applied by farmers are generally below those needed to replace K removal in grain. Our aim was to determine whether increased K concentration in wheat plants during anthesis would increase tolerance to frost induced sterility (FIS). To maximise the likelihood of a frost event coinciding with critical stages of pollen development that are sensitive to frost, we sowed two cultivars of wheat (Mace, Wyalkatchem) with flowering dates 5-7 days apart) at four times (15 and 29 April, 15 May and 2 June) with nil, 80 kg K/ha (applied at sowing) and 80 kg K/ha (applied at sowing) plus micronutrients (Mn, Cu and Zn) applied as foliar sprays before anthesis. The initial soil K (bicarbonate extraction) was 49 mg K/kg in 0-10 cm depth but dropped to ~ 30 mg/kg at 10-30 cm depth. Only wheat at the final sowing date escaped significant frost events during pollen microspore stage. In sowing dates 1, 2 and 3 the control plants had 20-39 % frost induced sterility. Potassium added at 80 kg K/ha decreased FIS by 3-18 % (average 8 %) at sowing dates 2 and 3 but had no effect on FIS at sowing date 1 while at sowing date 4 FIS was minimal. At sowing date 1, leaf K at anthesis was 2.8 % in the nil K treatment, while at sowing dates 2 and 3, concentrations dropped to 2.4 and 2.0 %, respectively. At sowing date 4, leaf K at anthesis dropped to 1.7 % in the nil K but remained above the critical concentrations of 1.5 % K. Potassium fertiliser increased grain yield only at sowing dates 2 and 3 where FIS was also decreased. Yield increases were 0.1-0.3 t/ha for sowing date 2 and 0.2-0.5 t/ha for sowing date 3. This suggests that alleviation of FIS by increased plant K concentration was the main cause of K fertiliser response in wheat. We conclude that K fertiliser addition increased wheat tolerance to frost if the frost event coincided with pollen development and shoot K was below a critical threshold.

Role of Potassium in Potato

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Abstract
Potassium is an essential plant nutrient for potato and has a considerable effect on yield and quality of potatoes. Potassium deficiencies reduce the size, yield and quality of the potato tuber. Typical symptoms of Potassium deficiency are necrosis of leaf margins, premature leaf senescence. Potato plants take up large quantities of potassium throughout the growing season but the highest requirement for potassium is found during the bulking up stage of the tubers. Apart from the yield and quality of tuber, it reduces susceptibility to plant diseases and control the plant water status**.** Site specific potassium application is needed for optimum utilization by the crop. Volume of soil explored by roots, the availability of water and nitrogen and Phosphorus also influence the utilization of potassium in potato crop. For example, in some cases, increases in application of potassic fertilizers causes little or no increase in yield to applied potassium due to the less exposure of roots to soil. Therefore, in the short term a grower should know how much potash to apply for the best economic return for his/her own climatic and soil conditions. Potash supply also contributes to quality characteristics that may affect marketability of potatoes such as dry matter, sample size and tuber number, starch content, fry colour, internal blackening, susceptibility to mechanical bruising and flavour. The potassium content of Indian soils varies from less than 0.5% potassium to over 3% potassium; the average being 1.52% potassium. There is obviously an urgent need in delineating the K deficient areas and expected responses both in terms of quantity and quality in different agroclimatic regions of the country. Application of K on removal basis was found to maintain soil K balance apart from sustaining crop yields in potato crop. Among potassium sources, potassium chloride (MOP) is superior to potassium sulphate (SOP) where the produce is not susceptible with the chloride action.

Keywords: Muriate of Potassium, Potassium, Potato, Sulphate of Potassium

INTRODUCTION

Potato (*Solanum tuberosum* L.) is an economically important crop in India. It is the leading grown crop and one of the important cash crops in India. It is an herbaceous annual plant that grows up to 100 cm tall and produces tubers, which are botanically thickened stems and are also rich in starch. The potato belongs to the Solanaceae, and shares the genus *Solanum*. The crop growth stages are classified into five distinct phases such as sprouting, vegetative stage, tuber initiation, tuber bulking and maturation. Sprout develops from eyes on seed tubers and grows upward to emerge from the soil and roots begin to develop in the sprouting stage. Leaves and branches develop from above ground nodes and roots and stolons develop at below ground nodes in the vegetative growth. In the tuber initiation stage, tubers form at the stolon tips. Tuber cells expand with the accumulation of water, nutrients, and carbohydrates in the tuber bulking stage. At maturity plant turn yellow and lose leaves, tuber dry matter content reaches a maximum.

One of the major production factors of potato is the proper nutritional management mainly through fertilization. Fertilization especially potassium is considered one of the most important factors affecting the growth and yield of potato. Potassium is an essential plant nutrient for potato and has a considerable effect on yield and quality of potatoes. Many researchers recorded an increase of potato tubers yield as a result of increasing the levels of potassium (K) fertilization. Such increases in yield of potato tubers was either due to the formation of large size tubers or increasing of the number of tubers per plant or both (AM El-Gamal, 1985). Potassium also plays a key role in improving the quality of produce. Potato plants take up large quantities of potassium throughout the growing season but the highest requirement for

potassium is found during the bulking up stage of the tubers. Potassium requirements of potato tubers during the bulking stage are very high as they are considered to be luxury consumers of potassium. Apart from the yield and quality of tuber, it reduces susceptibility to plant diseases and control the plant water status**.**

Potassium deficiencies reduce the size, yield and quality of the potato tuber. Typical symptoms of Potassium deficiency are necrosis of leaf margins, premature leaf senescence. Potassium deficiency retards nitrogen uptake, slows down plant growth and impair the crop's resistance to diseases and its ability to tolerate stresses such as frost and drought. Applying Potassic fertilizer with a broadcast application prior to planting is most commonly recommended but in some conditions it is advisable to split the dressings 6-8 weeks apart. If the Potassium is band-applied, then the rate of application should be kept low to avoid salt injury to the developing sprouts. Excessive potassium causes reduced tuber specific gravity and reduced calcium and/or magnesium uptake. It also degrades soil structure.

PHYSIOLOGICAL ROLE OF POTASSIUM

Potassium has an important role in stomatal functioning and internal ionic concentration of the plant tissues. Its role is also found in improving protein synthesis, photosynthesis, carbohydrates and fats, increasing enzyme activity and translocation of photosynthates. Potassium plays an influential role in the process of nitrate reduction within the plant. Potato plants require nutrient for osmotic regulation and enzyme functions. The nutrient is highly mobile within plant tissues which promote the transport of starch and sugars. Potatoes require large amounts of potassium, since this nutrient is crucial to metabolic functions such as the movement of sugars from the leaves to the tubers and the transformation of sugar into potato starch.

It is involved in regulating the amount of water in the plant; in the absence of sufficient potassium then the crop do not use water efficiently. Also adequate potassium levels in the plant help it to withstand water stress during periods of drought. Potassium plays a vital role in maintaining the turgidity of plant cells to obtain maximum leaf extension and stem elongation due to its turgor maintenance capacity. This helps to achieve rapid ground cover to maximize the sunlight interception and which will leads to accelerate the growth rate rapidly in the critical periods of the growing season.

UTILIZATION OF POTASSIUM IN POTATO CROP

A large number of experiments have confirmed that application of potassium plays an important role on yield of potato crop. However, the increase in yield to an application of potassic fertilizer will depend on the supply of potassium from the soil. To achieve optimum yield, one should apply recommended dose of potassic fertilizer to the crop at right time and in adequate amount. As in all experimental data, there was considerable variation for different sites and years due to variations in climate and soil. In general, the response to added K is usually large at low levels of soil potassium and the requirement for added K tends to decrease as soil potassium level increases. However, site specific potassium application is needed for optimum utilization by the crop. Volume of soil explored by roots, the availability of water and nitrogen and Phosphorus also influence the utilization of potassium in potato crop. For example, in some cases, increases in application of potassic fertilizers causes little or no increase in yield to applied potassium due to the less exposure of roots to soil. Therefore, in the short term a grower should know how much potash to apply for the best economic return for his/her own climatic and soil conditions.

S Umar and Moinuddin (2001) confirmed that proper potassium application would be essential and inevitable for obtaining maximum economic yield of potato. They conducted two year experiment in the Gangetic alluvium with sandy loam soil of pH 7.8. the experiment comprised 16 treatments including all combinations of four potato cultivars (Kufri Chandramukhi, Kufri Jyoti, Kufri Bahar and Kufri Sindhuri), four levels of potassium (0, 60, 120 and 180 kg K_20/ha), and two potassium sources, MOP and SOP. They

found that the potato tuber yield increased significantly with applied Potassium (MOP) up to 120 kg k_20/ha.

SK Singh and SS Lal (2012) concluded that application of 100 kg K2O and 150 kg N/ ha can be economically recommended for cultivation of Kufri Pukhraj under planting condition of Bihar as it favoured crop growth, high yield and enhanced K and N use efficiency. The experiment was laid out in randomized block design with three replications having 16 treatment combinations of four levels of N (0, 75,150 and 225 kg/ha) and four levels of K (0, 50, 100 and 150 kg K_2O/ha) at constant dose of P (60 kg P_2O_5/ha).

Table 1. Grade wise Potato yield as influenced by potassium application

Treatment	Grade wise tuber yield (t/ha)			
	<25g	25 – 50g	50 – 75g	>75g
0 kg/ha	2.02	9.08	7.06	4.08
50 kg/ha	1.55	10.88	10.24	6.31
100 kg/ha	1.23	10.73	12.21	8.07
150 kg/ha	1.06	10.77	12.90	8.75
SEm ±	0.50	0.35	0.57	0.49
CD (0.05)	NS	1.01	1.64	1.40

(Source: Singh and Lal, 2012)

BH Adhikary and KB Karki (2006) suggested that application of potassium (K_2O) at the rate of 50 kg/ha basal and 50 kg/ha top-dressed in 45 days could increase potato tuber yield satisfactorily in extremely acid soil condition.

SK Bansal and SP Trehan (2011) in “Effect of potassium on yield and processing quality attributes of potato” concluded that the Potassium application increases the size of tubers, especially, if K supply of the soil is low to medium. Larger tubers are preferred by the processing industry, thus the profitability for the potato grower will be higher.

Potassium is quite often associated with improved tuber quality. The quality parameters differ with the use of produce, i.e., whether the potatoes are to be cooked, converted into chips or starch etc. Potash supply also contributes to quality characteristics that may affect marketability of potatoes such as dry matter, sample size and tuber number, starch content, fry colour, internal blackening, susceptibility to mechanical bruising and flavour. Many other factors are also there to affect these characteristics often to a greater degree than potash and additional potash supply will not improve the characteristic where it is being controlled by another factor. Internal blackening or black spot is aggravated when tubers have large dry matter content and is alleviated by applying larger amounts of potash. Muriate of potash is somewhat more effective than sulphate of potash in reducing the occurrence of this problem but an adequate amount of K is the more important factor. Lighter colours on frying can be very important for crisping potatoes and adequate potash supply can improve this aspect of quality. However use of sulphate of potash results in a product with a better flavor. Cooking quality and other quality parameters are also influenced due to nutritional management, i.e., mainly application and supply of potassium. Some evidence to suggest that potash reduces disintegration on boiling and mealiness of the cooked product.

Zameer khan *et al.* (2010) conducted a field experiment to study comparative effect of source, levels and methods of K fertilization on yield and quality of potato produce. They conclude that the Potassium treatments not only increased K concentration but also affected N and P contents in potato tubers. The quality parameters like dry matter, specific gravity, starch contents, vitamin-C and ash contents were also affected with K fertilization.

Table 2. Effect of source and level of K on quality of potato

Treatments	Dry matter	Specific gravity	Vit.C (mg/100g)	Starch contents (%)	Sugar contents (%)	Ash contents (%)
Control (N @250)	17.36	1.069	17.12	10.88	1.24	6.90
N & P @ 250 125 kg/ha	18.07	1.074	17.72	11.85	1.26	8.66
K_20 @ 150 kg/ha SOP	19.60	1.081	19.61	12.80	1.40	9.72
K_20 @ 225 kg/ha SOP	20.57	1.092	19.57	13.55	1.48	9.09
K_20 @ 150 kg/ha MOP	19.49	1.087	20.33	12.23	1.37	8.64
K_20 @ 225 kg/ha MOP	19.66	1.086	19.40	12.78	1.41	8.42

(Source: Zameer khan *et al.*, 2010)

Influence of the potassium fertilizer source on crude protein content in tubers was reported by Singh and Bansal (2000) who studied the effect of the two sources of potassium on the yield and the economics of potato production in an inceptisol of western Uttar Pradesh, India.

After analyzing several experiments SK Bansal and SP Trehan (2011) recommend that the use of K_2SO_4 improves quality parameters of tubers for processing under a wide range of site and agronomic management conditions. And also found that the potassium application decreased reducing sugars and lighten chip colour under low potassium level.

Potassium influences synthesis, location, transformation and storage of carbohydrates, tuber quality and processing characteristics as well as plant resistance to stress and diseases (Ebert, 2009). According to Al-Moshileh and Errebi (2004), highest yield and improved quality parameters were achieved when a rate of 450 kg SOP per ha was used.

POTASSIUM STATUS IN INDIAN SOIL

The potassium content of Indian soils varies from less than 0.5% potassium to over 3% potassium; the average being 1.52% potassium. Total potassium is usually higher in the arid, young alluvial and black clay soils than in the more weathered red and laterite soils located in high rainfall areas (Anonymous,

1998). Light textured red, lateritic and alluvial soils, acidic alluvial and shallow black soils are prone to K deficiency under intensive cropping. The focus has been on nitrogen followed by phosphorus and very little potassium application resulting in a huge imbalance. The release of K is very slow and K additions are essential at sensitive growth stages in particularly K loving crops. Dominant as well as associated minerals in clay and silt fraction of soils mostly contribute to variations in K fertility of Indian soils. In the year 2020, the deficit of K in Indian agriculture has been projected to be around 8.1 million tonnes/annum while the estimates of N and P balances are positive. There is obviously an urgent need in delineating the K deficient areas and expected responses both in terms of quantity and quality in different agroclimatic regions of the country (Subba Rao *et al.*, 2011).

In the Eastern Ghat, Tamil Nadu uplands, Deccan Plateau, Eastern (Chhota Nagpur) Plateau, Western Ghat and Coastal Plains having Red, lateritic and acidic alluvial soils are tend to be low in exchangeable and non-exchangeable K. Swell-shrink soils are found in the Central Highlands (Malwa, Budelkhand and E. Satpura), Gujarat Plains, Kathiawar Peninsula, Daccan, Eastern Ghats: they are high in exchangeable and medium to high in non-exchangeable K. Within these regions, there are red soils low to medium in exchangeable and non-exchangeable K. A range of alluvial soils in the Northern Plains, Central Highlands, Assam and West Bengal Plains are medium to high in exchangeable and medium to very high in nonexchangeable K. Brown forest and podzolic soils in the Western Himalayas are variable in both exchangeable and nonexchangeable K. Coastal alluvial soils in Manipur are high in exchangeable but low in non-exchangeable K. Though soils of alluvial belt of northern India are rich in nonexchangeable K (Subba Rao, *et al.*, 2011).

According to Hassan, (2002) among 371 districts for which information is available, the respective number of districts characterized as low, medium, and high are 76, 190, and 105, respectively. Information presented were based on soil samples made available by soil testing laboratories run by state departments of agriculture and the fertilizer industry Thus, 21% of the districts are low, 51% are medium, and 28% are high. Available soil K was extracted with 1N ammonium acetate (NH_4OAc, pH 7.0) and soils containing less than 130 kg K_2O/ha were categorized as low, between 130 and 335 kg K_2O/ha as medium, and above 335 kg K_2O/ha as high. Comparing these results with those presented earlier report, the low and high categories have decreased by 0.6 and 6.4%, respectively, while the medium category increased by 7%. All this indicates that K fertilizers were scantily applied in the last two decades as the low category has virtually remained the same and the high area has fallen. The magnitude of crop response has been on upward trend in many areas as a consequence of K fertility decline in these regions.

Multiple cropping or growing potassium loving crop as mono cropping, without giving adequate amount of potassic fertilizer is one of the prime causes for heavy withdrawal of potassium from the Indian soils. Due to heavy withdrawals of potassium from soil under high yielding and fertilizer responsive varieties, the potassium status of soil is changing rapidly. It is of great importance to keep a close watch on such depletion of soil potassium through regular monitoring to ensure that potassium does not become a limiting factor in crop production. Application of potassic fertilizers in appropriate doses should be given to avoid the occurrence of potassium deficiency in Indian soils. In the past, low yielding traditional varieties grown without or with only a little bit of nitrogen fertilizer did not put any particular stress on soil potassium. Hence, even soils, which are currently rated sufficient in available K may begin to show response to K with intensification of agriculture under extensive use of N and P fertilizers.

POTASIC FERTILIZERS AND ITS USE IN POTATO CROPS

Potassium occurs in nature as various salts that occur in very large, mainly underground, deposits. These deposits can be mined and the salts purified to supply the potash fertilizers used commercially. The source of potassium plays an important role on the quality and the yield of potato tubers. There are five different mineral sources of potassium in the world, like potassium chloride or muriate of potash containing 60-62% K_2O, Potassium sulphate or sulphate of potash containing 48-52% K_2O, potassium

magnesium sulphate containing 20-23% K_2O, potassium nitrate containing 44% and bittern potash containing 7% potash in it (Hussain, 2015). Among these sources of potassium, mostly SOP and MOP are important. Muriate of potash (MOP) accounts for 99% of all potassium used in India due to less expensive than sulphate of potash (SOP). But MOP has excess chloride in it, which causes quality reduction in some specific crops. To prevent the quality reduction, SOP is recommended for obtaining superior quality produce. The yield response and accumulation of dry matter and starch were higher when potassium was supplied as SOP than MOP (Anonymous, 1998). If the sulphur content is not required, the potash content of SOP is more costly per kg K_2O than that of MOP. But SOP provides specific quality attributes for potatoes. According to Zehler, (1982) MOP is not a better source of K in arid areas as compare to SOP due to its hazardous effects.

Apart from MOP and SOP there is another fertilizer named potassium nitrate use as specialized fertilizer for high value crops where nitrogen as nutrient is needed in conjunction with potassium. This fertilizer provides two nutrients because it contains 44% K_2O and 13% N. Potassium nitrate is mainly used in fertigation along with irrigation water by enhancing efficient utilization of resources. It is sometimes used as a top dressing for potatoes to secure quality benefits, but its relatively high price demands a high return to make it cost effective. Potassium nitrate is generally not used as a source of potassium, but some scientists reported that it is a better source of potassium than MOP for getting higher yield and superior quality of potato tubers. The use of sulphate of potash instead of muriate of potash may be beneficial where larger numbers of small-medium size tubers are required such as for seed, canning, salad etc. For fry colour characteristics, MOP appears to be marginally superior to SOP. SOP can also reduce the severity of tuber cracking. But Vitamin C content also increased by the application of MOP was reported independently by both Kaviani *et al.* (2004) and Akhtar *et al.* (2010).

Bhandari *et al.,* (1987) found that SOP was better for potato tubers because of negative effects of chloride on starch and dry matter by MOP application. These results were similar to the findings of Prummel, (1983). Potassium, Ca and Mg showed a marked increase in the soil in result to KCl application (Shaaban *et al.,* 2012). There was no significant difference in response of potato regarding the yield amongst both the applied potassium sources and levels but tuber yield was relatively higher in MOP treatments than that of SOP (Zameer khan *et al.*, 2010). MOP application has no negative effect due to high solubility characteristics and irrigation water movement (Rashid *et al.,* 1992; Mian *et al.,* 1998). Tariq *et al.,* (2011) found that SOP supply less potassium to soil than MOP.

Chlorine content increased as depth increases because chloride ions are mobile in soil and leached down. While chloride level decreased when SOP is applied (Tariq *et al*., 2011). Davide *et al.,* (1986) in punjab showed that SOP is important source than MOP. MOP is not a preferred source of K (to improve quality of leaves) over SOP in saline soils (Morad, 1979).

Fertilization with MOP affected quality characteristics of potatoes stronger than the application of potassium as SOP. Increasing rates of MOP decreased more severely dry matter, starch and vitamin C contents in potato tubers. The dry matter and starch of potato (Bhandari *et al.,* 1987) and the tuber contents of cysteine, ascorbic acid, methionine and protein which otherwise significantly increased by SOP application (Duka, 1973).

When MOP was applied at higher rates to the potato it resulted in reduction of tuber dry weight (Allison *et al.,* 2001). Chloride is an essential micronutrient and it is beneficial under many conditions e.g. in osmoregulation and disease suppression (Fixen, 1987). MOP can be used but there is a condition along its usage is that it must be used along with excess good quality irrigation water (Hussain *et al.,* 2015).

After analyzing the aforesaid scientific researches conducted at different climate and soil condition, we can conclude that the impact of use of SOP and MOP is varied for a number of parameters of the potato crop. Therefore application of either fertilizer should be done on the basis of their suitability.

CONCLUSION

Various physiological role of potassium also confirm its importance in potato. Potassium plays a vital role in influencing potato yield and quality. Its application not only increased the number and yield of large size tubers but also significant effect seen in case of small size potato tubers. Application of K on removal basis was found to maintain soil K balance apart from sustaining crop yields in potato crop. Among potassium sources, potassium chloride (MOP) is superior to potassium sulphate (SOP) where the produce is not susceptible with the chloride action. Otherwise, use of SOP advantageous in many aspects in various crops. In economics point of view, application of MOP as fertilizer is recommended by various scientists worldwide.

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Proline Concentration in Leaves of Eggplants Grown on Salinity Conditions

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Abstract
Eggplant is a horticultural species that has been largely consumed in world due to medical and nutritive potentials. Kayamori and Igarashi 16 studying an antocyanin extracted of *Solanum melongena* reported that this fruit promotes reduction of the total cholesterol in rats. Currently domestic production of potash fertilizer in Brazil as K_2O is above 16 % and import is 83 %. The main potassium fertilizer used in agriculture is potassium chloride followed by potassium sulphate to a lesser extent. Potassium sulfate is less "salty" than the potassium chloride. Proline is an amino acid produced using glutamate and arginine under normal conditions, and glutamate is the main pathway in stress conditions. This amino acid has function of cell protection against denaturation processes when plants are exposed to inadequate situations as mineral, salt and water stresses, because this organic compound is highly soluble in water. The aim of this study was to investigate the influence of potassium stress through two potassium fertilizer (KCl and K_2SO_4) treatments over leaf proline and fruit production in eggplant, as well as the modifications in electrical conductivity of soil. The experiment design used was factorial scheme with randomized blocks, 2 potassium sources (KCl and K_2SO_4) combined with 4 levels of K_2O (250, 500, 750 and 1000 kg ha^{-1}). The highest fruit production was obtained with K_2O 500 kg ha^{-1} using KCl compared to K_2SO_4 with an average electrical conductivity of 2.76 and 2.16 dS m^{-1}. In this study it was observed that excessive level of KCl and K_2SO_4 as K_2O 1000 kg ha^{-1} resulted in decrease of fruit production and increase of proline concentration in leaves of the eggplant.

Keywords*:* *Solanum melongena*, mineral stress, potassium, proline.

Sources and Doses of Potassium on the Production of Root in Eggplants

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Abstract
Currently domestic production of potash fertilizer in Brazil as K_2O is above 16 % and import is 83 %. The main potassium fertilizer used in agriculture is potassium chloride followed by potassium sulphate to a lesser extent. Potassium sulfate is less "salty" than the potassium chloride. Other aspect of potassium is linked to assimilation, because under adequate supplement in soil, the plant absorption of potassium can be four times higher than that of phosphorus, and equal to or greater than nitrogen, in which there are three macronutrients absorbed in large amounts in higher plants. This study was carried out at the Department of Plant Production, Sector Horticulture, Sao Paulo State University-UNESP, Botucatu Campus, Sao Paulo State, Brazil in order to evaluate the effect of sources and increasing doses of potassium in roots of eggplant. The experimental design was randomized blocks in factorial scheme 2 x 4 (two sources of potassium: KCl and K_2SO_4 and four doses of K_2O, 250, 500, 750 and 1000 kg ha^{-1}) and three replications. For the experiment, we used Oxisol medium texture (615 g of sand, 45 g of silt and 340 g of clay per kg soil). The soil passed through sieve of 5 mm and packed in plastic pots with a capacity of 32 liters of soil where plants were grown. The pots were distributed with a spacing of 0.63 m between plants and 1.0 m between rows each pot being grown with a plant. The evaluated characteristics were: root dry mass and volume of the root. It was concluded that sources and excessive doses of mineral K_2O induces stress in eggplants and affect the roots being less harmful K_2SO_4 source.

Keywords: *Solanum melongena* L. Potassium. Root. Dry matter.

Effect of Potassium Sources on the Antioxidant Activity of Eggplant

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Abstract
Potassium participates in the essential processes in plant physiology, however, the effects of K sources on plant metabolism have been little studied. Also, in certain cases, K sources and concentrations may cause undesirable effects, e.g., soil salinization. The objective was to evaluate the effect of K sources and levels on the enzyme activity of the antioxidant system and protein content in eggplant leaves and to determine the most suitable K sources for these physiological characteristics. The experiment was conducted in randomized blocks, in a 2 × 4 factorial design, consisting of two K sources (KCl and K_2SO_4) and rates (250, 500, 750, and 1000 kg ha^{-1} K_2O), with four replications. The following variables were evaluated: plant height, number of leaves per plant, superoxide dismutase (SOD), catalase (CAT), and leaf protein content. There was an increase in CAT activity with increasing K levels until 30 days after transplanting (DAT), when K_2SO_4 was applied and until 60 DAT, when KCl was used; after this period, the enzyme activity decreased under both sources. The activity of SOD increased in the presence of KCl, but was reduced with the application of K_2SO_4. For both K sources, increasing rates reduced the protein content and number of leaves per plant, and this reduction was greater under KCl application. Thus it was concluded that KCl tends more strongly to salinize the soil than K_2SO_4. Both for KCl and for K_2SO_4, the increasing rates adversely affected the activities of CAT and SOD and the levels of leaf protein in eggplant. The potential of KCl to reduce the enzyme activity of SOD and CAT, leaf protein content and plant growth of eggplant was stronger than that of K_2SO_4.

Keywords: *Solanum melongena* L., potassium, superoxide dismutase, catalase, protein.

Potato Yield and Dry Matter Response to Different Sources of Potassium Fertilizer in England

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Abstract
Limited available information pertaining to the performance of polyhalite (14% K_2O, 17% CaO, 6% MgO and 19% S, POLY4®) on potato prompted establishment of a trial on loamy soils in Staffordshire, England in 2015. The first objective was to assess three different sources of potassium: Muriate of Potash (MOP), Sulphate of Potash (SOP), and POLY4 at 0 (Control), 100, 200, 300 and 400 kg K_2O ha^{-1} supplying different rates of Mg, S and Ca. All treatments received standard N and P nutrients. Each source of potassium was similar for yield and each resulted in higher tuber yield than the control. POLY4 and control recorded significantly higher dry matter content than MOP treatment.

The second objective assessed combinations of polyhalite and MOP in different proportions to meet total crop K_2O requirements. The first treatment was standard N and P control, second treatment was Control+Mg, supplied with 80 kg of MgO through Kieserite. Treatments 3 and 4 were applied at 300 kg of K_2O from MOP and POLY4 respectively. Treatments 4, 5, and 6 were dry blends in which 16%, 25% and 62% of 300 kg K_2O need was met by polyhalite, respectively. The remainder of the 300 kg K_2O requirement was met by MOP. Treatments 7 and 8 were similar to treatments 4 and 5 but were also supplied Kieserite to meet 80 Kg MgO requirement. No significant differences in tuber yield were observed between control and MOP. However, treatments containing POLY4 in different proportions resulted in significantly higher yield than the controls. Treatment 8 resulted in significantly higher yield than MOP. Results indicate the effectiveness of POLY4 both as a straight fertilizer or combined with MOP to meet the potato nutrient requirements.

Evaluation of POLY4 (Polyhalite) as a Fertilizer in Comparison to Sulphate of Potash for Tobacco

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Abstract

Polyhalite ($K_2SO_4.MgSO_4.2CaSO_4.2H_2O$, POLY4®) can potentially expand the options of low chloride potash sources for tobacco. In order to evaluate the product, two replicated, RCB trials were conducted at Xundian Daheqiao farm, Yunnan Agricultural University in successive years. Recommended fertilizer amount for the local variety, YN87 (RF) is 105 kg N ha^{-1}, and N: P_2O_5: K_2O = 3:1:5 in Xundian county, Yunnan province. N and P fertilization levels were fixed at the RF, Ammonium phosphate nitrate (30-6-0) and Diammonium phosphate (18-46-0) were used as N and P fertilizers for this experiment. Potassium fertilizer was POLY4 against Sulphate of Potash (SOP) at 88, 116, 175 and 263 kg K_2O ha^{-1} assessed for yield and quality attributes.

Yield and economic returns were significantly enhanced due to potassium fertilization irrespective of sources in both 2014 and 2015. Potassium fertilizer sources did not respond significantly differently, although the POLY4 fed crop gave numerically higher yields. Similarly leaf potassium uptake significantly responded to potassium application in 2014. Reducing sugar concentration was significantly higher for POLY4 compared to SOP and control in 2014.

Crop financial value also responded significantly to potash application, products were not significantly different; however, POLY4 supported a numerically higher value. In 2014, black shank disease incidence was significantly reduced under POLY4 compared to SOP. Bacterial wilt was similarly reduced with potassium fertilization, although there was no significant difference between potassium sources. We conclude that POLY4 could be used as a source of potassium in tobacco crop nutrient management under local conditions at Yunnan China.

Evaluation of Polyhalite in Comparison to Muriate of Potash for Corn Grain Yield in the Southern Highlands of Tanzania

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ABSTRACT

Recent exploration of new multi-nutrient potassium fertilizers such as polyhalite and a lack of understanding on its effect on corn grain yield performance motivated establishing six corn trials in the Southern Highland region of Tanzania, under rain-fed conditions, in 2015. The objective was to elucidate whether 20 kg of K_2O from two different sources beyond the recommended practice of 120-60-0 kg ha^{-1} (N, P_2O_5 and K_2O), respectively helps in increasing corn (Zea mays L.) grain yields or not. Measured treatments were: 1) Control in which no fertilizer was applied; 2) Recommended practice of 120-60-0 (NP treatment, 120-60-0); 3) NP treatment + Muriate of Potash (MOP); 4) NP treatment + Polyhalite (POLY4); and 5) NP treatment + MOP + Kieserite (MOP + Kieserite). Treatments 3, 4 and 5 received 20 kg K_2O ha^{-1} through MOP, POLY4 and MOP respectively. Kieserite was applied to the treatment 5 to balance the 28 kg S ha^{-1} as provided by the POLY4 treatment. Measured variables were grain yield, stover weight, number of cobs, vigour and plant populations. Treatments of interest were compared by using single degree freedom linear contrasts. As expected all treatments significantly outperformed control at all locations. The NP treatment, POLY4 and MOP+Kieserite recorded significantly higher grain yields than MOP at one, two and two out of six locations respectively and recorded numerically higher grain yields at four, five and five locations out of six. On average across the six locations; NP treatment, POLY4 and MOP+Kieserite recorded a higher grain yield of 357, 621 and 662 kg ha^{-1} than MOP respectively. These results indicate the importance of both potassium and sulphur nutrition and that POLY4 could be used as a fertilizer source in the Southern Highland regions of Tanzania.

INTRODUCTION

Moisture and soil nutrients are major constraints for narrowing the yield gap in Africa (Fischer et al., 2014). Continuous cropping coupled with under application of fertilizers lead to nutrient mining, soil depletion and lower productivity. The old, highly leached soils in Africa's humid and sub-humid zones have inherently low nutrient levels. Nitrogen and phosphorus are generally considered as the most limiting nutrients for crop production in Africa, (Bationo and Mokwunye, 1991). Scientists at ICRISAT addressed this issue through micro dosing technology, which advocates the application of small and affordable quantities of fertilizer either at the time of planting or as a part of top dressing (ICRISAT, 2009). Micro-dose technology has been widely promoted due to the low fertilizer application rate and high probability of yield response (Palé et al., 2009) and a favorable fertilizer/grain price ratio. The application and usefulness of this technology is variable as per soil, climate and crop. For example, in Burkino Faso, it involves an application of 19 kg of N, 19 kg of P_2O_5 and 19 kg of K_2O. We extended this technology to the application of potassium to evaluate the effects of 20 kg of K_2O application through two different sources.

The global usage of potassium chloride (MOP) as a fertilizer and different testing methods for plant available potassium were recently questioned and critiqued by Khan et al. in 2014. Their survey of 2100 yield response trials resulted in no beneficial response to MOP fertilizer application possibly due to chloride toxicity (Khan et al., 2014). Bar-Yosef et al. (2015) critiqued the above findings saying that lack of a beneficial response to MOP by Khan et al. (2014) could be due to other growth limiting factors such as moisture and nitrogen application. They further critiqued that MOP should be evaluated at a specific

agro climatic zone to avoid the masking effect of agro ecological factors. In the same year, Khan et al. (2015) responded to this commentary and stood by their debate that MOP application is not necessary to improve crop yields. They further mentioned that results of 224 surveyed trials majorly indicated reduced grain yields through MOP application in North America. In their 2014 paper, potassium sulphate (SOP) was recommended as an alternative to MOP. However, as mentioned by Yousuf et al. 2015, the cost of SOP is a constraint for its wide spread usage.

A search for alternate potassium sources lead to the exploration of polyhalite in North Yorkshire in the United Kingdom (Kemp et al. 2016). This could ultimately lead to decreased reliance on MOP as a potassium source. Another advantage of using polyhalite could be its lower processing losses compared to SOP. Hence there is a need to gather more evidence on the agronomic performance of polyhalite. Thus improved understanding is essential for Africa due to demand for more cost effective resources under local conditions.

Polyhalite was evaluated for its potassium content by Fraps and Schmidt (1932). However, its use as a commercial fertilizer is only recently emerging with the discovery of large quantities in the Zechstein deposits in the North Sea basin, east of the United Kingdom (Kemp et al. 2016). POLY4 is the trademark name of a commercial granulated polyhalite fertilizer from Sirius Minerals which is undergoing global agronomic trials. POLY4's nutrient value is 14% K_2O, 17% CaO, 6% MgO and 19% S , with a solubility in water of 27 g L^{-1} at 25 °C and is pH neutral (Sirius Minerals, 2016). However, no studies have been published that relate to the agronomic performance of POLY4 on any crop under African conditions.

The majority of the soils from Tanzania's humid and sub-humid regions was categorized as severely weathered, acidic, infertile and had limited but variable nutrient releasing capacities to sustain low-input agriculture (Szilas et al., 2005, Bisanda et al., 1998). Funakawa et al. (2012) analyzed 94 soil samples collected from different parts of Tanzania and enumerated the average texture, dominant clay mineral, C content, soil pH, base saturation % as sandy clay loam to clay loam, kaolinite, 22 g kg^{-1}, 6.1, 95%, respectively. Cation exchange capacity (CEC), exchangeable K, Mg, Ca and Al were reported as 14, 1.1, 2.78, 6.98, 0.21 cmolc kg^{-1} respectively. Critical nutrient deficiencies of nitrogen (N) and phosphorus (P) were observed (Bisanda et al., 1998). According to Wickama et al. (2015), 40% of corn area under subsistence farming has potassium levels below the critical minimum, signifying the potential for response to potassium fertilization

The Southern Highlands of Tanzania (between 7°N and 11.5°S and longitudes between 30°W and 38°E) is an agriculturally important area growing a range of crops such as maize, beans, wheat, potatoes, vegetables and many others. Elevation ranges between 400 to 3000 m.a.s.l and the mean annual rainfall varies from 750 mm to 3500 mm. Rainfall pattern is unimodal, from November to May. Forty-six percent of Tanzanian corn (Zea mays L.) production is from this region. Corn is the major food and cash crop of the region and is grown primarily as a monocrop system (Bisanda et al., 1998). Corn grown in this area is within mega maize environment – 1V, a dry mid-altitude subtropical conditions as defined by Fischer et al. (2014) and has a potential yield of 9 t ha^{-1}. Currently sulphur (S) and calcium (Ca) deficiencies have increased in the Southern Highlands, such that fertilizers containing S and Ca are increasingly important in ensuring balanced nutrition of crops in support of high yield and quality of the produce.

Current fertilizer recommendations to offset nutrient deficiencies in most parts of the Southern Highlands for corn are 80-120 N kg ha^{-1} in two splits; and 23- 69 kg P_2O_5 ha^{-1} as basal application (Mowo et al, 1993) and Lyimo and Temu (1992). Generally the sources of these nutrients are urea, single super phosphate (SSP) or triple super phosphate (TSP), Di-Ammonium Phosphate (DAP) and calcium ammonium nitrate (CAN). These products separately supply the crop's nutrient requirements of calcium and sulphur in addition to N and P.

The specific objective of the current study was to evaluate POLY4 (the trademark name of a commercial granulated polyhalite from Sirius Minerals) as a multi-nutrient fertilizer for corn in the Southern Highland conditions of Tanzania and quantify the probability of yield response by changing the potassium source from MOP to POLY4.

MATERIALS AND METHODS

Six corn research trials were established in 2014-15 in major corn growing agro ecological zones of the Southern Highlands of Tanzania as listed in Table 1. Locations were selected in such a way that it represents the major corn growing belt of the Southern Highland region's conditions. Composite soil samples from a depth of 0-25 cm were taken from the experimental sites and sent for analysis at the Aagricultural Research Institute-Uyole and Sokoine University of Agriculture soil laboratory to provide information on the general fertility status of the trial sites. Parameters analyzed included soil pH, CEC, exchangeable bases (Ca, Mg, K and Na), particle size analysis, total available phosphorus, total nitrogen, organic carbon, sulphur (S) and micro nutrients (Fe, Zn, Cu and Mn). Soil pH was determined as described by McLean (1982) and the EC was determined using an electrical conductivity meter (Okalebo et al., 1993). The CEC of the soil was determined using the ammonium acetate saturation method as described by Chapman (1965). Exchangeable Ca^{2+} and Mg^{2+} was determined by atomic adsorption spectrophotometry (AAS) from the ammonium acetate leachate while K and Na were determined by the flame photometer method (Chapman, 1965). Total N was determined by the Micro Kjeldahl digestion-distillation method according to the procedure described by Bremner and Mulvaney (1982). Available phosphorus was determined by the Bray and Kutz method and for soils with pH less than 5.5 the Olsen method (Olsen and Sommers, 1982) was used. Organic carbon content was determined by the Walkey and Black method as described by Nelson and Sommers (1982). The particle size analysis was determined by the hydrometer method after dispersing the soil samples with sodium hexametaphosphate solution (Day, 1965). The textural classes were determined using the USDA textural class triangle (Soil Survey Staff, 1992; Okalebo et al., 1993).

Experiments were sown in the month of November with the onset of rains. Land preparation was done by cultivation followed by one discing. Details of dates and site management were listed in the Table 2.

Treatments were the same in five sites: 1) Control, where no fertilizer was applied; 2) NP treatment, where N and P_2O_5 were applied at 120 and 30 kg ha^{-1} respectively; 3) MOP treatment, where 20 kg K_2O was applied in addition to N and P_2O_5 as applied in treatment NP; 4) POLY4 treatment, where POLY4 supplied 20 kg K_2O ha^{-1} in addition to the same N and P_2O_5 application; 5) MOP + Kieserite ($MgSO_4$), was the same as the MOP treatment, in addition to the application of Kieserite to supply the same amount of sulphur as in the POLY4 treatment. At the dry area in Ismani location, N and P_2O_5 were applied at the rate of 80 and 20 kg ha^{-1} respectively, other applications being similar.

Nitrogen was split applied once at pre-planting and another one at V6 growth stage. All phosphorus and potassium fertilizers were applied at seven days before planting.

Experimental design at each site was a randomized block design with four replications. Each experimental plot was 6m by 5m. Spacing between rows was 75 cm and between plants is 30 cm. Variety UH 615 was seeded at a rate of 25 kg ha^{-1}.

Agronomic data collection started with plant vigour. The vigour were scored from each treatment plot when plants were about to tassel by using visual scientist judgement guided by a scale of 0-5 score. Whereby 0 score means no plants in the plot to be assessed and 5 means best phenotypic expression (gene by environment interaction) expected. This was based on observing plant stand, healthiness of plants as expressed by leaf colour from the bottom to a flag leaf greenness, stalk size and plant height when a used

corn variety in the experiment is supplied with balanced nutrients to tap its genetic grain yield potential under field conditions.

When all plants have tasselled in the field, 10 plants were selected at random from the inner area of (4.5 by 4.5 meters) rows and their heights were measured from the soil surface to the base of the first silk by using a stiff metallic tape measure/ruler. Average heights of the 10 plants measured were used as an indicator plant height of a treatment.

When all crops have dried in the field, July to August in southern highlands of Tanzania, in a net harvest area (4.5 by 4.5 meters), plant stand and cobs harvested from each treatment plot were counted. Total weights of cob and stover per harvest area were measured by using a field measuring scale balance. The stover yields per hectare were directly computed from net area harvested and weights measured. Two samples were taken from the dried cobs in each treatment plots harvested, grains moisture were recorded by using grain moisture tester (Draminsi Moiture meter). Finally the grain yields in a hectare basis for each treatment plot were computed from the cob weight, adjusted grain moisture (13%) and net area harvested.

Statistical analysis was carried out using Genstat software version 17 (VSN international, 2011) using ANOVA. Due to interest in the comparison of specific treatments, data was analyzed at each location using single degree freedom orthogonal contrasts when the p value for treatments was less than 0.1. Similarly, data was also analyzed over all trials by using location as a random variable. Here, replication/block was nested within location. Multiple linear regressions were used to identify the important yield attributes influencing the yield.

Table1. Details of experimental trials, regions, coordinates, elevation, description and soil series.

Trial name	Uyole	Mbimba	Ismani	Seatondale	Milundikwa	Suluti
Region	Mbeya	Mbeya	Iringa	Iringa	Rukwa	Ruvuma
Latitude	08°.54900′ S	09°.04614′ S	07°.33410′ S	07°.47569′ S	07°.40355′ S	10°.32491′ S
Longitude	033°.30840′ E	032°.56380′ E	035°.45623′ E	035°.41792′ E	031°.23507′ E	036°.04540′ E
Altitude (m)	1783	1501	1343	1537	1838	872
Soil series	Mollic Andosol	Humic Nitosol	Chromic Cambisol	Ferralic Cambisol	Ferralic Cambisol	Orthic Ferrasol
pH (H_2O)	5.63	5.23	5.59	5.5	5.46	5.3
Organic Carbon (g kg^{-1})	20	18.4	8.4	6.1	25.5	6.2
N (g kg^{-1})	1.7	2.5	2.3	2.5	2	1.9
P (mg kg^{-1})	2.06	5.22	4.16	13.33	5.17	10.05
CEC (cmol(+)/kg)	17.66	15.84	14.86	4.88	16.3	12.08
K (mg kg^{-1})	917	246	234	117	445	230
Ca (mg kg^{-1})	1240	394	774	356	944	270
Mg (mg kg^{-1})	149	149	403	192	257	210
Na (mg kg^{-1})	262	214	204	209	233	218
S (mg kg^{-1})	13	16	36	20	9	12
Fe (mg kg^{-1})	105.56	77.45	77.56	26.33	60.74	113.89
Zn (mg kg^{-1})	2.73	0.99	0.98	1.4	0.88	1.85
Mn (mg kg^{-1})	104.92	109.6	87.7	26.89	56.65	119.61
Texture	Sandy clay loam	Clay	Sandy clay	Sandy loam	Sandy clay	Sandy clay
Sand (%)	52.55	42.35	60.05	82.05	45.05	63.95
Silt (%)	21.9	13.05	3.9	2.4	12.9	0.97
Clay (%)	25.55	44.6	36.05	15.55	42.05	35.08

Table 2. Dates of various agronomic activities in six corn trials

	Activity / Location	Uyole	Mbimba	Ismani	Seatondale	Milundikwa	Suluti
1	Planting	20/12/2014	24/12/2014	29/12/2014	31/12/2014	09/01/2015	07/01/2015
2	1st Weeding	05/01/2015	22/01/2015	26/01/2015	23/01/2015	07/02/2015	29/01/2015
3	1st Top dressing	16/01/2015	27/01/2015	03/02/2015	16/02/2015	16/02/2015	30/01/2015
4	2nd Weeding	06/02/2015	05/03/2015	03/03/2015	21/02/2015	10/03/2015	14/02/2015
5	2nd Top dressing	20/02/2015	06/03/2015	04/03/2015	04/03/2015	11/03/2015	16/02/2015
6	Harvesting	10/08/2015	26/07/2015	18/07/2015	19/07/2015	16/07/2015	21/07/2015

RESULTS AND DISCUSSION

Yield

When the analysis was done over all locations, each treatment provided with fertilizer significantly outperformed Control. POLY4 and MOP+Kieserite treatments recorded significantly higher grain yield than MOP. Recommended NP practice was on par with MOP, POLY4 and MOP+Kieserite. Lower yields in MOP treatment compared to POLY4 and MOP+Kieserite could be attributed to the competition between chloride and sulphate anions which should be higher in MOP treatments due to the addition of chloride anions coupled with the lack of sulphur application (Table 3, Figure 1).

Data was also analyzed by site to look for the detailed performance of each treatment. Significant differences among treatments for corn yield were observed at all locations except at Ismani (Fig. 1A). The lack of response to fertilizer at Ismani could be attributed to dry temperature and low rainfall. Mean yields across the treatments at Ismani was 2549 kg ha^{-1} when compared with a mean yield of 5601 kg ha^{-1} for the remaining locations. Treatments containing K_2O application such as MOP, POLY4 and MOP + Kieserite recorded 481, 496 and 1571 kg ha^{-1} of numerically higher grain yield than the recommended practice of NP treatment. Efficient turgor maintenance from potassium application could be a reason for this trend.

Multiple linear regressions indicated that the major yield attribute influencing yield at this site were number of cobs followed by plant vigour. These two variables explained 70% of the variation in yield.

Contrary to the trend observed at Ismani, significant differences among treatments were observed at the remaining five sites (Fig. 1B to Fig 1F). All fertilizer applied treatments significantly outperformed Control treatment and these results illustrate the importance of N and P in southern high land conditions for corn in Tanzania.

Treatments NP, POLY4 and MOP+Kieserite recorded significantly higher grain yields than MOP at Uyole (Fig. 1B). High exchangeable soil K content, 917 mg kg^{-1} of soil (Table 1) was observed at this trial site. More understanding is required for this yield reduction from the MOP treatment when compared with the NP treatment. Chloride anions competing with available sulphate ions resulting in reduced tissue sulphur concentrations could have hindered yields in MOP treatment, explaining this result. However, tissue nutrient concentration was not measured in these trials. The yield attribute influencing yield at Uyole was plant vigour which accounted for 43% of the total variation of yield.

Another instance of yield decrease for MOP was observed at Mbimba. Here, MOP and MOP+Kieserite recorded significantly lower grain yields than POLY4 (Fig. 1C). Even though not statistically significant, NP recorded 747 and 1177 kg ha^{-1} of higher grain yield than MOP and MOP+Kieserite treatments. Similarly, at Uyole, the only significant variable explaining variation i.e. 46% in yield was plant vigour.

At Suluti, MOP+Kieserite significantly outperformed the MOP treatment but not NP or POLY4 treatments. The MOP treatment recorded 392, 655 and 1349 kg ha^{-1} numerically lower yields than the NP, POLY4 and MOP+Kieserite treatments (Fig. 1D). Again, similar to the trend observed at Ismani, Uyole and Mbimba locations, the major yield attribute influencing yield was crop vigour. Crop vigour along with cob number explained 94% of variation in yield.

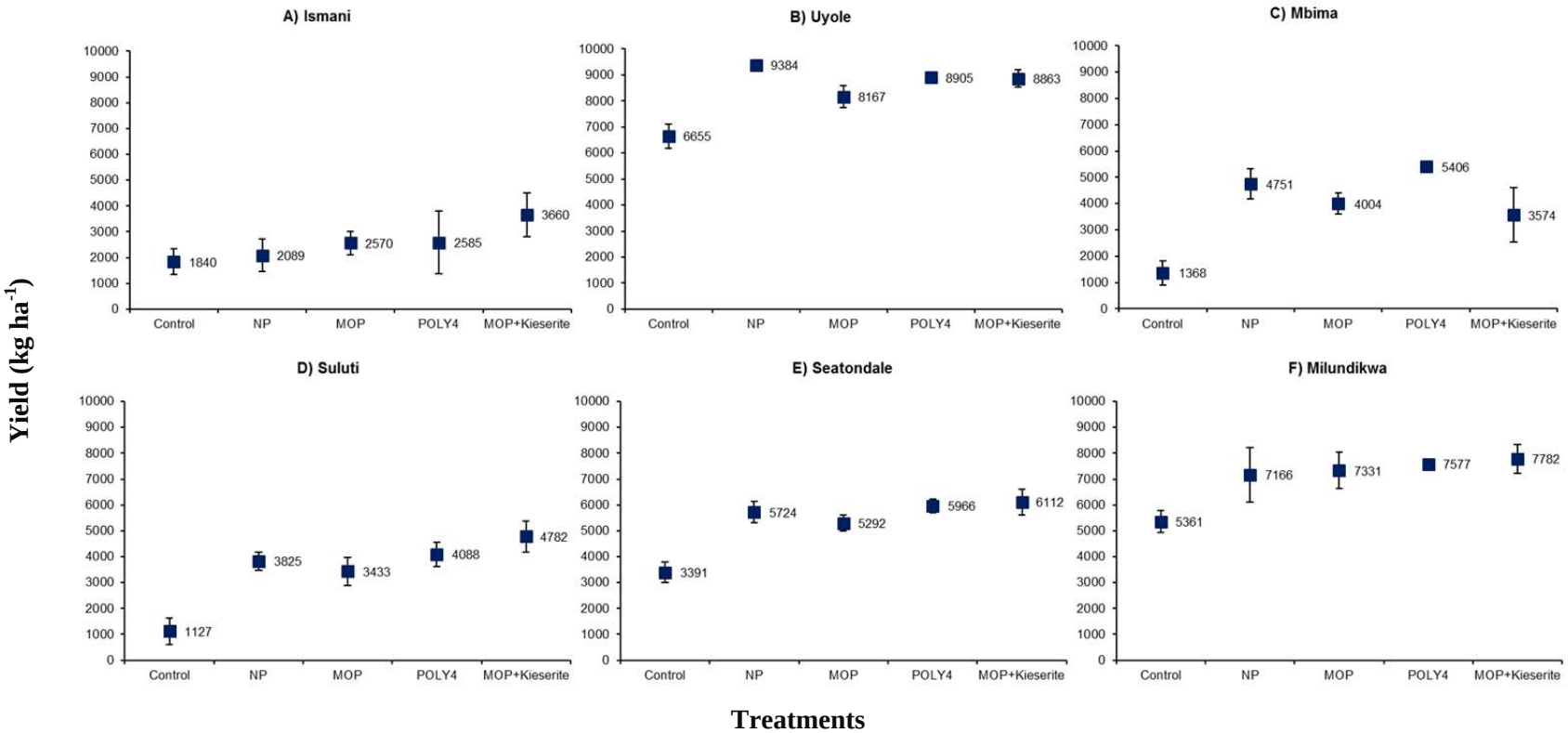

Figure 1. Effect of treatments on corn grain yield, kg ha^{-1} at six different locations in Southern Highlands of Tanzania. Error bars indicate the standard error of mean. Data labels are mean corn grain yields.

Table 3. Table of p values for ANOVA and treatments of interest through contrast analysis for corn grain yield and yield attributes. Analysis was done over all locations. Replication was nested within each location.

Treatments	Grain yield	Stover weight	Crop vigour	Plant height	No. of plants	No. of cobs
ANOVA	<.001	0.085	<.001	<.001	NS	0.002
Control vs POLY4	<.001	NS	<.001	<.001	0.018	<.001
NP vs POLY4	NS	NS	0.115	NS	NS	NS
MOP vs POLY4	0.037	NS	0.083	NS	NS	NS
MOP+KIE vs POLY4	NS	NS	0.525	NS	NS	NS
NP vs MOP	NS	NS	0.874	NS	NS	NS
MOP+KIE vs MOP	0.026	NS	0.019	NS	NS	NS
NP vs MOP+KIE	NS	NS	0.028	NS	NS	NS
Control vs NP	<.001	0.009	<.001	<.001	NS	0.017
Control vs MOP	<.001	0.035	<.001	<.001	NS	0.005
Control vs MOP+KIE	<.001	NS	<.001	<.001	NS	<.001

At the remaining two locations; Seatondale and Milundikwa, no significant differences among the NP, MOP, POLY4 and MOP+Kieserite treatments were observed (Figure 1E and Figure 1F). At Seatondale, and Milundikwa, variables plant height and number of cobs explained 84% of variation in grain yield.

In summary, data analyss over all locations indicated that POLY4 and MOP+Kieserite recorded significantly higher yields than MOP (Table 3). Data analysis by location indicated significantly reduced yields for MOP when compared with NP, POLY4 and MOP+Kieserite at 1, 2 and 2 instances out of 5 responding sites respectively. MOP recorded numerically lower yields than NP, POLY4 and MOP+Kieserite numerically at 4, 5, and 4 out of 5 locations respectively (Figure 1). These results could be attributed to the sulphur nutrition from either POLY4 or Kieserite and competition between chloride and sulphate anions. Another reason could be attributed to the higher adsorption or fixation of potassium from MOP to the clay particles. Such adsorption or fixation could be lower for POLY4 or MOP+Kieserite due to the competition between monovalent (K^+) and divalent (Ca^{2+}, Mg^{2+}) cations. This six-location data concludes that POLY4 could be used as source of K under the Southern Highland conditions of Tanzania and was on par with MOP+Kieserite on corn grain yield performance.

There could be other factors such as synchrony between availability of nutrients and peak crop nutrient demand, and differences in rates of application of S, Mg and Ca. There is a need for further and more detailed research including tissue and grain nutrient concentrations to understand the performance of these products.

No statistically significant differences between NP and POLY4, or NP and MOP+Kieserite were observed at all locations. However, POLY4 recorded numerically higher yield than NP practice at 4 out of 5 responding locations and the difference across the locations was 218 kg per hectare (Figure 1). In comparison, MOP+Kieserite recorded numerically higher yield than NP treatment at 3 out of 5 responding locations and the difference across all these locations was 53 kg ha^{-1} (Figure 1). The difference between POLY4 and MOP+Kieserite across all locations was 166 kg

ha^{-1}. Data showed that the probability of yield response could be increased by switching from MOP to POLY4 as a source of potassium under these micro K dosing conditions.

Sutradhar et al. (2016) evaluated MOP, polyhalite and MOP+polyhalite blends in Minnesota for corn grain yield. Increased grain yield from polyhalite compared to MOP was attributed to sulphur from polyhalite. These results support the findings of the current study.

Similar to the current results regarding the reduced yields for MOP treatment, Wortmann *et al.,* 2009 analyzed 34 corn trials in Nebraska under irrigated conditions and concluded that MOP application at 40 kg ha^{-1} reduced grain and biomass yields. At most of these places soil residual potassium was more than 125 ppm.

Plenty of literature is available on the performance of MOP on corn and other crops. However, very few peer reviewed studies were available from the literature in the last two decades pertaining to polyhalite's performance as a fertilizer.

Tiwari *et al.*, (2015) evaluated polyhalite as a fertilizer in mustard and sesame and reported increased yields from its application when compared with MOP under sandy loam soils in North India. They attributed such increased yields to the sulphur content of polyhalite. However, in their study the major source of potassium in the polyhalite treatment was MOP.

Vigour

POLY4 and MOP+Kieserite treatments were found to be more vigorous than MOP across all locations (Figure 2, Table 3). Similar to yield, significant differences among treatments were observed at all the locations (Figure 2). As expected, Control was less vigorous than other treatments across all sites. Multiple linear regressions indicate that crop vigour was influencing and explaining the variation in yield. In general, no significant differences among NP, MOP, POLY4 and MOP+Kieserite were observed. However, POLY4 recorded numerically higher vigour scores than NP, MOP and MOP+Kieserite at 5, 3 and 1 locations out of 6 respectively.

Significant correlations between vigour and grain yield were observed at all measured locations. Observed correlation coefficients were 0.74, 0.7, 0.61, 0.79, 0.92, 0.68 at Ismani, Mbimba, Milundikwa, Seatondale, Suluti, Uyole and respectively.

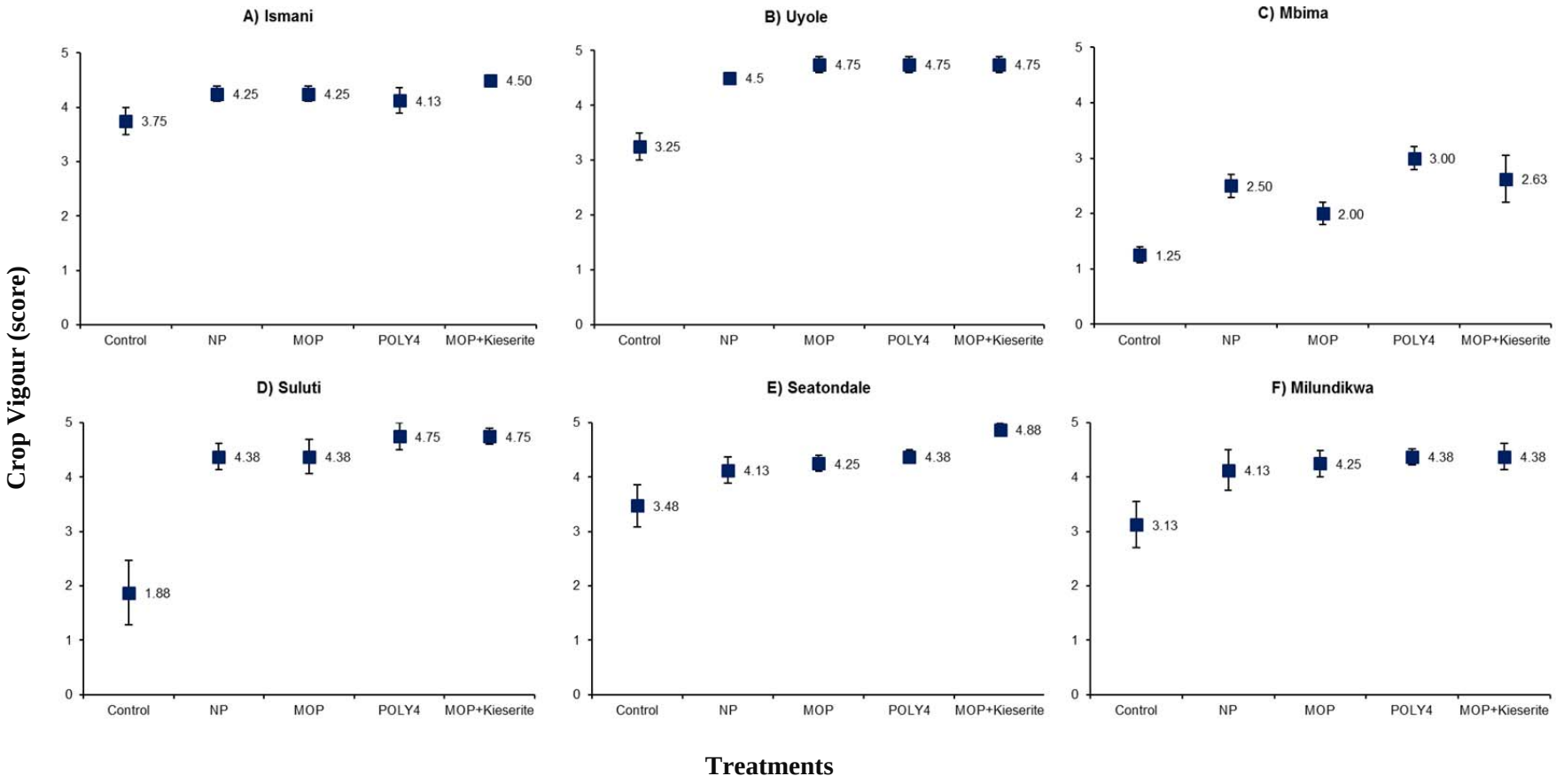

Figure 2. Effect of treatments on corn vigour at six different locations in Southern Highlands of Tanzania. Error bars indicate the standard error of mean. Data labels are mean corn vigour.

Stover weight, plant population, and number of cobs

When the analysis was done for all locations, no significant differences were observed among NP, MOP, POLY4 and MOP+Kieserite for Stover weight, plant population and number of cobs (Table 3).

Significant correlations between plant height and grain yield were observed at all locations including Ismani. Observed correlation coefficients were 0.74, 0.5, 0.62, 0.85, 0.88, and 0.4 at Ismani, Mbimba, Milundikwa, Seatondale, Suluti and Uyole respectively.

As observed for plant height and vigour, significant correlations between the number of cobs and grain yield were observed at all measured locations except Uyole. Observed correlation coefficients were 0.8, 0.54, 0.58, 0.85, and 0.95 at Ismani, Mbimba, Milundikwa, Seatondale, and Suluti respectively.

SUMMARY

In the Southern Highlands region of Tanzania, six corn trials were conducted in 2015 to evaluate polyhalite, trademarked by Sirius Minerals as POLY4, versus recommended NP practice, MOP and MOP+Kieserite. Application of MOP alone did not increase corn grain yield at any of the tested 6 locations but significantly depressed yield at one location. MOP treatments recorded numerically lower yields than NP treatments in at 4 out of 6 instances. Such reduced yields were not observed for POLY4. On the other hand, POLY4 treatments significantly increased yield compared to NP at one of 5 responding sites and numerically enhanced yield at 5 out of 6 sites. MOP+Kieserite in general performed similar to POLY4 , we conclude this indicates the value of sulphur to corn yields at these locations since soil magnesium levels were high . Comprehensive research including tissue and post-harvest soil nutrient analysis is essential for confirming, explaining the reasons and mechanisms of the observed results in the current study.

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Potassium Deficiency Symptoms of Important Horticultural Crops

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ABSTRACT
Nutrient deficiency symptoms can be used as a rapid diagnostic tool for identifying factors that might limit crop yield and quality. Deficiency symptoms are not the best approach for dealing with nutritional shortages, because by the time symptoms are visible, plant productivity has already been impaired with so-called "hidden hunger". However for many farmers, close observation of plant symptoms is their only tool available to fine-tune their plant nutrition program. Additionally, monitoring the progression of the developing deficiency symptoms provides insight into physiological processes in the leaves.

Nutrient deficiency symptoms have been characterized for many of the major grain crops of the world, but little work has been done to document these diagnostic symptoms for important horticultural crops. This current work was initiated to add to the collection of nutrient deficiency symptoms to be used as a management tool, especially for small-scale farmers who often lack access to plant and soil analysis.

A carefully controlled hydroponic production system was established in the greenhouse of Tennessee State University. Vegetable seeds or seedlings were sown in oasis cubes and later transferred to buckets containing a complete modified Hoagland/s nutrient solution devoid of one essential nutrient. A series of high resolution photographs of the plants were taken as the nutrient deficiency symptoms developed. A variety of horticultural crops have now been grown and documented. More details of the growing conditions and set up are available from Dr. Pitchay.

A series of e-books is being developed by the International Plant Nutrition Institute (IPNI) for each specific crop. The first book documents nutrient deficiency symptoms of broccoli. The ebook Plant Nutrition Diagnostics: Broccoli is available for free download from iTunes: http://apple.co/2jbC4vz. Additional images are available for a variety of crops, including broccoli, cucumber, spinach, squash, okra, romaine lettuce, papaya, blueberry, and others.

Potassium deficiency symptoms are often misdiagnosed for other symptoms, including other nutritional deficiencies, abiotic stress (drought and high temperature), and biotic stress (such as leaf blight). The development of necrotic lesions in leaves appear rapidly under high light intensity and temperature, and with water stress.

Classic expressions of K deficiency include compact deep green plants with shorter and fewer internodes and smaller leaves, which is followed by rapid development of necrotic spots along the margins and across leaf blades of matured and recently matured leaves. In most cases, the lesions of necrosis begin without prior chlorotic lesions. Whereas in some cases, chlorosis develops surrounding the necrotic spots as the necrosis enlarges at advanced stage.

Unique lesions of K deficiency in Broccoli, Cucumber, Spinach, Squash, Okra, Romaine lettuce, Papaya and Blueberry are as follows:

Unique Potassium Deficiency Lesions by Species

Species	**Description of lesions**
Broccoli	Internodes of maturing and recently matured leaves of K-deficient plants develop purplish concentric circles with green, normal looking tissues in the center. Gradually, the underside of these leaves shrivel, followed by the development of irregular sunken light chlorosis (light green) concentric circles with normal islands of tissues. The lesions progress further with severe shriveling of leaf stalks and spreading of purplish pigmentation on the internodes. Eventually, necrosis develops across the entire lamina.
Cucumber	Leaves appear deeper green and lesions of grayish necrosis develop unexpectedly on recently matured leaves and more mature leaves lower on the stem.
Spinach	Lesions of light greenish sunken, irregular necrotic spots develop on recently matured leaves. The lesions rapidly coalesce and progress to distinct whitish necrotic spots interveinally on the acropetal leaf area.
Squash	Necrotic spots of light whitish pin-head sized lesions develop interveinally across the leaf blades mainly closer to the primary veins, which then enlarge to irregular sunken necrotic spots and eventually into large necrotic spots of 0.5 to 1 cm size.
Okra	Greyish necrotic irregular spots develop interveinally across margins of recently matured leaves, which coalesce into large necrotic lesions with chlorotic tissues surrounding it.
Romaine lettuce	Lesions of dark greyish irregular sunken necrotic spots begin at the acropetal area of recently matured leaves. These necrotic lesions rapidly coalesce into large irregular necrotic patches randomly across the lamina.
Papaya	Necrosis begins as greenish-gray patches just inside the leaflet margins of recently matured leaves and rapidly progress to wide-spread necrosis and the tissue collapses along the terminal margins. As patches increase in size and number towards the leaf base, areas between the necrotic patches turn chlorotic and the leaves eventually abscise.
Blueberry	Irregular light colored necrotic lesions coalesce into large brownish necrotic spots, which then enlarge to patches of necrosis randomly across the matured and recently matured leaves.

Comparative Study of Potassium and Nitrogen Fertilization on Yield and Utilization Efficiency of Phosphorus and Potassium by Wheat

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Abstract

To study the effect of potassium and nitrogen fertilization treatments on wheat yield, P &K uptake and P & K utilization efficiency for wheat (*Triticum aestivum, L.*), variety Sakha 93, two field experiments were conducted on a clay saline soil at El-Serw Agricultural Research Station, Agricultural Research Center, Egypt during 2011/2012 and 2012/2013 winter seasons. The experiments were carried out in a split plot design with four replicates. Main plots were assigned to potassium applications (0, 47.4 & 94.8 kg K ha^{-1}). The sub plots were divided by mineral nitrogen treatments as follows: 44.5, 89, 133.5, 178 and 214 kg N ha^{-1}. Wheat yield (grain & straw) and P & K-uptake by (wheat grain & straw) increased with increasing potassium rate up to 94.8 kg K ha^{-1}, but P & K utilization efficiency by wheat crop was decreased. Also, these results showed that 214, 178, 133.5, 89 and 44.5 kg N ha^{-1}, respectively gave the highest values of the previous parameters except the PU_tE and KU_tE, where the order of values was upward with the order of the previous treatments. The interaction between 94.8 kg K ha^{-1} and 214 kg N ha^{-1} gave the highest wheat yield (grain & straw) and P & K uptake by grain and straw and gave the lowest PU_tE and KU_tE in both seasons. So, it prefers to add 94.8 kg K and 214 kg N ha^{-1} for economic production of wheat grain and straw especially in saline soil. Also, the highest results of PU_tE and KU_tE in both seasons were obtained with interaction between 0 kg K ha^{-1} and 44.5 kg N ha^{-1}, it indicates that shortages in uptake of phosphorus & potassium with nitrogen & potassium deficiency.

Keywords: Wheat· Nitrogen· Potassium· Fertilization· Phosphorus· Efficiency·

INTRODUCTION

Wheat (*Triticum aestivum, L.*) is one of the most important cereal crops not only in Egypt but all over the world. Because wheat production in Egypt is not enough domestic consumption, this has led to require much attention concerned to increase production to meet the high demand and reduce the gap between production and consumption of wheat. Therefore, great efforts have been made to achieve the best transactions and methods of agricultural to get maximum productivity of different wheat varieties with optimal quality properties.

Agricultural intensification is through the use of varieties of high production crops and the development of pesticides and chemical fertilizers, irrigation, mechanization has led to a significant increase in cereal production in developing countries over the past three decades (Matson et al., 1998). However, there is a growing global challenge of getting food with protecting the environment and this challenge will be, especially with the production of strategy crops such as maize, rice and wheat. (Cassman et al., 2002).

Salinity becomes one of the most important and serious agricultural problems. Moreover, it is an ever-present threat to crop productivity (Termaat et al., 1985). Fertilizer management can strongly affect crop productivity under conditions of drought or salinity. Thus, the addition of nutrients can either enhance or decrease plant resistance to salinity (Gibson, 1988).

Be necessary to add fertilizer and / or amendments to supply the appropriate nutrients and get to the maximum yield. Many agricultural experiments also demonstrated that the efficiency of applied fertilizers, no more than 50% of the nitrogen, 10% of the phosphorus and 40% of potassium. Plants that

have high efficiency of nutrient absorption and utilization greatly enhance the efficiency of the application of fertilizers and reduce the high costs of agricultural and prevent loss of nutrients and thereby reduce environmental pollution (Baligar et al., 2001).

Potassium is one of the essential nutrients for the plants, which directly helps in the production of the crop and determine its quality. Also, potassium involved in many physiological processes such as photosynthesis, enzyme activation, water relations and assimilates transport can have direct consequences on crop productivity. Therefore, Potassium deficiency can lead to a reduction in both the number of leaves produced and the size of individual leaves (Pettigrew, 2008).

Baque et al. (2006) found that the significantly improved yields, yield contributing characters and N, P and K uptake of wheat was with higher levels of potassium (312 kg ha^{-1}). El-Abady et al. (2009) reported that foliar application of potassium at the rate of 2.49 % K gave the highest values of growth, yield and its components and grain quality characters followed by 1.25 % K as compared with control treatment (without potassium application). Rahimi (2012) indicated that effect of potassium on grain yield was highly significant. Tababtabaei and Ranjbar (2012) showed that the highest grain and straw yields were obtained by application of 74.7 kg K ha^{-1}.

Plants respond strongly to additions of nitrogen, which is regarded as the mainly in the construction amino acids, proteins and enters in many physiological processes in the plant (Wilkinson, 2000). Nitrogen fertilization is an important and essential factor affecting wheat production in all over the world, especially in Egypt, because most of Egyptian soils contain insufficient nitrogen. Several research conducted in Egypt proved that there is a significant effect of nitrogen levels on most of the characteristic growth, yield and yield components. The optimum nitrogen fertilizer levels for wheat in Egypt vary widely in amounts, it was ranged between 97.2 and 285.7 kg N ha^{-1} according to environmental conditions such as type and properties of soil (Tammam and Tawfils, 2004; Salem, 2005; Mansour and Bassiouny, 2009).

Abou-Salama et al. (2000), Antoun et al. (2010) and Rahimi (2012) found that nitrogen fertilizer at the rates of 119.1, 178.6 and 238.1 kg N ha^{-1} significantly increased yields and its components. Also, Ahmed (2002) found that the grain yield of wheat increased by increasing nitrogen fertilizer levels up to 190.5 kg N ha^{-1}, while Seleem and Abd El–Dayem (2013) reported that the best significant values of grain and straw yields were obtained by adding 142.9 or 214.3 kg N ha^{-1}.

NPK uptake by grain and straw were significantly increased by nitrogen fertilizers when raised from 59.5 to 119.1, 178.6 and 238.1 kg N ha^{-1} (Antoun et al., 2010).

Internal utilization efficiency (IE) of a nutrient (Nutrition Utilization efficiency) (kg yield per kg nutrient uptake), this measurement can be interpreted by (Dobermann, 2007) as follows:

1- The plant's ability to transform nutrients was obtained from all sources (soil and fertilizer) to the economic return (grain).
2- Depends on genotype, environment and management.
3- A very high IE suggests a deficiency of that nutrient.
4- Low IE suggests poor internal nutrient conversion due to other stresses (nutrient deficiencies, heat stress, drought stress, mineral toxicities, and pests).

Usually potassium efficiency describes the ratio of the potential yield that can be achieved under a potassium deficiency (Damon and Rengel, 2007). Varieties and genotypes which have high efficiency of potassium are usually exhibit a higher capacity to take up relatively more K in K deficient soil (K uptake efficiency, KU_pE) (Trehan and Sharma, 2002; Zhang et al., 2007) and/or a higher dry matter production per unit of potassium taken up (K utilization efficiency, KU_tE) (Woodend et al., 1987; El Bassam, 1998).

However, a high KU_pE or KU_tE may not mean that a high yield or biomass, and biomass production or yield remains are the most important goal. Siddiqi and Glass (1981) proposed another index for nutrient-use efficiency as follows: the ratio of biomass and tissue nutrient concentration, simultaneously taking into account the biological production and KUE (biomass/tissue nutrient concentration).

Therefore, this investigation was established to determine the effect of mineral potassium and nitrogen applications on yield, P & K-uptake by grain and straw and P & K Utilization Efficiency for wheat under the environmental conditions of El-Serw district, Damietta Governorate.

MATERIALS AND METHODS

Experimental design and preparing

Two field experiments were conducted at El-Serw Agricultural Research Station, Agricultural Research Center (ARC) in Egypt during the two successive winter seasons of 2011/2012 and 2012/2013. The objective of these experiments was to improve productivity of wheat (variety Sakha 93) under mineral potassium and nitrogen fertilization and increasing efficiency use of applying these fertilizers for wheat.

The experiments were carried out in a split plot design with four replicates. The main plots were allocated to two potassium fertilizer levels as the following: K_0 (0 kg K ha^{-1}), K_1 (47.4 kg K ha^{-1}) and K_2 (94.8 kg K ha^{-1}) in the form of potassium sulphate (39.8% K) Potassium fertilizer was applied broadcasting in one dose before the first irrigation. The sub plots were devoted to five nitrogen treatments as follows: A (214 kg N ha^{-1}), B (178 kg N ha^{-1}), C (133.5 kg N ha^{-1}), D (89 kg N ha^{-1}) and E (44.5 kg N ha^{-1}),the nitrogen fertilizer in the form of ammonium nitrate (33.5 % N) was applied at the aforementioned rates in two equal doses prior the first (25 days from sowing) and the second (46 days from sowing) irrigations. Each experimental unit was 3 × 3.5 m occupying an area of 10.5 m^2.

Calcium superphosphate fertilizer (6.76 %P) was added at the rate of 238 Kg ha^{-1} as basal for each plot before ploughing.

Wheat seeds, CV. Sakha 93, were sowen on November 18th and 25th in the first and second seasons, respectively. Wheat harvesting was done on 20th April 2012 and 1 May 2013 in both seasons, respectively.

Soil analysis

Soil samples were taken from the experimental field before conducting from soil layer (0-30cm depth), then air-dried and ground to pass through 2 mm sieve. Soil physical and chemical properties were carried out according to Klute, 1986 and Page et al, 1982.

Table 1: Physical and chemical soil characteristics of the experimental sites during the two seasons.

Growing season	Particle size distribution%					OM %	$CaCO_3$ %	C.E.C (meq /100g soil	pH	EC, dSm^{-1}
	Coarse sand	Fine sand	Silt	Clay	Texture class					
1st	1.40	10.60	20.95	67.05	Clayey	0.75	1.39	44.95	8.0	5.20
2nd	1.68	10.70	21.11	66.51	Clayey	0.82	1.31	43.32	7.8	4.40

Growing season	Cations and anions in the soil water extract (1:5), meq/100 g soil								NPK available (ppm)		
	Cations				Anions				N	P	K
	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	Cl^{-}	SO_4^{--}			
1st	3.68	3.56	16.05	0.22	---	1.34	16.43	5.74	30	8.02	472
2nd	3.91	3.49	16.51	0.24	---	1.51	16.81	5.83	31	7.96	461

Plant analysis

Nutritional analysis

Oven-dried samples of wheat (grain & straw) were ground in a mill using a 50-mesh screen. These samples were digested in H_2SO_4 concentrated and H_2O_2 30%, according to Yash (1998).

P and K uptake and utilization efficiency

After wheat harvest, grain and straw yields and P and K-uptake, by grains and straw were estimated as kg ha^{-1}:

Nutrient element uptake = (Nutrient element% × Yield) / 100

The internal utilization efficiency of a nutrient (Nutrition "Nut." Utilization efficiency such as PU_tE and KU_tE) (kg yield.kg^{-1} nutrient uptake) (Dobermann, 2007) was calculated as follows:

Nut.-U_tE = Grain Yield / Nut. uptake by (grain and straw)

Where grain yield as kg ha^{-1} and Nut. uptake by (grain and straw) as kg (nutrient element) ha^{-1}.

The statistical analysis

The statistical analysis was carried out according to Steel and Torrie (1980) to compare the treatments values.

RESULTS

Grain and straw yield (t ha^{-1})

Data presented in Table 2 show that adding potassium and nitrogen fertilizer significantly affected on wheat grain and straw yields (t ha^{-1}) by increasing Potassium fertilizers up to 94.8 kg K ha^{-1} and nitrogen rate up to 214 kg N ha^{-1} in both 1st and the 2nd seasons. Baque et al. (2006) and Rahimi (2012) obtained similar results when they treated wheat plant with potassium levels. On other hand, Abou-Salama et al. (2000), Antoun et al. (2010) and Rahimi (2012) stated that nitrogen fertilizer at the rates of 119.1, 178.6 and 238.1kg N ha^{-1} significantly increased yields and its components of wheat.

Also, data showed that the interaction between potassium levels and nitrogen treatments had a significant effect on grain and straw yield in both the 1st and the 2nd seasons. Also, Table 3 show that, the highest values of wheat grain yield (6.743 & 6.860 t ha^{-1}) and straw yield (9.269 & 9.507 t ha^{-1}) were obtained when 94.8 kg K ha^{-1} overlapped with 214 kg ha^{-1} in 1st and 2nd seasons, respectively, following the

highest values of wheat grain yield were obtained with ($K_2 \times N_2$), ($K_1 \times N_1$), ($K_2 \times N_3$) and ($K_0 \times N_1$), respectively. The conclusion from this, the important role of potassium in wheat grain production, where preferably added 94.8 kg K ha^{-1} for economic crop of wheat, also for producing the best wheat yield in saline soil (Ec > 4 dS m^{-1}), it preferably add 214 kg N ha^{-1} and 94.8 kg K ha^{-1}.

Phosphorus uptake by wheat grain and straw (kg P ha^{-1})

Data in Table 3 show that there was significant increase in phosphor uptake by both wheat grain and straw (total phosphorus removed by the crop from the soil in grain and straw) in both the 1st and the 2nd seasons due to applying potassium and nitrogen fertilizer levels. Also, as in previous variables, the highest values of P uptake were obtained by applying 214 kg N ha^{-1} as nitrogen factor and 94.8 kg K ha^{-1} as potassium treatments, where there was a positive relationship between each factor separately (potassium or nitrogen) and P uptake. Baque et al. (2006) reported that uptake of P was enhanced with the increasing potassium levels. But, Antoun et al. (2010) obtained similar results when they used nitrogen treatments.

Also, data in Table 3 show that interaction effect between potassium and nitrogen treatments was significant on P uptake by wheat grain and straw in both 2011/2012 and 2012/2013 seasons. The highest values of P uptake for wheat grains in both 2011/2012 and 2012/2013 seasons, were obtained with 214 kg N ha^{-1} and 178 kg N ha^{-1}, respectively when were applied with 94.8 kg K ha^{-1}. But the highest values of P uptake for wheat straw in both the 1st and the 2nd seasons were with ($K_2 \times N_1$), ($K_1 \times N_1$) and ($K_2 \times N_2$), respectively.

Potassium uptake by wheat grain and straw (kg K ha^{-1})

Data presented in Table 4 show that potassium uptake significantly increase by wheat grain and straw (total potassium removed by the crop from the soil in grain and straw) in both the 1st and 2nd seasons due to potassium treatments. Also, the highest mean value of K uptake was obtained with 94.8 kg K ha^{-1}. Baque et al. (2006) obtained similar results.

Also, there was a significant increment in K uptake by wheat grain and straw in both the 1st and the 2nd season, by nitrogen treatments, the highest mean values of K uptake by grains and straw in both the 1st and the 2nd seasons were recorded with N_1, N_2, N_3, N_4 and N_5, respectively. Similar results were obtained by Antoun et al. (2010). Such as P uptake, also, there was a positive relationship between each factor separately (potassium or nitrogen) and K uptake.

Also, the data in Table 4 show that the interaction effect between potassium and nitrogen treatments was significant on K uptake by wheat straw in both 1st and 2nd seasons and wheat grain in the 1st season, but, this effect was significant at 5% in wheat grain in the 2nd season. The highest values of K uptake for wheat grains and straw in both the 1st and the 2nd seasons, were obtained with ($K_2 \times N_1$), ($K_2 \times N_2$) and ($K_1 \times N_1$), respectively.

Phosphorus Utilization Efficiency (PU_tE) (kg grain kg P $uptake^{-1}$) by wheat crop

Data in Table 5 showed that there was no significant decrease in PU_tE in both 1st and the 2nd seasons by increasing potassium fertilizer rates up to 94.8 kg K ha^{-1}. But, there was a significant increment in PU_tE due to applying nitrogen fertilizer in both seasons. The highest value of PU_tE was obtained by N_5 followed by N_4, N_3, N_2 and N_1 treatments.

Also, Data showed the effect of the interactions among potassium application and nitrogen treatments on phosphorus utilization efficiency for wheat crop in the 1st and 2nd seasons. This interaction was no significantly decreased in PU_tE for wheat crop in both seasons. The highest values of PU_tE were obtained by this interaction were with ($K_0 \times N_5$), ($K_1 \times N_5$) and ($K_2 \times N_5$), respectively.

Potassium Utilization Efficiency (KU_tE) (kg grain kg K uptake^{-1}) by wheat crop

Data in Table 5 showed that there was a significant decrease in KU_tE in both the 1st and 2nd seasons by increasing potassium fertilizer rates up to 94.8 kg K ha^{-1}. Also, there was a significant increment in KU_tE by applying nitrogen fertilizer in both seasons. The highest value of KU_tE was obtained with N_5, N_4, N_3, N_2 and N_1, respectively.

Also, Data showed that the effect of the interactions between potassium application and nitrogen treatments on potassium utilization efficiency by wheat crop was no significantly decreased in both the 1st and the 2nd seasons. The highest values of KU_tE were obtained by this interaction were with ($K_0 \times N_5$), ($K_1 \times N_5$) and ($K_0 \times N_4$), respectively in the 1st season and ($K_0 \times N_5$), ($K_0 \times N_4$) and ($K_1 \times N_5$), respectively in the 2nd season.

DISCUSSION

Grain and straw yield

Wheat grain and straw yields (t ha^{-1}) increased by increasing Potassium fertilizers up to 94.8 kg K ha^{-1}, this is due to the a limited K supply slows plant growth and decreases biomass production, thus increasing potassium fertilization cause consequently to increase production of grain and straw. These interpretations matching to (Hermans et al. 2006; Rengel and Damon 2008). Pettigrew (2008) pointed to the importance of potassium due to its involved in many physiological processes, potassium impact on water relations, photosynthesis, assimilate transport and enzyme activation can have direct consequences on crop productivity. Also, increased nitrogen fertilization led to increased production of wheat yield due to strongly respond to additions of nitrogen, which is regarded as the mainly in the construction amino acids, proteins and enters in many physiological processes in the plant (Wilkinson, 2000). Also, potassium and nitrogen fertilization can strongly affect crop productivity under conditions of salinity, due to the addition of nutrients can either enhance or decrease plants' resistance to salinity by helping the plant to strong growth, thus increasing the wheat yield with increased potassium and nitrogen fertilization as the most important elements for plant growth under saline soil.

Phosphorus and potassium uptake by wheat grain and straw

Increasing phosphorus and potassium uptake by increasing potassium and nitrogen fertilization, due to the potassium and nitrogen are the most important nutrients for plants, where many physiological processes rely on them, especially those responsible for absorbing elements by enhancing roots and thus increasing the concentration of nutrients in plant such as phosphorus and potassium. Baque et al. (2006) reported that uptake of P was enhanced with the increasing potassium levels. But, Antoun et al. (2010) obtained similar results when they used nitrogen treatments.

PU_tE and KU_tE by wheat

From the foregoing, it is clear that nitrogen deficiency leads to high of PUtE and KUtE. This increase in Part and KUtE indicates that there is a decrease in phosphorus and potassium uptake. And therefore conclude that a nitrogen deficiency leads to phosphorus and potassium deficiency even with the availability in the soil absorption plant. This interpretation is consistent with Dobermann (2007) who indicated that a very high nutrients utilization efficiency suggests a deficiency of that nutrient.

CONCLUSION

It could be concluded that the important role of potassium and nitrogen in wheat production, where preferably added 94.8 kg K ha.$^{-1}$ and 214 kg N ha^{-1} for an economic crop of wheat especially in saline soil. Nitrogen deficiency leads to high symptoms of phosphorus and potassium deficiency even with the availability in the soil absorption plant.

ACKNOWLEDGEMENTS

The research was financially supported by Soils, Water and Environment Research Institute, Agricultural

Research Center, Egypt.

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Table 2. Wheat grain and straw yield (t ha^{-1}) as affected by the interaction between potassium and nitrogen treatments during 2011/2012 and 2012/2013 seasons.

Treatments	2011/2012								2012/2013							
	Grain yield				Straw yield				Grain yield				Straw yield			
	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean
N_1	5.360	6.117	6.743	6.073	7.481	8.245	9.269	8.332	5.467	6.271	6.860	6.199	7.988	8.388	9.507	8.628
N_2	4.836	5.133	6.340	5.437	6.790	7.060	9.040	7.630	5.055	5.252	6.531	5.613	7.167	7.460	9.086	7.904
N_3	4.267	4.362	5.769	4.799	5.674	6.274	7.550	6.499	4.336	4.438	5.855	4.876	6.119	6.426	7.757	6.767
N_4	3.410	3.724	4.862	3.998	4.340	5.562	6.548	5.483	3.893	3.838	5.055	4.262	4.431	5.769	6.724	5.641
N_5	2.569	2.805	3.705	3.026	3.690	4.514	5.124	4.443	2.655	2.814	3.883	3.117	3.807	4.617	5.417	4.613
K Mean	4.088	4.428	5.484		5.595	6.331	7.506		4.281	4.523	5.637		5.902	6.532	7.698	
F. test	**				**				**				**			
LSD 5%	0.162				0.286				0.136				0.314			
LSD 1%	0.219				0.386				0.186				0.633			
F. test K	**				**				**				**			
F. test N	**				**				**				**			

*Significant at 5% level. ** Significant at 1% level.

K_0 = 0 kg K ha^{-1}. K_1 = 47.4 kg K ha^{-1}. K_2 = 94.8 kg K ha^{-1}.

N_1 = 214 kg N ha^{-1}. N_2 = 178 kg N ha^{-1}. N_3 = 133.5 kg N ha^{-1}. N_4 = 89 kg N ha^{-1}. N_5 = 44.5 kg N ha^{-1}.

K = Potassium treatments. N = Nitrogen treatments.

Table 3. Phosphorus uptake (kg P ha^{-1}) by grain and straw of wheat plant as affected by the interaction between potassium and nitrogen treatments during 2011/2012 and 2012/2013 seasons.

Treatments	2011/2012								2012/2013							
	Grain				Straw				Grain				Straw			
	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean
N_1	13.671	15.769	18.843	16.094	8.307	9.817	10.031	9.385	13.998	15.943	19.307	16.416	8.710	10.236	10.286	9.744
N_2	11.126	11.902	15.988	13.006	8.145	8.693	9.502	8.780	11.579	12.195	16.590	13.455	8.221	8.871	9.681	8.925
N_3	8.733	9.283	13.831	10.616	7.260	7.543	8.652	7.818	9.245	9.424	14.174	10.948	7.514	7.752	8.457	7.908
N_4	5.900	6.743	10.040	7.561	5.764	6.160	6.955	6.293	6.855	7.038	10.388	8.094	5.762	6.007	7.038	6.269
N_5	2.783	2.936	5.298	3.672	4.879	5.479	5.862	5.406	2.917	2.976	5.567	3.820	4.905	5.379	6.024	5.436
K Mean	8.443	9.327	12.800		6.871	7.538	8.200		8.919	9.515	13.205		7.022	7.649	8.297	
F. test	**				**				**				**			
LSD 5%	0.614				0.400				0.636				0.407			
LSD 1%	0.831				0.543				0.860				0.550			
F. test K	**				**				**				**			
F. test N	**				**				**				**			

*Significant at 5% level. ** Significant at 1% level.

K_0 = 0 kg K ha^{-1}. K_1 = 47.4 kg K ha^{-1}. K_2 = 94.8 kg K ha^{-1}.

N_1 = 214 kg N ha^{-1}. N_2 = 178 kg N ha^{-1}. N_3 = 133.5 kg N ha^{-1}. N_4 = 89 kg N ha^{-1}. N_5 = 44.5 kg N ha^{-1}.

K = Potassium treatments. N = Nitrogen treatments.

Table 4. Potassium uptake (kg K ha^{-1}) by grain and straw of wheat plant as affected by the interaction between potassium and nitrogen treatments during 2011/2012 and 2012/2013 seasons.

Treatments	2011/2012								2012/2013							
	Grain				Straw				Grain				Straw			
	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean
N_1	1.071	1.286	2.093	1.483	65.924	79.109	88.171	77.735	1.086	1.303	2.090	1.493	70.071	80.769	88.660	79.833
N_2	0.821	1.027	1.714	1.188	57.464	63.412	81.055	67.310	0.855	1.068	1.752	1.225	60.362	63.864	81.733	68.653
N_3	0.555	0.721	1.095	0.790	45.938	47.674	64.652	52.755	0.633	0.743	1.169	0.848	49.421	50.893	67.367	55.894
N_4	0.340	0.460	0.781	0.527	36.029	39.990	53.693	43.237	0.467	0.630	0.798	0.631	39.112	40.481	57.029	45.540
N_5	0.148	0.207	0.483	0.279	24.943	29.419	40.602	31.655	0.212	0.297	0.505	0.338	25.921	29.574	43.357	32.951
K Mean	0.587	0.740	1.233		46.060	51.921	65.635		0.650	0.808	1.263		48.978	53.116	67.629	
F	**				**				*				**			
LSD 5%	0.050				3.060				0.136				3.231			
LSD 1%	0.067				4.148				------				4.376			
F K	**				**				**				**			
F N	**				**				**				**			

*Significant at 5% level. ** Significant at 1% level.

K_0 = 0 kg K ha^{-1}. K_1 = 47.4 kg K ha^{-1}. K_2 = 94.8 kg K ha^{-1}.

N_1 = 214 kg N ha^{-1}. N_2 = 178 kg N ha^{-1}. N_3 = 133.5 kg N ha^{-1}. N_4 = 89 kg N ha^{-1}. N_5 = 44.5 kg N ha^{-1}.

K = Potassium treatments. N = Nitrogen treatments.

Table 5. PU_tE and KU_tE by wheat crop as affected by the interaction between potassium and nitrogen treatments during 2011/2012 and 2012/2013 seasons.

Treatments	2011/2012								2012/2013							
	PU_tE				KU_tE				PU_tE				KU_tE			
	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean	K_0	K_1	K_2	N Mean
N_1	243.88	239.08	233.53	238.83	80.01	76.09	74.70	76.93	240.75	239.54	231.81	237.37	76.83	76.41	75.59	76.28
N_2	250.95	249.24	248.72	249.64	82.97	79.66	76.60	79.74	255.30	249.31	248.60	251.07	82.58	80.88	78.23	80.56
N_3	266.80	259.24	256.59	260.88	91.78	90.13	87.75	89.89	258.73	258.38	258.72	258.61	86.63	85.95	85.43	86.00
N_4	292.35	288.62	286.08	289.02	93.76	92.06	89.25	91.69	308.55	294.21	290.08	297.62	98.36	93.36	87.42	93.04
N_5	335.29	333.33	331.99	333.54	102.39	94.68	90.18	95.75	339.43	336.80	335.00	337.08	101.60	94.21	88.53	94.78
K Mean	277.86	273.90	271.38		90.18	86.52	83.70		280.55	275.65	272.84		89.20	86.16	83.04	
F .test	ns				ns				ns				ns			
LSD 5%	-----				-----				-----				-----			
LSD 1%	-----				-----				-----				-----			
F. test K	ns				**				ns				**			
F. test N	**				**				**				**			

*Significant at 5% level. ** Significant at 1% level.

K_0 = 0 kg K ha^{-1}. K_1 = 47.4 kg K ha^{-1}. K_2 = 94.8 kg K ha^{-1}.

N_1 = 214 kg N ha^{-1}. N_2 = 178 kg N ha^{-1}. N_3 = 133.5 kg N ha^{-1}. N_4 = 89 kg N ha^{-1}. N_5 = 44.5 kg N ha^{-1}.

K = Potassium treatments. N = Nitrogen treatments.

Use of P Industry Waste as Slow Release Organic Potassium Silicate Fertilizer to Sustain Wheat Crop Production under Salt Stress Environment

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Abstract

The main constituent of slow releasing organic potassium silicate fertilizer is amorphous silica, which is the major by-product or waste of the phosphate industry. This waste was dumped in the soil since the industry was established and now a day, it is very important to process that waste. For this, the waste which mainly consists of amorphous silica is used to manufacture a new product named slow releasing organic potassium silicate fertilizer. The process for producing a slow releasing organic potassium silicate fertilizer comprises a step for slurring a mixture consisting essentially of amorphous silica, potassium hydroxide, pulverized coal and aluminum chloride. Then solidifying material prepared by dissolving zinc sulphate, magnesium chloride and iron oxide in water. After cooling, the slurries mixture is solidified with solidifying mixture and then granulating the mixture, a step for drying the granulated product to a nearly dry state and a step for calcing is done for the removal of toxic fluoride compounds and to enhance solubility of end product.

Wheat is major staple food crop of Pakistan, its yield severely affected by salinity stress, a field experiment was conducted to evaluate the role of slow release organic potassium silicate fertilizer in alleviating salinity stress in two contrasting wheat (*Triticum aestivum* L.) genotypes, Auqab-2000 (salt sensitive) and SARC-3 (salt tolerant). Both genotypes were grown in normal [electrical conductivity (EC = 1.23 dS m^{-1}) and natural saline field (EC = 11.92 dS m^{-1}) conditions with three levels of K-Si organic fertilizer (0, 75, and 150 g g^{-1} K-Si) with three replications in a randomized complete block design. Salinity stress significantly ($P < 0.01$) decreased all of the growth parameters, increased sodium (Na^+) concentration, and decreased potassium (K^+) concentration in shoots of both genotypes grown in field. Induction of K-Si organic fertilizer significantly ($P < 0.05$) decreased growth reduction in both genotypes caused by salinity stress. The grain yield under salt stress decreased from 62% to 33% and from 44% to 20% of the maximum potential in Auqab-2000 and SARC-3, respectively, when 150 g g^{-1} K-Si was used. Auqab-2000 performed better in normal field conditions, but SARC-3 produced more straw and grain yield in saline field conditions. Enhanced salinity tolerance and improved growth in wheat by potassium silicate application was attributed to decrease Na^+ uptake, its restricted translocation toward shoots, and enhanced K^+ uptake.

Enhanced the Pigeonpea Productivity through K-Foliar Nutrition Spry with Agronomic Techniques

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Abstract

Study the influence of transplanting and foliar nutrition spray enhances the growth of pigeonpea. In this study, different age of transplanting seedling combine with foliar nutrition spray. Potassium is major source for avoiding the flower dropping at the reproductive stage of pigeonpea with transplanting techniques it would be enhanced the CGR, Chlorophyll content and DMP Different age of seedling (14 days old seedling raised in protray, 21 days old seedling raised in protray, 28 days old seedling raised in protray) and Foliar spray of nutrients (DAP, Pulse wonder, polyfed and KNO_3) were Planting the seedling at the same time of all age of seedling sprayed as individual and in combination at flowering stages. Planting 21 days old seedling (M_3) during both seasons increased CGR, Chlorophyll content (SPAD meter used). Foliar application of polyfed (one per cent) and multi K (one per cent) (S_4) foliar spray during both seasons increased yield attributes followed by polyfed foliar spray (one per cent) which was on par with DAP (two per cent) spray treatment. Reduced flower dropping and improved the number of pod setting. Based on the investigation increased pigeonpea productivity.

Potassium Omission Effects for Main Crops in Bulgaria

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Abstract
"Best agricultural practices for sustainable crop nutrition in Bulgaria" was the topic of an extensive research project supported by IPNI. A total of 104 field trials on 12 different sites have been carried out from 2009 to 2012. Omission plot trials (control, N, P, K, NP, NK, PK, NPK, NPKMg) were arranged in field crops (wheat, barley, maize, sunflower, oilseed rape), vegetable (potato, tomato, pepper), fruit (peach, apricot, chokeberry) and wine grapes. The trial sites represent the major growing regions of the respective crop and cover the predominant soil and climate conditions in Bulgaria. Therefore, the results can be generalized for the whole country. For every experiment, a detailed program was worked out. The fertilization rates were defined based on the nutrient status of the selected plots according to the principles of Good Agricultural Practice. After harvest of the tested crops, the nutrient efficiency indicators were calculated based on recorded yields, soil and plant analyses.

The paper presents the potassium (K) omission effects obtained in plot trials. The exchangeable K content in the tested soils varied from low to high levels (from 3 to 33 mg 100 g^{-1}). The results show significant differences in the K omission effects between crops and sites. In general, the omission effects are lower at wheat. For arable crops, the highest omission effect is registered for barley on the soil with highest K content (Pomorie). The K omission effect of arable crops is poorly related to soil K content. It is higher on the most productive soils and in favourable years with high yield level. The K omission effect for vegetable and fruit crops is higher than for field crops and its share of the total NPK omission effect reaches 75% for potato.

INTRODUCTION

It is to be stated that fertilisation practise in Bulgarian agriculture is strongly deteriorated. A soil nutrient monitoring system did not exist for more than twenty years. Currently there are almost no soil testing of production fields and site-specific fertilizer recommendations taking place in Bulgaria. The rates of the fertilizers used are without exception expected to be under the rates that would be required. The balance of potassium in Bulgarian agriculture is negative and its recovery is less than 10% (Nikolova and Popp, 2007). The development of competitive agriculture in Bulgaria needs a competent nutrient management. This was the situation in Bulgaria, when University of Forestry, Sofia and International Plant Nutrition Institute (IPNI) joint forces to work together on a project to improve cultivation systems in Bulgarian's agriculture through efficient and sustainable use of plant nutrients. The project consists of various tasks:

- summary and update of the information about the nutrients response depending on the crop and site specificity in the country,
- evaluation to the extent possible of the soil nutrient status on national and regional level,
- development of a nutrient management system for farmers advising,
- training and teaching of farmers and students in good fertilization practices,
- contribution for improving the fertilization practice in the country.

To achieve the tasks the following activities are planned:

- soil test survey,
- soil fertility and response research,
- development of tools for site specific nutrient management,
- organising public availability of the project outputs.

Finally, besides IPNI and University of Forestry, Agricultural University Plovdiv, Institute of Soil Science "N. Poushkarov", Soil Resources Agency and K+S KALI GmbH as an external supervisor are involved in the BMPSCN project

MATERIAL AND METHODS

Omission Plot Field Trials

Among many other aspects, e.g. soil testing survey and summarising the past relevant soil fertility research, field omission plot trials (N, P, K, NP, NK, PK, NPK, NPKMg) are carried out in regions, which represent typical soil and climate conditions for the experimental crops in Bulgaria. The field trials are focused on the most economically important arable and horticulture crops in the country – wheat, barley, maize, sunflower, oilseed rape, potato, tomato, pepper, apricot, peach, chokeberry and wine grape (Figure 1). For every one experiment, a detailed program is worked out. Soil nutrient content of the major nutrients and expected yield determine the nutrient application rates with mineral fertilisers according to the principles of Good Agricultural Practice. No organic fertilisers, like farmyard manure, slurry or compost are applied. Therefore, the fertilisation rates are defined accurately based on the nutrient status of the selected plots. During the crop vegetation, the experiments are observed carefully for the development stages, pest attacks and other factors. The detailed weather data are monitored from the next available weather station. At harvest besides determining the yield, soil and plant samples from the main and secondary production of the experimental crops are collected for analyses. Chemical composition, nutrient uptake, quality parameters are determined.

Calculation of Omission Effect

Besides many other parameters, the omission effect of the primary nutrients N, P and K were calculated according to the following formula:

- N omission: $Yield_{NPK} – Yield_{PK}$ in kg ha^{-1}
- P omission: $Yield_{NPK} – Yield_{NK}$ in kg ha^{-1}
- K omission: $Yield_{NPK} – Yield_{NP}$ in kg ha^{-1}

Calculation of K share in total omission effect

The K share in total omission effect was calculated as percentage of the sum of N, P and K omission effects. It realises the importance of potassium on crops grown in Bulgaria. It is not only true for horticultural crops, but even for arable crops K has a significant effect in yield increase. The calculation is done as follows:

$$K \text{ share in } \% = Omission_K / (Omission_N + Omission_P + Omission_K) \%$$

RESULT

Nutrient use efficiency (NUE) is important modern concept in the evaluation of crop production systems and several NUE indicators are developed for this evaluation (Doberman A., 2007; Fixen P.E., 2009; Murell T.S., 2009).

In the present study K omission effect for tested crops is used as indicator for potassium (K) use efficiency assessment (Table 1.). In general, the results obtained for all crops showed that the most effective is the balanced NPK fertilization and all K omission values are positive.

Arable crops: The lowest omission effect in kg ha^{-1} for arable crops is registered for wheat and the highest for barley, almost four times higher than for wheat. K omission effect is relatively high for maize. (Fig. 2.). In average for all tested arable crops in the crop rotation, the highest K omission effect is obtained in Pomorie (Fig. 3.) – the soil with highest K content (Table 2.). This effect is twice higher than the trial sites in the North (Tervel and Gorsko Slivovo). It could be mentioned that the K omission effect of arable crops is poorly related to soil K content. It is higher on the most productive soils and in favorable years with high yield level.

Besides the direct K omission effect, its share in the total NPK omission effect is indicative for K use efficiency. The share of potassium in the total NPK effect varies significantly across crops and sites (Table 1.). For field crops in some cases it is higher than the share of N and P and reaches its maximum for barley in Gorsko Slivovo (40.6%) and for wheat in Tervel (36.1%). For maize significant variation is observed between the sites – K share in the sites of North Bulgaria is low, only 5-9% and in South part of the country is relatively high – 22 - 26%. For sunflower K covers about 20% of the total nutrient omission effect and the differences between the sites are not significant.

Horticulture crops: The results outline sizable specificity of the trial sites. Potatoes are tested in two locations and the results differ significantly – both yield level and omission effects, which in average is about 2,718 kg ha^{-1} (Fig. 4.). Although the K omission effect in Merdanya (1,558 kg ha^{-1}) is lower than in Smolyan (3,878 kg ha^{-1}), its share in the total nutrient effect is about 75% - the highest K effect registered in the project trials. In the same location (Merdanya) the K omission effect for tomato and pepper is lower than for potato (Fig. 5.). K share in the total NPK omission effect is also lower than for potato. In the other location (Petrich) potassium omission effect for tomato and pepper is high – resp. 21,558 and 8,967 kg ha^{-1} - and the K contribution in the total nutrient effect is higher than in Merdanya. The summarized results for the tested vegetable crops show that potassium omission lead to significant yield losses – highest for tomato – about 10,741 kg ha^{-1} for tomato and 7,548 kg ha^{-1} for pepper. The omission effect of potassium for tomato and pepper is the highest between the three nutrients.

The potassium response for peach is also quite different in both locations and K omission effect is in accordance with K level in the soil. Apricot and chokeberry are grown on the same location, which is typical for these crops. The results for potassium efficiency are relevant to K content in the soil. In general, for fruit crops significant K omission effects could be mentioned (Figure 6.). It is highest for peach and reaches almost 3 t ha^{-1} in average. In most of the cases, the share of K in the total NPK omission effect is higher than respective N and P effect and reaches about 46% for chokeberry.

The summarized results show that contrary to the common belief in the country, potassium is an efficient nutrient. Its omission in the fertilization practice produces significant yield losses. The fact that the K omission effect for most of the crops is poorly related to soil K content show necessity of extending the site specific factors, taken into consideration in nutrient management. Potassium show high efficiency on soils with high productivity and in years with favorable climate conditions.

These results are significant for the fertilization practices in Bulgaria. The Bulgarian farmers are persuading to good potassium status of the soils in the country and potassium application practically is behind the needs. Today, when high productive crop varieties are grown, smart potassium fertilization could be efficient tool for economic, environmental, and social benefits. Important preconditions for improving the nutrient use efficiency are farmer's education and well trained advisers.

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Table 1. Potassium omission effects of tested crops in kg ha^{-1}

Crop	**Site/Soil**	**Exch. K** [mg $100g^{-1}$]	**K omission effect** [kg ha^{-1}]	**K share in total omission effect** [%] (N+P+K=100)
Wheat	Tervel	31	339	36.1
	G. Slivovo	28	63	13.9
	Pomorie	33	63	4.6
	Sadievo	24	73	3.9
Barley	Tervel	31	75	9.3
	G. Slivovo	28	788	40.6
	Pomorie	33	1,155	24.1
	Sadievo	24	113	8.4
Maize	Tervel	31	107	9.0
	G. Slivovo	28	70	5.0
	Pomorie	33	642	22.0
	Sadievo	24	898	26.3
Sunflower	Tervel	31	93	18.0
	G. Slivovo	28	85	17.1
	Pomorie	33	369	22.4
	Sadievo	24	379	26.8
Potato	Merdanya	15	1,558	74.7
	Smolyan	3	3,877	23.3
Tomato	Merdanya	17	2,628	33.9
	Petrich	11	21,558	37.7
Pepper	Merdanya	32	6,128	32.3
	Petrich	14	8,967	41.9
Peach	Petrich	12	2,931	36.4
	Sliven	25	1,033	22.1
Apricot	Silistra	26	1,326	40.0
Chokeberry	Elena	26	835	45.8

Table 2. Soil characteristics and initial nutrient status in the top soil

Location	Soils	Clay content (<0.01 mm) %	Humus content %	pH (H_2O)	pH (KCl)	Available P_2O_5 mg $100g^{-1}$	Available K_2O mg $100g^{-1}$
Tervel	Fine-Silty, Mixed Mesic Cumulic Haplustols	63.74	3.15	6.2	5.2	13.5	31.0
Gorsko Slivovo	Fine-Silty, Mixed Mesic Tipyc Haplustalfs	53.78	2.58	6.1	5.6	3.9	28.0
Pomorie	Fine, Smectictic, Mesic Vertic Haploxererts	52.03	2.45	6.7	5.3	2.3	33.0
Sadievo	Fine, Smectictic, Mesic Vertic Haploxeralfs	56.13	2.06	5.9	5.3	< 2.0	24.0

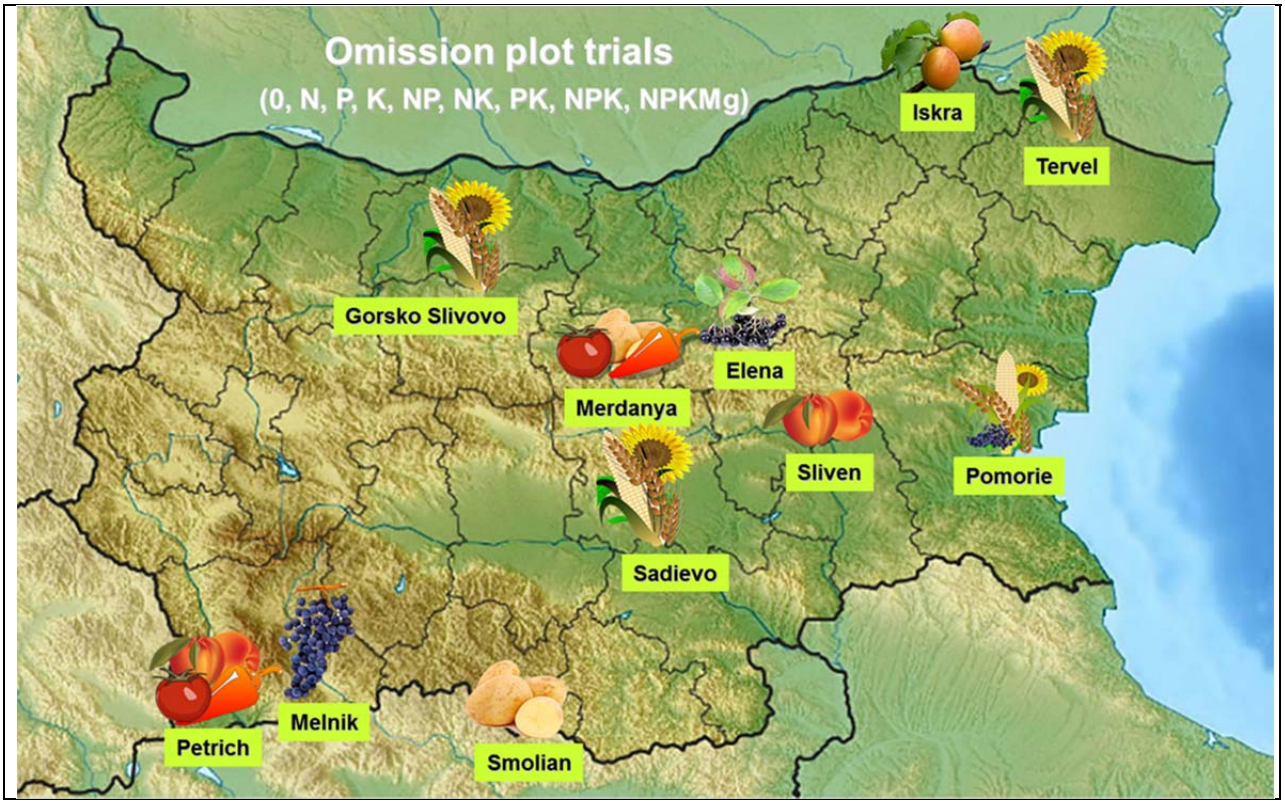

Figure 1. Omission plot trials – locations and crops

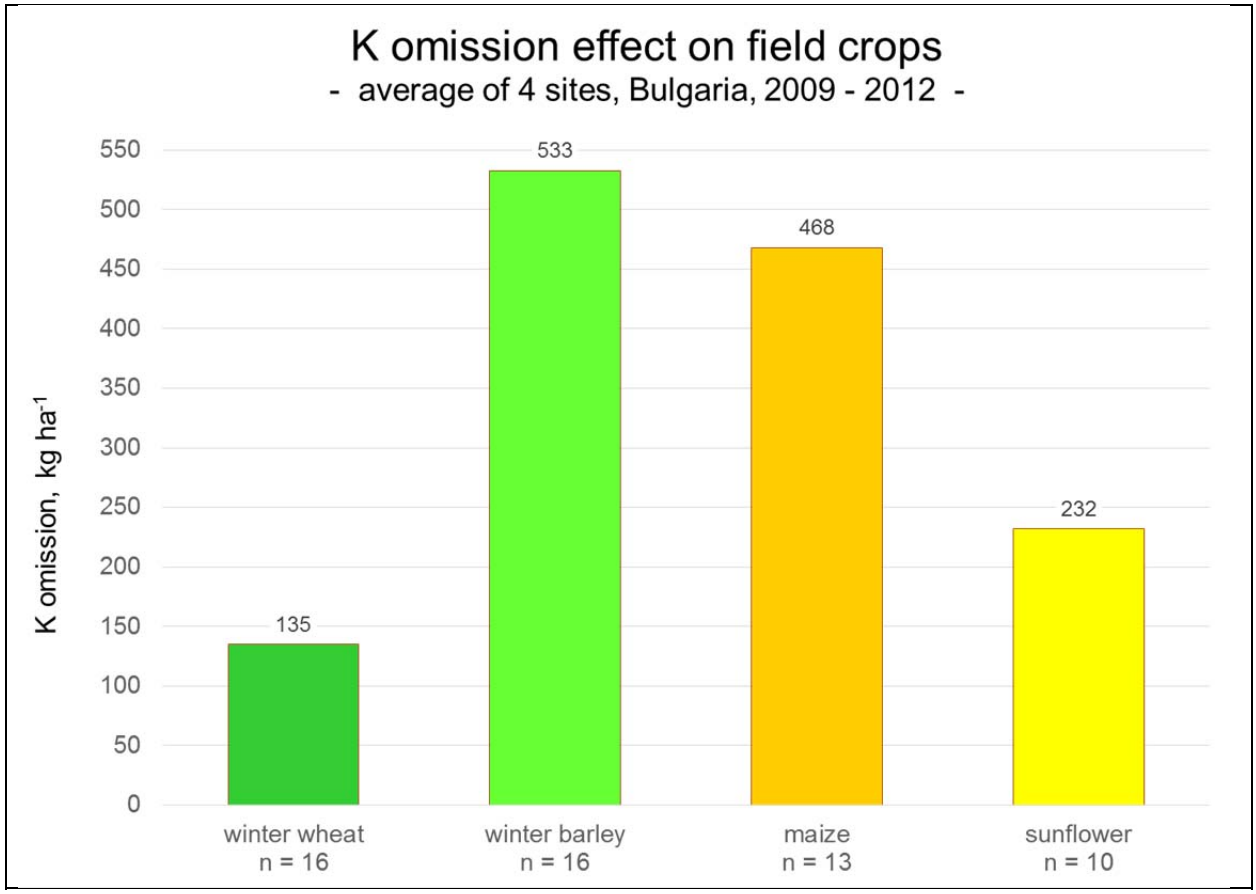

Figure 2. K omission effect on field crops

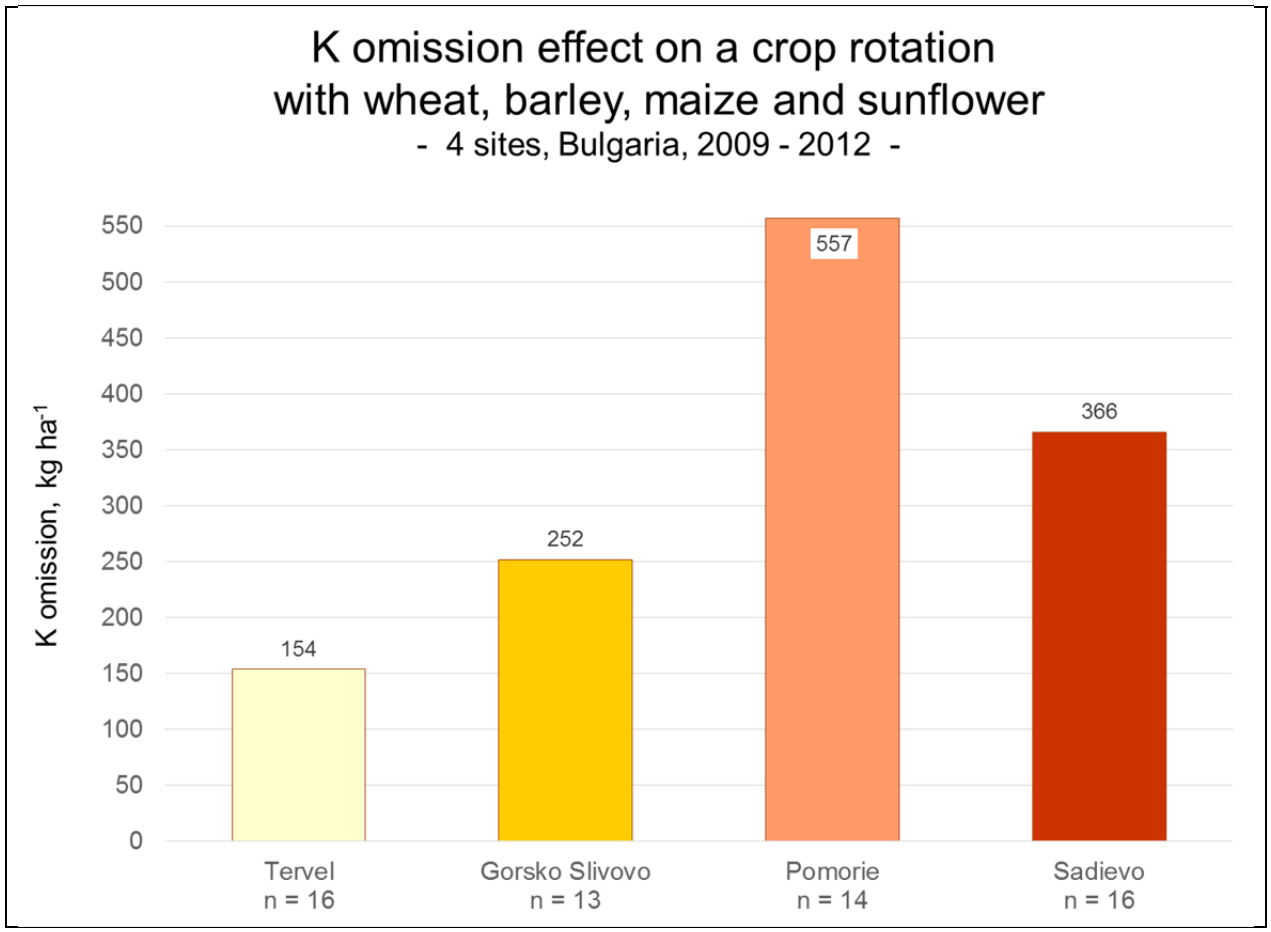

Figure 3. K omission effect on crop rotation

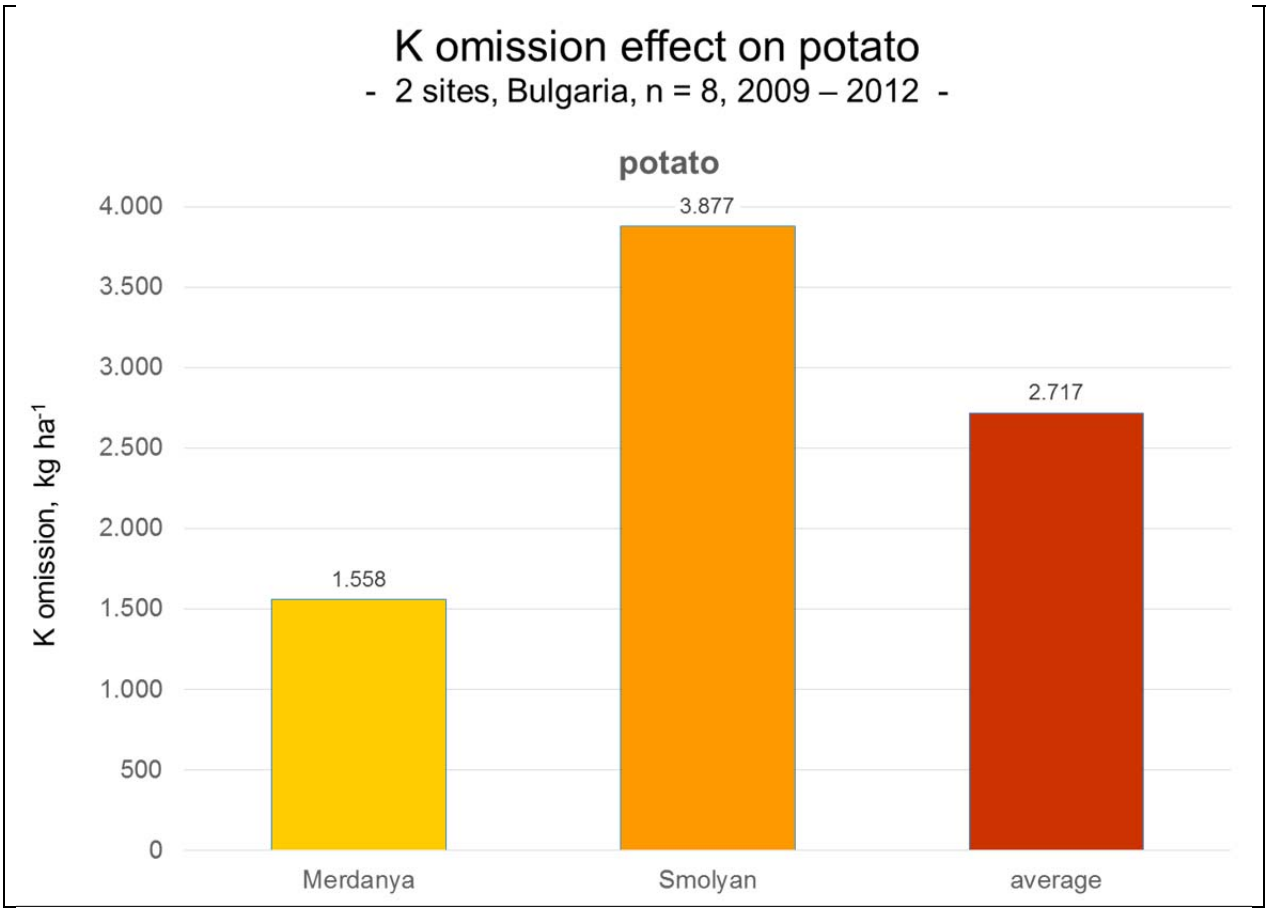

Figure 4. K omission effect on potato

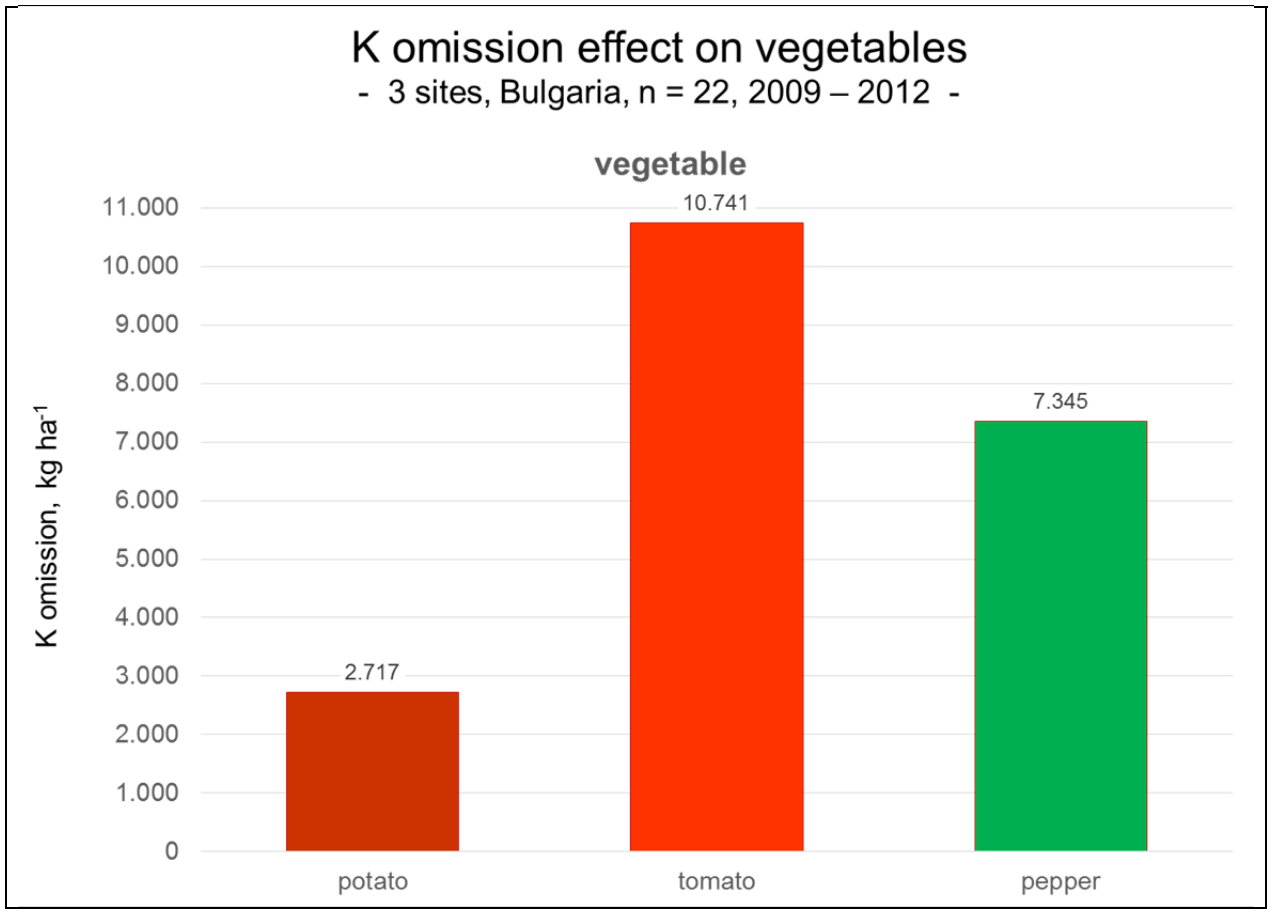

Figure 5. K omission effect on vegetables

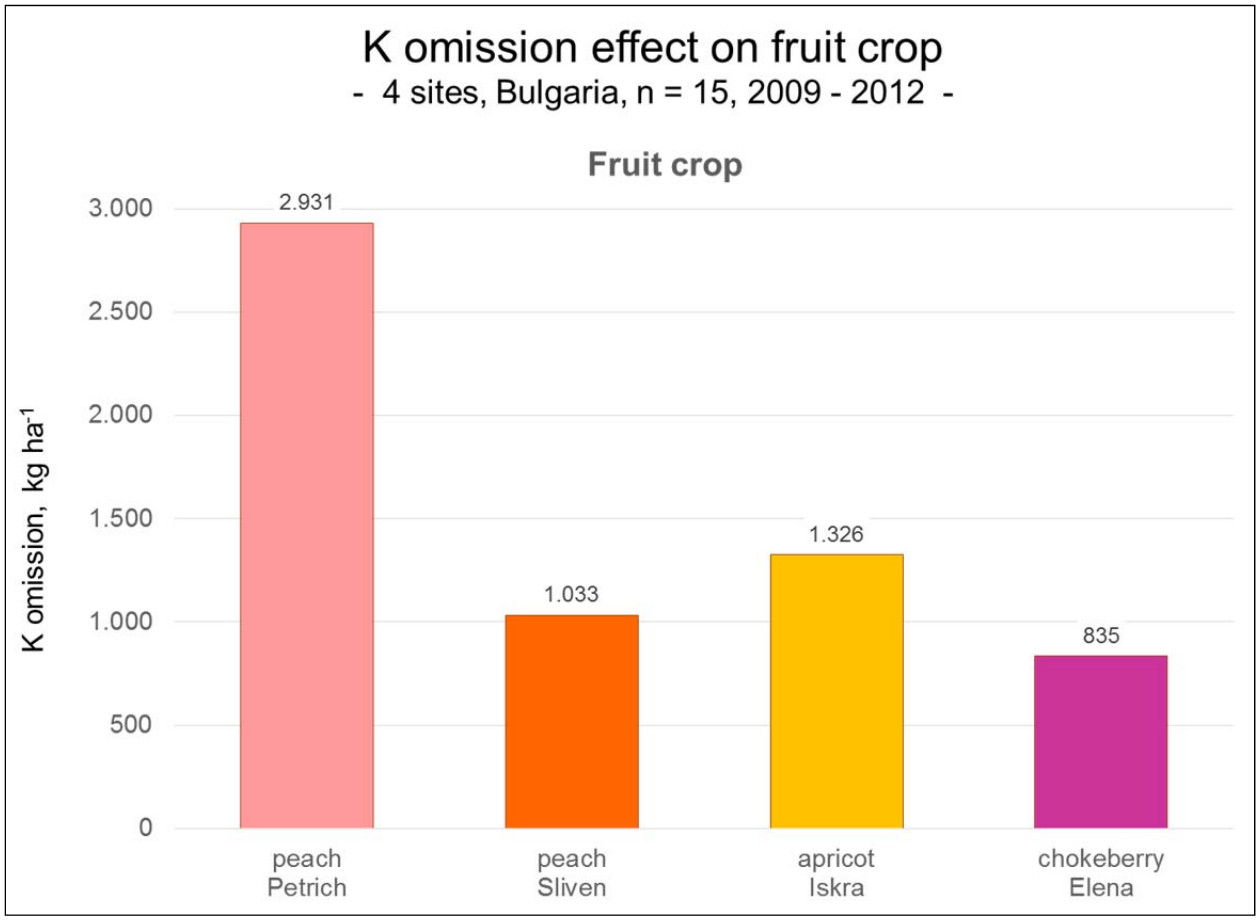

Figure 6. K omission effect on fruit crops

Deep Banding P Improves Access to K in Central Queensland Cropping Systems

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Abstract
Central Queensland in Australia has a strong summer dominant rainfall pattern and opportunity cropping systems are based on stored soil water. Because there has been little fertilizer use since clearing, the subsoils in particular have become nutrient depleted.

Two field experiments were established to investigate the immediate and then residual benefit of deep placed (20 cm) nutrients (40 kg P/ha, 200 kg K/ha, 40 kg S/ha). Nitrogen was managed seasonally and some crops had starter P but no further K or S fertilizers were added. The Capella site (chickpea 2012, wheat 2013, chickpea 2014, sorghum 2015, chickpea 2016)) and the Gindie site (sorghum 2011, chickpea 2013, sorghum 2015, chickpea 2016) were assessed for yield and nutrient uptake and removal.

The combined presence of P and K increased K uptake compared to K alone on one site where P was likely more limiting than K. Since 2011, when the nutrients were supplied alone the total yield increases over the control were 11% and 2% to K alone, and 6% and 9% to P alone at the Gindie and Capella sites respectively. However, when P and K were supplied together, yields increased by 20% and 10% at the two sites. When compared to the control treatments, the combined presence of P and K showed synergy in nutrient uptake, with more K uptake when supplied together compared to being supplied individually. Results varied with seasonal conditions, they do show that the banded nutrients were accessed and yield responses to deep placed P and K were durable over time. It is suggested that critical soil test values may need to consider season, rooting volume and crop species, as well as soil nutrient concentrations.

Keywords: Nutrient uptake, cropping systems, nutrient placement, chickpea, sorghum, wheat.

INTRODUCTION

The northern Australian cropping region covers around 4Mha and is characterized by summer rainfall on relatively heavy soils (Vertosols), which support summer crops (sorghum, mung bean) and winter crops (wheat, barley, chickpea) growing on incident or stored soil water respectively. The cropping system is largely opportunistic and selection is largely based on the risk of failure due to drought. Winter crops are sown when there is adequate stored soil water such as following a summer fallow, while summer crops are sown when the first summer rains occur which (hopefully) signal the start of the wet season.

Large scale broad acre cropping commenced in Central Queensland in the 1950's and since the 1980's has been based on zero-tillage, controlled traffic and crop residue retention. Native soil fertility was high, especially on the Vertosols, but this has declined over time such that a significant proportion of the crop nitrogen (N) requirement is now supplied by fertilisers (Dalal and Probert 1997). The reliance on stored subsoil water by winter crops means that roots growing in the moist subsoil exploit largely immobile K and P from that layer, while the drier topsoil reserves are not used. Unless deep soil samples are taken, these deficiencies can go undetected.

Over the long term that has been little P or K used, with the consequence that the exports of P and K are significant and improved crop management has raised yields but also increased nutrient export. The removal of crop nutrients depends on the grain concentration and yield, with average rates P removal are around 2.9-3.2 kg P/t of grain for wheat, sorghum and chickpea, but K removal in chickpea (11.0 kg K/t) was at least twice that for wheat (4.1 kg K/t) and sorghum (3.1 kg K/t (Bell and Moody 2001). On average, cropped soils across all these northern regions contained 55% (±5%) of the exchangeable K reserves of the uncropped reference sites. This depletion is resulting in increasingly complex nutrient management decisions for growers (Bell et al. 2010, 2012). These results clearly confirm the impacts of multiple nutrient depletion and therefore declining soil fertility and so current research is evaluating strategies such as deep placement of K to address nutrient stratification.

Because these systems are zero-tilled, there is little or no vertical mixing of the drier top soil layers, so immobile nutrients such as P and K can become depleted in the subsoil. Because of cycling of K, in particular, to the surface, the topsoil can become enriched with K rich crop residues, and reserves held there not fully exploited because this top layer is usually dry during the winter cropping season. The seasonal wetting and drying pattern of the soil, which in turn drives root growth and nutrient removal further exacerbates the stratification of nutrients in the profile. The drier topsoils (0-10 cm) may show adequate soil test values, but extractable K in the subsoil (10-30 cm) needs to be measured to determine K availability for crop growth (Bell et al. 2009, Moody et al. 2010). Revised soil testing protocols to take account of stratified nutrients have been proposed in some regions (Brennan and Mason 2006).

In response to these challenges, the hypothesis was developed that relatively high rates of nutrients could be place in the subsoil (10-30 cm) to provide for several crop phases. Even though the initial disturbance would be significant, the idea was to make adequate nutrient available for several crops so that in the intermediate period the field could be undisturbed. The experiments reported here aimed to assess the long-term responses to P, K and S, alone and in combination, when placed at ~20 cm deep.

METHODS

Sites were selected in farmer's paddocks at Gindie (23.0724^{o}S, 148.142^{o}E, approx. 22 km south of Emerald) and Capella (23.086^{o}S, 148.023^{o}E, approx. 50 km north of Emerald) in central Queensland, Australia. Both sites had low P, K and S soil test values, especially in the subsoil layers (Table 1). The experiments were established by deep banding (~20 cm deep) P (40 kg P/ha), K (200 kg K/ha) and S (30 kg S/ha) alone and in combination, and comparing performance to a deep ripped treatment with no nutrients (control). The experiment was designed with 12 controls per site and six replicates of each treatment arranged in a randomised complete block.

Deep banding occurred during the 2011winter fallow and the bands were 50 cm apart. The sites were sown and managed by the farmer as they would for the rest of the field, with crop selection and agronomic management following normal commercial practice for that soil type and region.

At peak growth, biomass samples were taken to estimate crop growth and nutrient acquisition. Yield and grain nutrient concentration were also take by hand sampling to determine economic performance and nutrient removal. Crop sequences to date have been chickpea-wheat-chickpea-sorghum-chickpea and sorghum-chickpea-sorghum-chickpea at Capella and Gindie, respectively. No additional deep nutrients were provided after the initial treatments were applied, although some in-furrow fertilizers were applied at crop seeding, and this was across all experimental treatments. In-crop nitrogen was managed by the grower-co-operator and this was done across all treatments.

RESULTS AND DISCUSSION

The soil test values for the two sites (Table 1) indicate low to very low Colwell P values, below the 95% critical soil test range for sorghum (17-30 mg/kg), field pea (21-28 mg/kg) and wheat (18-30 mg/kg) (Bell

et al. 2013a, Bell et al. 2013b), while the ex-K values are around the critical soil test range for northern Vertosols (~0.4-0.6 cmol(+)/kg), (Guppy pers. comm.) at Gindie and Capella. The sulfur soil test values are near the critical range (2.4-3.2 mg/kg, Anderson et al. 2013), and so these sites reflect those with multiple subsoil deficiencies (Bell et al. 2010), although the K limitation is likely larger at the Gindie site than the Capella site.

The grain yields over the nine site years are summarized in Table 2. At neither site there was a significant response to S alone in any of the crops other than in the wheat crop in 2013 at Capella. At Capella, P alone showed a strong response in the first and second year crops, but not in the subsequent crops. The response to K alone was significant only on the 2013 wheat crop, however when P and K were supplied together (as PK or PKS) the numerically highest yields were seen in four of the five crops at Capella. Similar patterns were seen at Gindie in the first two crops, with combined P and K giving the highest yields, but in the 2014/15 sorghum K rather than P dominated this response. Yields from the 2016 chickpea crop (as yet not statistically analysed), there appears to be an additive response to the P and K treatments at the Capella site, but this was not seen at the Gindie site in this crop in 2016.

Results have differed between sites and years, and among crops at a site and because these aspects are confounded, so it is not possible to assess the responses due to crop differences alone. It has been reported that chickpea can mobilize soil organic P due to phosphatase root exudates (Li et al. 2004), which may be a reason for the declining P responses seen in the rotations reported here. The additional uptake of P into the crop due to the presence of deep banded P was around 5 to 6 kg P/ha higher at both sites (Figure 1) with the largest differences in the first year. So, access had improved, but there would still be a large reserve of the 40 kg/ha deep banded P still in the soil.

The synergistic effect of having both P and K supplied was clear at the Capella site, with crop K uptake almost 50 kg K/ha higher over the first three crops where both were supplied compared to when K and P were supplied separately. Based on soil test values, this site was less K and more P constrained than the Gindie site, so that the added P could have stimulated roots to proliferate so that more of the banded K could be accessed. The importance of combined P and K supply shows up in crop yields from both sites. In terms of yields (Table 2), the synergy appears most strongly at Capella for four of the five crops and at Gindie for the first two crops. Even though K removal is modest (data not presented), the K taken up by the crops is likely moved from the subsoil to the topsoils which further exacerbates the positional unavailability of K in these systems.

The effect of season on accessing deep P and K is also likely to be important, with root activity likely near the bands when the soil profile was wet enough. In the initial crop year, with good moisture availability, both sites showed a 20% grain yield response to deep P. In the much drier 2013 season (no in-crop rainfall after planting), effects of deep P were still evident at both sites (14% in Gindie chickpeas and 8% in Capella wheat), but effects of K were clearly evident only at Gindie. There was a suggestion of an additive P+K effect at Capella and a very significant additive effect of P+K at Gindie. The Gindie site was particularly interesting, as while the only nutrient limit at that site in the previous sorghum crop was P, the 2013 data suggest K availability was a greater limitation in the 2016 chickpea crop (14% response to P but 27% response to K), while the additive effects of residual P and K were substantial (51% grain yield increase).

The good responses to deep banded K in 2013 could be a consequence of the dry season (no in-crop rainfall) so that shallow soil K reserves were not accessible. Chickpeas at Capella in 2014 (also a dry year) showed a response to P and K together, rather than when they were supplied alone. At Gindee, the sorghum crop did not respond to added P, although the K responses were still sustained. Wetter soil profiles enable more root exploration of the soil volume so that the crop has access to larger amounts of background K that where profiles are drier or otherwise constrained. Other factors such as row spacing

and rooting patterns may affect the response to deep K, but these data illustrate that as soils reserves decline, it is essential to supply the right combination of fertiliser nutrients in the right place to maximise crop productivity and seasonal water use efficiency.

CONCLUSIONS

Deep placed nutrients, in this case P and K at 20 cm, showed synergistic responses over a range of crops and environmental conditions. Responses were more apparent in drier years where crop roots drew water and nutrients from the subsoils rather than from a larger soil volume.

The results also illustrate that root access to soil volume could enable plants to access adequate P and K even though the nutrients are at low concentrations. So modifying critical soil test values may need to consider season, rooting volume and crop species, as well as soil concentrations.

These responses were seen in different crops for six of the nine site-years of the experiments. These results support the feasibility of deep placement of nutrients at the start of a cropping cycle to meet nutrient demands in this opportunity cropping system.

ACKNOWLEDGEMENTS

This research is supported by the Grains Research and Development Corporation, Canpotex P/L (through Agrow P/L), the University of Queensland and the Queensland Department of Agriculture and Forestry. The enthusiastic collaboration of the landholders who provided the sites is also acknowledged.

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Table 1. Soil test values at the start of the experiments at Gindie and Capella central Queensland.

		Gindie		Capella	
Analyte	unit	0-10 cm	10-30 cm	0-10 cm	10-30 cm
pH ($CaCl_2$)		7.2	7.8	8.1	8.3
CEC	cmol(+)/kg	35.3	38.4	73.7	74.6
OC	%	0.6	0.5	0.7	0.7
Colwell P	mg/kg	13	<5	10	<5
BSES-P	mg/kg	10	5	14	9
Ex-K	cmol(+)/kg	0.17	0.07	0.46	0.16
KCl-40 S	mg/kg	3	2	3	2
DTPA Zn	mg/kg	0.2	0.1	0.3	0.1

Table 2. Grain yields (t/ha) for crops grown with the various deep placed nutrition 2011 to 2016.

Site and crop/year	Control	K	P	S	PK	PS	KS	PKS	LSD (P<0.05)
'Stranraer' Capella									
Chickpea 2012	2.33	2.34	2.75	2.32	2.89	2.79	2.30	2.83	0.17
Wheat 2013	2.08	2.19	2.25	2.19	2.36	2.25	2.20	2.34	0.09
Chickpea 2014	1.51	1.59	1.57	1.53	1.69	1.65	1.60	1.75	0.10
Sorghum 2015	3.05	3.10	3.10	3.10	3.06	3.16	3.10	3.22	ns
Chickpea 2016	2.37	2.36	2.36	2.32	2.46	2.57	2.33	2.62	0.12
'Bendee' Gindie									
Sorghum 2011/12	2.32	2.39	2.78	2.36	2.90	2.81	2.35	2.81	0.14
Chickpea 2013	1.15	1.47	1.32	1.21	1.74	1.18	1.52	1.61	0.26
Sorghum 2014/15	2.94	3.40	2.99	2.90	3.38	3.25	3.19	3.25	0.20
Chickpea 2016	2.35	2.48	2.45	2.43	2.49	2.41	2.23	2.40	†

† Final statistical analyses not completed at the time of publication.

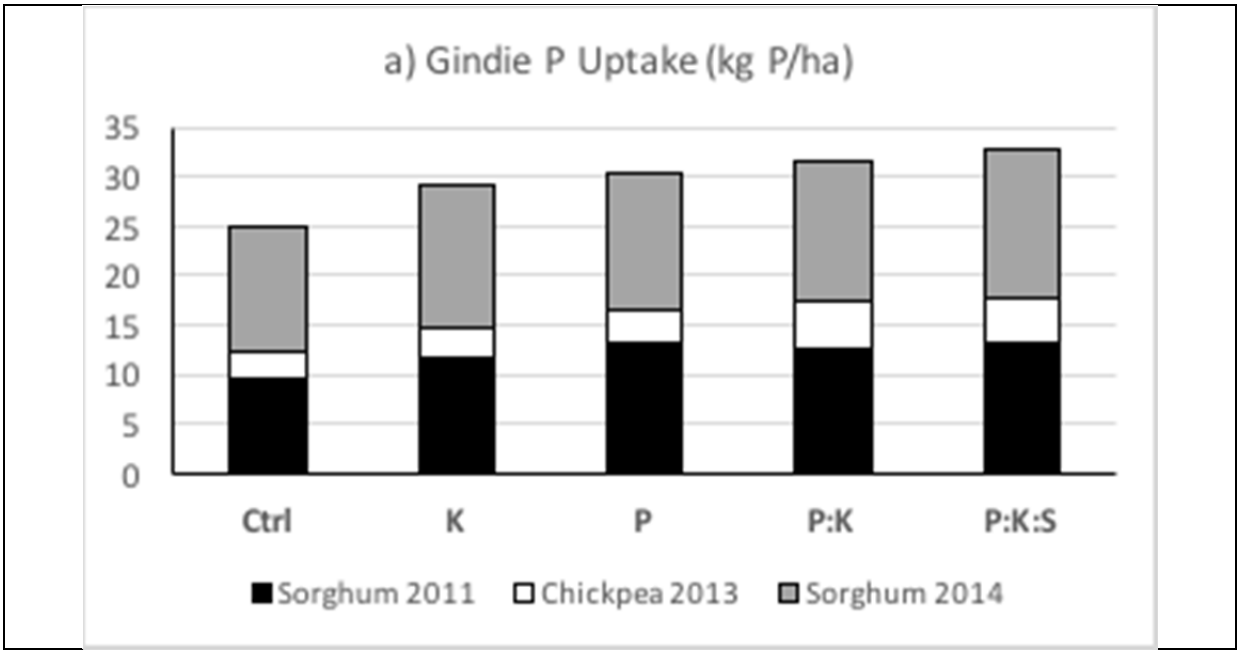

Figure 1a. Uptake of P in total dry matter in response to deep placed nutrients at Gindie in 2011, 2013 and 2014. Standard errors of the means in 2011 are Control ±0.5, treatments ±0.9; for 2013 Control ±0.3, treatments ±0.4; for 2014 Control ±0.6, treatments ±1.0.

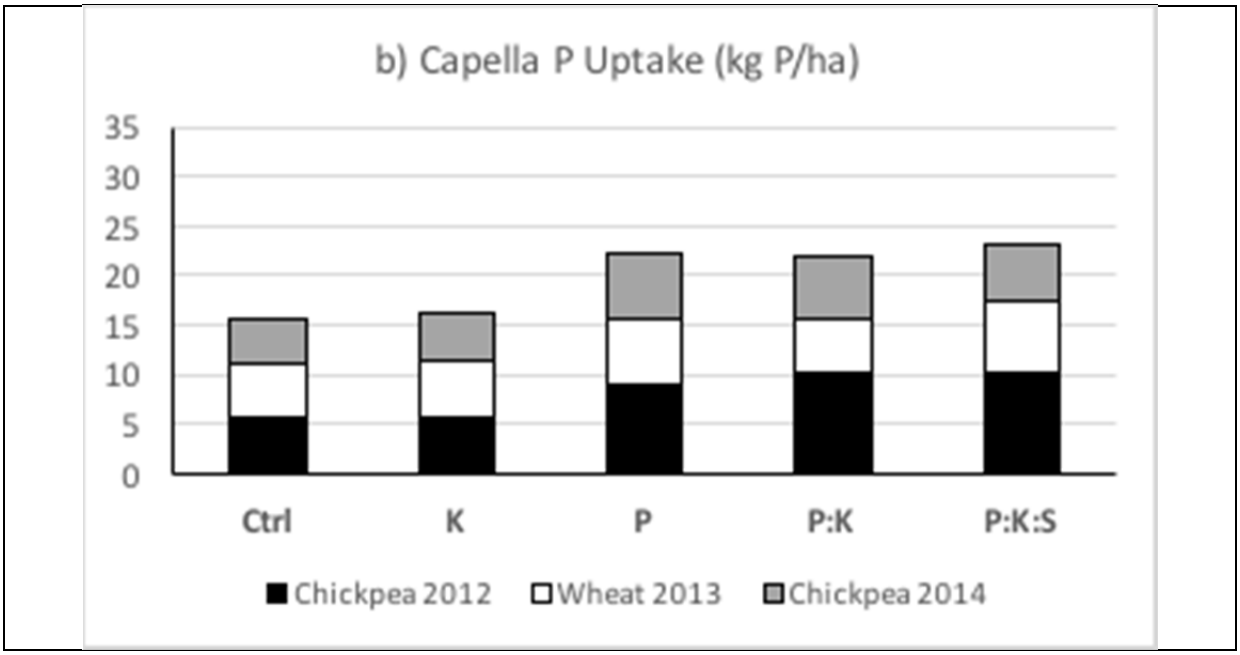

Figure 1b. Uptake of P in total dry matter in response to deep placed nutrients at Capella in 2012, 2013 and 2014. Standard errors of the means in 2011 are Control ±0.2, treatments ±0.4; for 2013 Control ±0.3, treatments ±0.6; for 2014 Control ±0.2, treatments ±0.3.

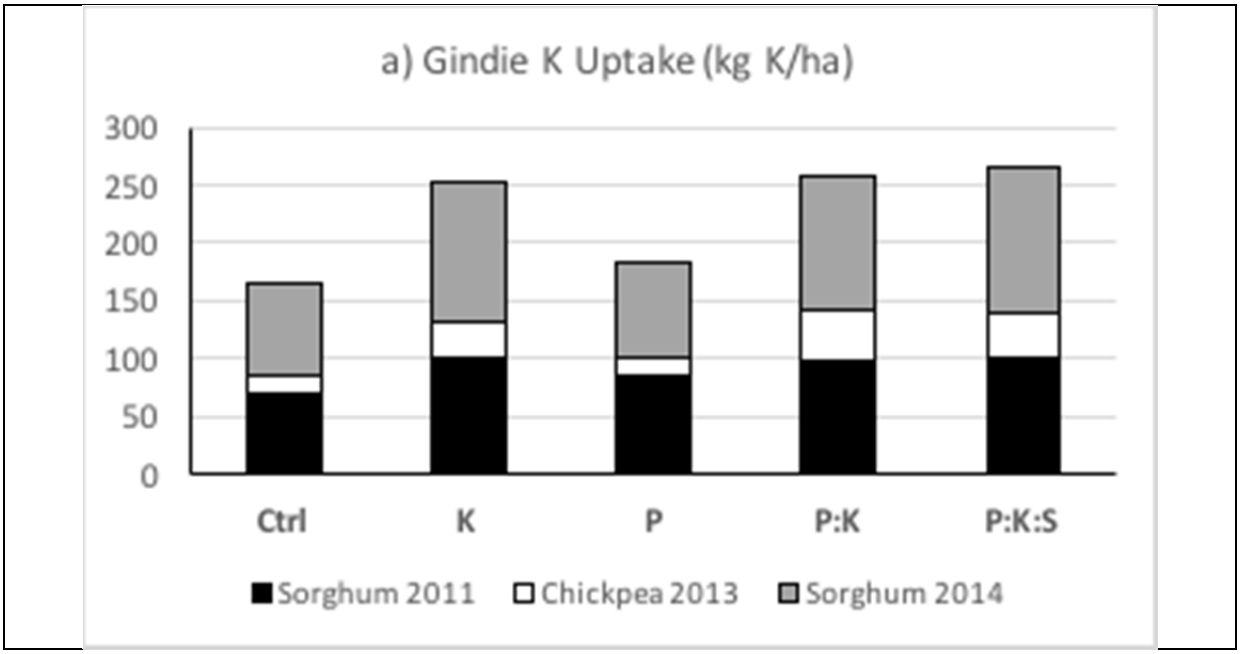

Figure 2a. Uptake of K in total dry matter in response to deep placed nutrients at Gindie in 2011, 2013 and 2014. Standard errors of the means in 2011 are Control ±1.9, treatments ±3.2; for 2013 Control ±1.9, treatments ±3.2; for 2014 Control ±0.7, treatments ±1.3.

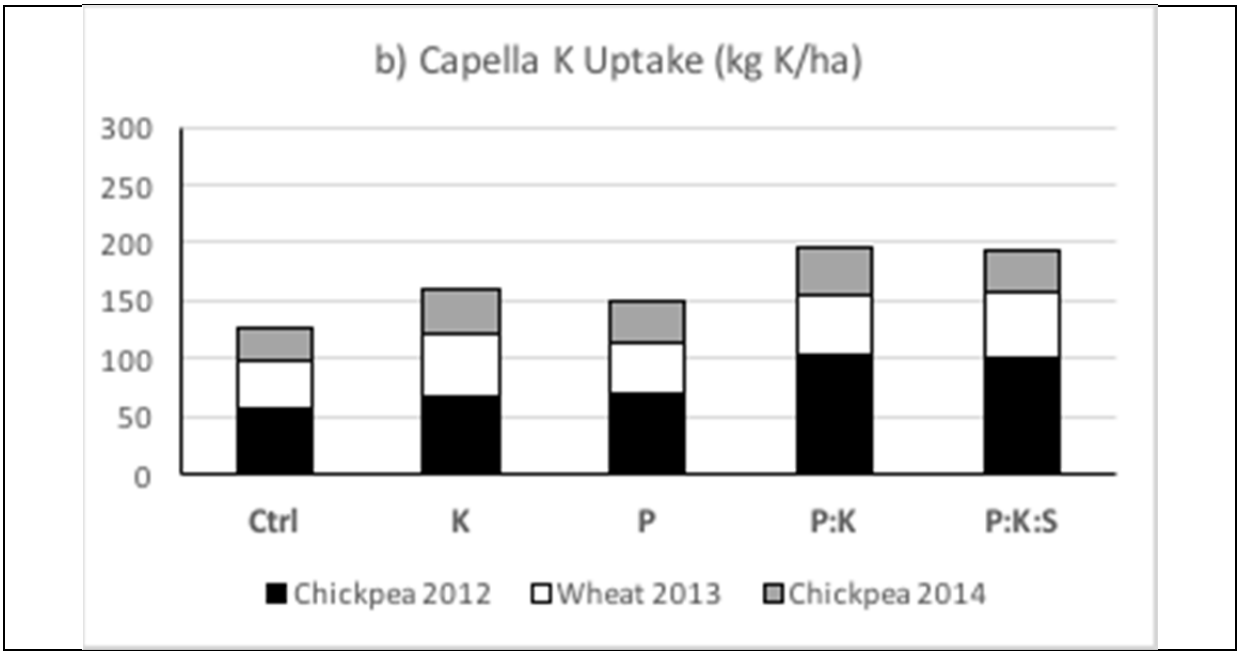

Figure 2b. Uptake of K in total dry matter in response to deep placed nutrients at Capella in 2012, 2013 and 2014. Standard errors of the means in 2011 are Control ±4.5, treatments ±7.5; for 2013 Control ±2.9, treatments ±4.8; for 2014 Control ±4.3, treatments ±7.1.

Potential Saving of Potassium Requirement on Oil Palm Planted Over Marine Alluvial Soil

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BACKGROUND

Potassium are essentially required in a minimum quantity that is adequate for the basic biochemical functions of the oil palm. Adequate availability of nitrogen and phosphorus would thus seem to be more important for the production of oil palm fruit bunches in the presence of just sufficient quantity of potassium for essential physiological processes. To come out with basis of potassium rate for oil palm planted on coastal marine alluvial soil, two experiments were laid out in order to determine the optimum requirement and its effect on oil palm growth and yield performance.

EXPERIMENT 1

This experiment was designed to study the potassium requirement of oil palms planted on marine alluvial soil. It was conducted in field OP1986 of East Estate, Carey Island. The trial commenced in October 1988 and was concluded in December 1997. Nevertheless, it was extended to study on residual effect of K manuring until 2004. Yet, the treatment effect was reviewed up till 1997.

Experimental design for this trial is split plot arranged in Randomized Complete Block Design (RCBD) with 4 replications. The main treatment for this trial is Muriate of Potash (MOP) rate while Urea + Rock Phosphate (RP) rates as the sub treatment (Table 1).

RESULT & DISCUSSION

There is no significant difference on Fresh Fruit Bunch (FFB) yield between the treatments. However plots receiving 3 kg MOP/palm/yr gave the highest FFB yield in main treatment while N3P3 gave the highest FFB yield among the sub treatments (Table 3).

The cumulative Average Bunch Weight (ABW) from 1989 until 1997 showed no significant difference among the main and sub treatments. However, treatment with 3 kg MOP/palm/yr gave the highest ABW in main treatment while N3P3 gave the highest ABW among the sub treatments (Table 4).

Cumulative bunch number (no./palm) indicated no significant difference for all main and sub treatments. However, the highest bunch number was recorded in plots receiving 3kg MOP/palm/year while treatment N3P3 recorded highest bunch number as compare to other sub treatments (Table 5). For bunch weight, there was no significant difference observed for all the treatments. Nonetheless, treatment with 3 kg MOP/palm/yr gave the highest bunch weight in main treatment while treatment N3P3 gave the highest bunch weight in sub treatment (Table 6).

In conclusion, no significant difference was observed in all the parameters recorded among the treatments. However, total bunch weight was significantly higher in treatment receiving 3kg MOP with 2kg Urea and 1.5kg RP. Based on the trial, 3kg MOP with 2kg Urea and 1.5kg RP resulted in better yield throughout the trial period.

EXPERIMENT 2

Another experiment was designed to investigate the effect of different potassium manuring practices on oil palm performance. The trial was established in East Estate, Field OP1988P1. The trial design was

Randomized Complete Block Design (RCBD), using 18 recording palms with 6 replications. Four treatments were evaluated during course of the trial. Table below showed the period of the treatments.

RESULT & DISCUSSION

No significant different was noted on the bunch weight recorded from 1992 to June 2001 except in year 1994 where treatment D recorded the lowest result as compare to other treatments (Table 7). All treatments indicate an increasing pattern from 1992 to 1994 but dropped drastically in the following year. Cumulatively, the highest bunch weight was recorded in Treatment B.

Generally, the result on bunch number shows no significant different between treatments except in year 1996 whereby bunch number in treatment A significantly higher from other treatments (Table 8). It was noted that the bunch number from all treatments were increased from 1992 to 1993 but slightly dropped in year 1994. However, drastic declination of bunch number was noted in the following year up to year 2000.

Comparable result was recorded on FFB yield throughout the year except in 1994 (Table 9). All treatments showed an increasing pattern from 1992 to 1994. However, in 1995, the FFB yield dropped drastically followed by sudden increased in the next year. Although there was no significant different in cumulative yield, Treatment B gave slightly higher FFB than the other treatments. This was attributed to higher bunch weight and bunch number.

There was no significant different in ABW among the treatments (Table 10). It was noted that in 1992, the results for Treatment A, B and D were within the range of 5-6 kg as compared to Treatment C with ABW recorded in double digit. This was attributable to human error during data entry whereby 65kg bunch weight was recorded for a single bunch in third replication of Treatment C.

Generally, based on the cumulative results of bunch weight, bunch number and FFB yield indicates that there are no response of Potassium fertiliser to the yield component. However, alternate application (Treatment B) of potassium fertiliser gave the highest bunch weight, bunch number and FFB yield throughout the period of the treatments.

CONCLUSION

Based on the results obtained from both experiments, Sime Darby Plantation have come out with standard baseline fertiliser rates specifically for coastal environment ranging from 1.50kg/palm/year up to 2.50kg/palm/year according to age profile (Table 11).

From this practice, significant amount of saving could be materialised through optimum potassium application with relation to other major nutrients against normal fertiliser regime applied for inland environment (Table12).

Table 1: Design for Experiment 1

MOP rate (kg/palm/yr)		Urea + Rock Phosphate (kg/palm/yr)	AS Equivalent (21% N) kg/palm
A. 0		1. $N_{1(0.7)}P_{1(1.0)}$	1.50
B. 1		2. $N_{2(1.4)}P_{2(1.0)}$	3.00
C. 3	x	3. $N_{3(2.0)}P_{3(1.5)}$	4.38
D. 6		4. $N_{4(2.7)}P_{4(2.0)}$	6.00

Extra plots: zero N, P, K.

Table 2: Design for Experiment 2

	Period of Treatment			
Code	Aug'90 -Aug'92	Sept'92 -Aug'96	Sept'96 -Aug'98	Sept.'98 -Jun'01
A	0K	0K	0K	0K
B	0K	+K	0K	+K
C	+K	0K	+K	0K
D	+K	+K	+K	+K

Note: 0K – no potassium application
+K – with potassium application

Table 3: Fresh Fruit Bunch per hectare (tonne)

Treatment MOP (kg/palm/yr)	**1989-1997**	**3'99-12'99**	**2000**	**2001**	**Cumulative**
0	242.81	19.92	23.80	6.68	293.21
1	245.43	19.61	26.04	7.19	298.27
3	251.48	20.55	26.55	7.26	305.83
6	243.07	19.61	25.62	6.20	294.50
S.E	3.323	0.864	0.769	0.563	3.946
P-Value (ANOVA)	N.S	N.S	N.S	N.S	N.S
Urea + RP (kg/palm/yr)					
N1P1	247.50	19.95	25.02 A B	6.26	298.73
N2P2	240.25	20.70	27.06 A	6.34	294.35
N3P3	250.59	19.93	26.00 A B	7.26	303.78
N4P4	244.45	19.11	23.93 B	7.46	294.96
S.E	3.323	0.864	0.769	0.563	3.946
P-Value (ANOVA)	N.S	N.S	0.0393	N.S	N.S
C.V %	5.50	18.60	14.04	37.41	5.52

Table 4: Average bunch weight (kg)

Treatment MOP (kg/palm/yr)	1989-1997	3'99-12'99	2000	2001
0	11.39	19.49	19.90	18.85
1	11.43	19.98	19.71	18.21
3	11.68	20.24	19.79	17.96
6	11.38	20.10	19.89	17.53
S.E	0.108	0.254	0.325	0.514
P-Value (ANOVA)	N.S	N.S	N.S	N.S
Urea + RP (kg/palm/yr)				
N1P1	11.46	20.12 A B	19.50	17.76
N2P2	11.51	20.41 A	20.02	17.70
N3P3	11.53	20.01 A B	19.83	19.09
N4P4	11.37	19.28 B	19.94	18.00
S.E	0.108	0.254	0.325	0.514
P-Value (ANOVA)	N.S	0.0213	N.S	N.S
C.V %	3.94	5.85	6.79	11.50

*Treatments not connected by same letter are significantly different. (Tukey Test)
*1989-2000: Calendar Year (Jan-Dec)
*2001: Jan – Jun (6 months)

Table 5: Bunch number (no./palm)

Treatment MOP (kg/palm/yr)	1989-1997	3'99-12'99	2000	2001	Cumulative
0	156.9	7.6	8.9	2.8	176.0
1	158.1	7.3	9.7	2.9	177.9
3	158.4	7.5	10.0	3.0	178.7
6	157.3	7.1	9.6	2.6	176.6
S.E	2.10	0.31	0.34	0.21	2.47
P-Value (ANOVA)	N.S	N.S	N.S	N.S	N.S
Urea + RP (kg/palm/yr)					
N1P1	158.9	7.4	9.4	2.6	178.3
N2P2	153.5	7.4	10.0	2.7	173.6
N3P3	159.8	7.3	9.8	2.9	179.8
N4P4	158.5	7.4	9.1	3.1	177.7
S.E	2.10	0.31	0.34	0.21	2.47
P-Value (ANOVA)	N.S	N.S	N.S	N.S	N.S
C.V %	5.24	18.65	16.26	34.25	5.51

Table 6: Bunch weight (kg/palm)

Treatment MOP (kg/palm/yr)	1989-1997	3'99-12'99	2000	2001	Cumulative
0	1785.35	146.49	174.99	49.11	2155.94
1	1804.66	144.23	191.48	52.84	2193.18
3	1849.11	151.08	195.22	53.39	2248.78
6	1787.28	144.22	188.40	45.59	2165.46
S.E	24.435	6.348	5.656	4.139	29.02
P-Value (ANOVA)	N.S	N.S	N.S	N.S	N.S
Urea + RP (kg/palm/yr)					
N1P1	1819.84	146.74	183.95 A B	46.04	2196.52
N2P2	1766.52	152.21	198.96 A	46.65	2164.33
N3P3	1842.57	146.54	191.20 A B	53.38	2233.65
N4P4	1797.48	140.53	175.99 B	54.88	2168.86
S.E	24.435	6.348	5.656	4.139	29.02
P-Value (ANOVA)	N.S	N.S	0.0393	N.S	N.S
C.V %	5.50	18.60	14.04	37.41	5.52

Table 7: Bunch weight (kg/palm)

Treatment	1992	1993	1994	1995	1996	1997	1998	Mar-Dec'99	2000	Jan-Jun'01	Cumulative
A	70.44	214.19	269.81 A	170.59	202.43	200.40	216.19	193.99	196.85	89.06	1823.94
B	67.35	206.50	267.01 A	180.65	192.63	213.54	210.15	194.74	201.64	95.38	1829.59
C	65.20	222.35	262.29 A B	185.75	188.59	208.02	197.99	192.07	201.03	96.03	1819.31
D	61.13	194.88	229.34 B	179.49	183.16	198.94	198.15	198.40	193.87	99.63	1737.01
S.E	5.31	7.89	9.49	5.29	6.24	8.16	6.25	7.88	6.77	4.65	36.59
P-Value (ANOVA)	N.S	N.S	0.0194	N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S
C.V %	23.09	11.80	12.78	9.35	11.31	10.35	9.15	11.04	9.44	13.03	6.68

Table 8: Bunch Number per Palm

Treatment	1992	1993	1994	1995	1996	1997	1998	Mar-Dec'99	2000	Jan-Jun'01	Cumulative
A	12.6	26.9	26.0	18.4	17.3 A	14.1	12.6	10.3	9.6	5.0	152.8
B	11.8	26.6	25.9	20.3	16.8 A B	15.1	12.9	10.8	10.3	5.1	155.4
C	10.6	26.5	25.4	19.8	15.7 A B	14.7	11.7	10.3	9.8	5.2	149.5
D	11.3	23.9	22.9	19.9	15.8 B	14.1	12.4	11.3	9.8	5.5	146.5
S.E	1.02	0.92	0.92	0.53	0.38	0.53	0.37	0.50	0.29	0.34	2.25
P-Value (ANOVA)	N.S	N.S	N.S	N.S	0.0218	N.S	N.S	N.S	N.S	N.S	N.S
C.V %	24.93	10.84	11.10	7.52	8.96	8.91	8.89	12.59	8.25	16.67	5.00

Table 9: Fresh Fruit Bunches/Ha

Treatment	1992	1993	1994			1995	1996	1997	1998	Mar-Dec'99	2000	Jan-Jun'01	Cum
A	9.58	29.13	36.70	A		23.20	27.53	27.26	29.40	26.38	26.77	12.11	248.06
B	9.16	28.09	36.32	A		24.57	26.20	29.04	28.58	26.49	27.42	12.97	248.83
C	8.87	30.24	35.67	A	B	25.27	25.65	28.29	26.93	26.12	27.34	13.06	247.42
D	8.31	26.50	31.19		B	24.41	24.91	27.05	26.95	26.98	26.37	13.55	236.23
S.E	0.722	1.073	1.290			0.719	0.849	1.110	0.850	1.072	0.921	0.632	4.975
P-Value (ANOVA)	N.S	N.S	0.0194			N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S
C.V %	23.09	11.80	12.78			9.35	11.31	10.35	9.15	11.04	9.44	13.03	6.68

Table 10: Average Bunch Weight (kg)

Treatment	1992	1993	1994	1995	1996	1997	1998	Mar-Dec'99	2000	Jan-Jun'01
A	5.62	7.98	10.43	9.26	11.81	13.98	17.23	19.15	20.27	18.35
B	5.69	7.78	10.36	8.92	11.52	13.98	16.44	18.22	19.86	19.03
C	11.10	8.43	10.41	9.41	11.95	14.09	16.75	19.05	20.56	18.51
D	5.55	8.18	9.95	9.04	11.43	14.12	15.89	17.70	19.88	18.48
S.E	2.847	0.231	0.197	0.171	0.244	0.378	0.366	0.458	0.350	0.353
P-Value (ANOVA)	N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S
C.V %	110.97	7.67	5.77	5.66	5.79	7.31	7.14	7.84	4.64	5.40

*Treatments not connected by same letter are significantly different (Tukey Test).
*Only 10 months available data for 1999 (Mar-Dec)

Table 11: Average fertiliser rate on coastal soil

Year	Fertiliser Quantity (kg/palm/year)		
	Ammonium Sulphate	Rock Phosphate	Muriate of Potash
4 - 5	4.00	2.00	2.25
6 – 15	4.75	2.00	2.50
16 – 20	4.75	2.00	2.00
>20	4.00	1.00	1.50

Table 12: Potential saving from MOP reduction

MOP cut (kg)	New Average Application Rate kg/palm/yr	Total Saving MOP(ton)/ha@ 140 sph	Potential Monetary Saving (RM Million) @ RM1400/ton MOP
0.5	2.0	3500	4.9
1.0	1.5	7000	9.8
1.5	1.0	10500	14.7
2.0	0.5	14000	19.6
2.5	0.0	17500	24.5

Sub-surface Drip Fertigation Proved to be the Right Method of K Application in Sugarcane

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Abstract
India is the second largest sugar producer in the world, contributing to 25% global sugarcane production. The country has to produce 28 million t of sugar by 2020 to meet the future demand of growing population and the current productivity of 66.4 t ha^{-1} has to increase significantly to overcome this challenge. Previous study in India indicated that farmers hardly apply potassium while growing sugarcane, resulting in 14% (12.4 t ha^{-1}) yield decline. Study conducted in farmer's field of Tamil Nadu, India compared three methods of K application, sub-surface drip fertigation (SSDF), surface drip fertigation (SDF) and conventional soil application (Check). The experiment was laid out in a randomized block design, consisting of 11 treatments with variable fertigation options and 3 replications. A dose of 150 kg ha^{-1} K_2O through SSDF/SDF and 200 kg ha^{-1} K_2O to check was applied along with recommended rates of N and P to all the treatments. Along with other nutrients, K was applied through drip irrigation at an interval of 7 days during 15-210 days of crop growth in SSDF and SDF, whereas in Check, K was applied to the soil in equal splits at 30, 60, and 90 days after planting.

Significantly highest cane yield was recorded in SSDF (194 t/ha) followed by SDF (175 t/ha), which was 98 and 78% higher than check. The highest yield in SSDF was due to right placement of K, which resulted in maintenance of soil nearer to field capacity throughout the growth period in the active root zone which enabled better water utilization and high K uptake by sugarcane. The net profit obtained by farmers under SSDF was US$ 922 ha^{-1}, which was 1.8 times higher than the conventional method of K application. The study also showed higher PFP_K (1293 kg cane yield kg^{-1} K applied) due to SSDF, indicating an improved K use efficiency with right K placement.

Status of Potassium in Intensively Cultivated Soils of Kathmandu Valley

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Abstract

Five soil profiles were opened at different land uses in Kathmandu Valley. They were taxonomically classified as Typic Ustochrept, Dystric Ustochrept, Fluvaentic Ustochrept, Typic fluvaqents and Aquic Ustochrepts. Their fertility was evaluated using standard guidelines. Different forms of potassium were extracted using 0.5N HCl, 1N NH_4OAc, $BaCl_2$ and H_2O. The extracted values were correlated with each other. Potassium extracted by NH_4OAc (0.931) and $BaCl_2$ (0.934) were best correlated with 0.5N HCl. Only the Shankamul soils differed from the other soils in extracted K. Potassium from the rest of the soil profiles was at par with each other. Considering the status of K in different soils, highest nonexchangeable (0.5N HCl) content of 1508 mg k/kg was observed in Shankhamul soil (Fluventic Ustochrept) and the lowest amount was observed in H_2O (3.38 mg/kg) extracted Kw in Bungmati soil (Typic Ustochrept). Only Thimi soils (Typic Fluvaquents) had sufficient exchangeable K and Shankhamul soil had high exchangeable K. Rest of the soils (Typic Ustochrept, Dystric Ustochrept and Aquic Ustochrepts) had insufficient exchangeable K. The amount of nonexchangeable K in these soils was not high. Therefore, external application of K in the form of fertilizer is necessary to balance the requirement of this element in these soils.

Keywords: land use, Nepal potassium, soils

Potassium Application for Enhanced Growth and Fe-Zn use Efficiency of Salt-resistant and Sensitive Maize Genotypes in Response to Salinity

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Abstract

The status of mineral nutrients in plant body is important in determinging its behaviour to environmental stresses. Along with other mineral nutrients, potassium plays in important role in its performance under salt stress condition. A high K^+/Na^+ is required for maintenance of turgor, and cell osmoregulation, stomata opening and closing, synthesis of protein and photosynthesis. This study reports the effect of K application on the growth and Fe-Zn use efficiency of salt-resistant and sensitive maize genotypes (EV-5088 and Pak-Afgoee, respectively) in response to salinity. The treatments included different levels of NaCl (0 or 100 mM) and potassium (1x or 1.5x of Hoagland nutrient solution). The results showed that potassium had a significant ($P<0.05$) role in alleviation of the effect of salinity on maize crop at vegetative growth stages. Salt stress decreased the shoot fresh and dry weight, root and shoot length but this reduction was less with the application of potassium. In saline conditions, low leaf K^+ concentration was observed where as high Na^+ concentration was observed in both the genotypes. Salt-resistant genotype (EV-5098) maintained higher growth and yield compared to salt-sensitive genotype (Pak-Afgoee) under salt stressed conditions. Better growth of salt-tolerant genotype under salt stress was related to its higher accumulation of K^+ than salt-sensitive genotype. The genotypes EV-5098 maintenaied high K^+: Na^+ ratio, high Fe and Zn use efficiency under saline conditions whereas the genotype Pak-Afgoee was poor in these parameters. The maize genotypes showed increased growth with the addition of K under non-saline as well as saline conditions. Fe and Zn concentrations and Fe and Zn use efficiencies and growth of maize genotypes was improved by K application under saline conditions.

Adequate Boron Nutrition is Required for Improved Root Uptake and Shoot Accumulation of Potassium in Crop Plants

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Abstract

Plasma membrane-bound proton (H+)-ATPase activity in root cells is involved in potassium (K) uptake by generating electrochemical gradient across the membranes that is needed for K influx. Increasing published evidence is available showing that low supply of boron (B) results in significant alterations in ATPase activity and depolarization of the membranes. Consequently, a significant reduction in K influx across the plasma membranes is found under B deficiency based on the studies conducted in cell cultures, isolated membranes or root tips. These effects of B on K uptake are ascribed to its positive effects on the maintenance of structural integrity of cell membranes and/or effects on the activity of plasma membrane-bound proton (H+)-ATPase. To our knowledge, the relationship between B nutritional status of plants and root K uptake was not studied in detail in crop plants. In the present study, we investigated the role of B nutritional status of canola, soybean and maize plants on root uptake and shoot amounts of K. Hydroponic experiments were conducted by applying B at low, medium and adequate levels to monitor root uptake and shoot accumulation of K in young soybean, canola and maize plants. In all plant species tested, root growth was more sensitive to low B supply than the shoot growth. Both the concentration (%) and the total uptake (content) of K (as mg K per plant) were significantly lower under B deficiency, compared to adequate B supply. In well agreement with this result, short-term uptake studies demonstrated that root uptake of K was severely depressed under low B supply in soybean, canola and maize plants. Such distinct stimulating effect of adequate B nutrition on root K uptake was also found in case of phosphorus; but not with other nutrients. The results clearly show that adequate B nutrition is required for better root uptake of K and better K nutrition of crop plants.

Response of Cotton Genotypes Differing in Potassium-use-efficiency to Organic Potassium Fertilizer Developed from Fruit and Vegetable Waste Material

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Abstract
The presence of solid/organic waste in cities in huge amounts is a global issue. These organic wastes can be converted into useful soil amendments, after proper processing, to supplement plant nutrition. We developed a value-added, nutrient-enriched organic potassium (K) fertilizer from fruit and vegetable organic waste material and evaluated its efficacy to improve the growth, yield and quality of three cotton genotypes differing in their K-use-efficiency, viz. "NIBGE-2 (highly K-use-efficient), NIAB-78 (medium K-use-efficient) and CIM-506 (low K-use-efficient). Five treatments were given to compare the inorganic K fertilizer with a value-added K-enriched organic fertilizer at 25 and 50% of the recommended K fertilizer, i.e. 30 and 60 kg ha^{-1}, coupled with their integrated use at 25% of the recommended dose of K fertilizer (30 kg from inorganic + 30 kg from organic). Organic K fertilizer was prepared by mixing 25% and 50% recommended K fertilizer, i.e. 30 and 60 kg K_2O ha^{-1}. Organic K fertilizer was banded at 300 kg ha^{-1}, 7-8 cm deep alongside the seed row at a distance of 7 cm, at first irrigation. Pot experiment followed the completely randomized design while field experiment was launched in split-plot design (main plots: genotypes; sub plots: K doses). K nutrition positively affected growth, yield and quality attributes of cotton genotypes. Integrated K nutrition was found to be the best treatment, followed by sole K nutrition through organic fertilizer, for cotton growth and quality traits. Cotton genotypes did not respond differently to different K sources. We concluded that cotton genotypes responded similarly under organic and inorganic K nutrition, implying that the K-use-efficiency of cotton genotypes is independent of the nature of K sources.

Keywords: Cotton, potassium, organic K fertilizer, K-use-efficiency, organic waste

INTRODUCTION

Potassium (K) is the major contributing plant nutrient in cotton (*Gossypium hirsutum* L.) production (Makhdum et al., 2007). Adequate K nutrition positively affects biomass production (Zia-ul-hassan *et al*., 2011), lint yield & yield parameters (Gormus and Yucel, 2002, Pervez *et al*., 2004a; Zia-ul-hassan *et al*., 2014) and fiber quality (Gormus and Yucel, 2002; Pervez *et al*., 2004b; Zia-ul-hassan *et al*., 2014). This is because of the significant involvement of K in the leaf area expansion, rate of photosynthesis (Pettigrew 2003, Pervez *et al*. 2004c), leaf pressure potential, transpiration and water-use-efficiency (Pervez *et al*., 2004c) of cotton.

Due to its inefficient root system, cotton requires K in adequate amounts for its entire life cycle (Makhdum*et al*., 2007). However, most of the cotton genotypes of Pakistan are not K-use-efficient (Zia-ul-hassan*et al*., 2011). Whereas, K use in developing countries like Pakistan is highly negligible due to its high cost. Moreover, about one-third soils of Pakistan are K-deficient (Akhtar*et al*., 2003b). Earlier we have reported that 43% soils of Pakistan, belonging to important benchmark soil series, are K-deficient (Zia-ul-hassan et al. 2008). For these reasons, plant nutritionists in Pakistan are exploring the alternate low-cost sources and methods for low-K-input sustainable agriculture (Nawaz et al., 2006). To achieve

this goal, plant nutritionists in Pakistan have exploited the genotypic variation among crops and their species to categorize them for their efficiency to use chemical K fertilizer (Nawaz et al., 2006; Zia-ul-hassan andArshad, 2011; Zia-ul-hassan *et al*., 2011). Searching the nutrient efficient genotypes for different nutrients have been previously recorded (Yang *et al.,* 2003; Hakeem *et al.,* 2011). Hence, investigating the response of crop species and their genotypes, differing in their K-use-efficiency, supplied with various sources (both organic and inorganic) of K could boast the agricultural productivity.

Pakistan is confronting with volumes of solid waste. These organic wastes could successfully supplement plant nutrition, provided that they are effectively processed (Ahmad et al., 2008). Developing organic fertilizers from composted organic waste material, such as fruits and vegetable wastes, not only promotes healthy environment but also supports soil fertility and plant nutrition (Erhart et al., 2005; Arshad et al., 2007). The soil application of these organic fertilizers at substantially lower rates (≤500 kg ha^{-1}), integrated with only 50-75% chemical fertilizers, improves crop yield, product quality, nutrient uptake and soil health as compared to full dose of chemical fertilizers (Arshad et al., 2007).

In the present study, we have compared the response of cotton genotypes, differing in their K-use-efficiency, to inorganic v/s organic K nutrition.

Materials and Methods

The present study was conducted both in pots as well as in the field. During summer (Kharif) season. Pot experiment was launched in plastic pots with a capacity to accommodate 12 kg soil. The soil was collected from the area where field experiment was conducted (Lat: 31° – 26′ N, Long: 73° – 06′ E, Alt: 184.4 m). The physico-chemical properties of soil were the same as described in our earlier studies (Zia-ul-hassan et al., 2014). Accordingly, the soil was sandy clay loam, free from saline hazards (EC 1500 µS cm^{-1}), alkaline in nature (pH 7.8) and calcareous in reaction ($CaCO_3$258 g kg^{-1}). Moreover, the soil was low in organic matter (4.9 g kg^{-1}), total N (0.43 g kg^{-1}), Olsen's $NaHCO_3$-P (5.8 mg kg^{-1}) and NH_4OAc-K (106 mg kg^{-1}).

Three cotton genotypes were used in this study, viz. "NIBGE-2 (highly K-use-efficient), NIAB-78 (medium K-use-efficient) and CIM-506 (low K-use-efficient), on the basis of our previous ranking (Zia-ul-hassan *et al*., 2011).

For the development of organic K fertilizer organic waste material of fruits and vegetables was collected and sorted out to remove all unwanted substances (such as plastic bags, glass materials, stones, etc.). It was sun-dried for a couple of days and finally crushed to remove the excessive moisture/juice. The material was first air-dried and then oven-dried at 70 ^{o}C for 24 hours. The oven-dried material was ground to <2.0 mm particles using an electrical grinder. The crushed material was transferred to a locally fabricated composting unit consisting of drier, crusher/grinder and a processing unit (a vessel of 500 kg capacity) to convert organic waste materials into K-enriched organic fertilizer. Composting was done for five days under controlled temperature, moisture (40% v/w) and aeration (shaking at 50 rev min^{-1}). The temperature of processing unit ranged between 30 to 70 ^{o}C during second and third day of composting and declined gradually to 30 ^{o}C after fourth day. The moisture was maintained by using water and juices previously extracted from fruit and vegetable materials.

The raw (non-composted) and composted organic materials were analyzed for their carbon content (Nelson and Sommers, 1996) and nutrient status (Ryan et al., 2001). Thereafter, their C:N, C:P and C:K ratios were calculated. These data (Table 1) were used to compare the quality of raw and composted organic products and to assess their nutrient contribution for further necessary calculations about their application rates and K-enrichment.

Five treatments were given to compare the inorganic K fertilizer with a value-added K-enriched organic fertilizer at 25 and 50% of the recommended K fertilizer, i.e. 30 and 60 kg ha^{-1}, coupled with their integrated use at 25% of the recommended dose K fertilizer (30 kg from inorganic + 30 kg from organic). The crop received recommended dose of chemical fertilizers, i.e. 150, 75 and 120 kg N, P_2O_5 and K_2O ha^{-1}, respectively. Chemical K fertilizer was applied as per the treatment plan. Full dose of P and K, with half N was thoroughly broadcasted and mixed to the soil at sowing. The leftover N was applied at first and second irrigation in two equal splits. Organic K fertilizer was prepared by mixing 25% and 50% recommended K fertilizer, i.e. 30 and 60 kg K_2O ha^{-1}. Organic K fertilizer was banded at 300 kg ha^{-1}, 7-8 cm deep alongside the seed row at a distance of 7 cm, at first irrigation.

Pot experiment followed the completely randomized design while field experiment was launched in split-plot design (main plots: genotypes; sub plots: K doses). The experiments involved five K levels and three cotton genotypes with three replications. Five seeds were sown in each pot and after three weeks one seedling was maintained. Field experiment was comprised of sub-plots consisting five 6.0 m long rows spaced 0.75m. After three weeks of germination hand-thinning was performed to maintain four plants per m^2.The experiment followed the recommended production technology throughout.

In pot experiment, the data were collected from single plant whereas, in the field experiment, the data were recorded by randomly selecting five plants from each repeat for total bolls, weight of single boll and seed-cotton yield. Leaf-K concentration of the uppermost, fully expanded leaves on the main-stem of cotton plants, collected at blooming stage, was determined as detailed by Miller (1998). 0.5 g of 20-mesh dried leaf tissue was digested in HNO_3 (70%, 16 Molar) - $HCLO_4$ (70%, 11 Molar) and K was evaluated through flame photometry. K-use-efficiency was calculated as, seed-cotton yield per leaf-K concentration, as suggested by Siddiqi and Glass (1981).

Fiber quality analysis was performed as described earlier (Zia-ul-hassan et al., 2014). Accordingly, lint percentage was calculated as the weight of lint expressed as a percentage of the weight of the seed-cotton sample. The length, uniformity ratio and fineness of fiber were determined on a Zellweger Uster Spin lab High Volume Instrument 900 (USTER Technologies, Charlotte, Tennessee, USA)". Moreover, Pressley Strength Tester was used to measure fiber strength (Pressley, 1942).

The data were analyzed on 'Statistix' ver. 8.1 (Analytical Software©, 1985-2005). Mean separation was done by employing Tukey's test at alpha 0.05.

RESULTS

Growth, yield and quality of selected cotton genotypes as influenced by inorganic and organic K nutrition

Wide genotypic variations existed the among three cotton genotypes in relation to their response under inorganic and organic K nutritions (Table 2). Significant ($p<0.05$ to 0.001) main and interaction effects were noted for various growth and quality parameters under study due to different K sources and genotypes.

Pot experiment

The data regarding growth response of cotton genotypes in relation to single and integrated use of inorganic and organic K fertilizers are presented in Table 2. It is clearly evident from the data that either the integrated use of both inorganic and organic K sources each @ 30 kg ha^{-1} (K30+OK30) or the K application exclusively as K-enriched organic fertilizer @ 60 kg ha^{-1} (OK60) resulted in maximum response of cotton genotypes for various growth parameters. Generally, the low and medium use efficient genotypes responded at their highest to OK60 for most of the parameters, with the exception that both the seed cotton yield and K use efficiency of CIM-506 were highest at K30+OK30. Interestingly, the highly

K use efficient cotton genotype, viz. NIBGE-2 performed best for all the growth parameters at K30+OK30. A deep insight into the data reflected that irrespective to the dose of K application, K-enriched organic fertilizer performed either better or at par to its inorganic counterpart for all the parameters under study. Moreover, the growth response of cotton genotypes was significantly ($p<0.05$) better to the higher application rate of K (60 kg ha^{-1}) as compared to the lower one (30 kg ha^{-1}). At lower application rate, the K application through K-enriched compost (OK30) out yielded its inorganic counterpart (K30) and increased the number of bolls from 14-37%, average boll weight from 6 to 7%, seed cotton yield from 10-18% and K use efficiency from 26 to 33%. Same was true at higher K application rate as OK60 increased number of bolls from 6 to 10%, average boll weight from 1-22%, seed cotton yield from 4-11% and K use efficiency from 19-29% over K60. It was worthy to note that the highly K use efficient genotype, viz. NIBGE-2 responded comparatively better to inorganic K nutrition, whereas its less efficient counterparts (CIM-506 and NIAB-78) responded more to K added as K-enriched organic fertilizer.

Number of bolls per plant, in case of CIM-506 and NIAB-78, was minimum, i.e. 10.0 and 12.3 at K30 and increased to 16.3 (63%) and 17.0 (38%) at OK60, respectively (Table 2). In case of NIBGE-2, the number of bolls was 15.3 at OK30 and increased to 17.7 (16%) at K30+OK30. Similarly, average boll weight (g $boll^{-1}$), in case of CIM-506 and NIAB-78 was minimum, i.e. 4.7 and 5.1 at K30 and rose to 6.2 (32%) and 6.6 (29%) at OK60, respectively. In case of NIBGE-2, minimum average boll weight (6.0) was recorded at K30 which increased to 7.7 (28%) at K30+OK30. Moreover, seed cotton yield (g $plant^{-1}$) in case of CIM-506 was found minimum (11.9) at K30 which further increased to 17.6 (48%) at K30+OK30. In case of NIAB-78, minimum seed cotton yield of 14.3 was noted at K30 which reached to 20.9 at OK60. NIBGE-2 produced minimum and maximum seed cotton yield at OK30 (18.8) and K30+OK30 (23.3), respectively. The increase in seed cotton yield in case of NIBGE-2 was 24%, i.e. almost half of that offered by its less efficient counterparts. The results elucidated from the data with respect to the K use efficiency of cotton genotypes were not much different from those observed in case of seed cotton yield. In this study, CIM-506 responded more than NIAB-78 and NIBGE-2 to K nutrition, irrespective to its source of application. The response of NIAB-78 to K nutrition was of intermediate level, while the least response was noted in case of NIBGE-2. However, on overall basis, NIBGE-2 performed well than its less and medium K use efficient counterparts by generating maximum values for all the parameters under study.

Almost similar trend was observed (Table 3) with respect to the response of cotton genotypes to K nutrition in terms of improved fiber quality traits, viz. lint percentage (19%), fiber uniformity ratio (9%), fiber length (9%), fiber fineness (13%) and fiber strength (8%). Organic K fertilizer improved fiber quality traits of cotton genotypes more as compared to inorganic K nutrition, however, lint percentage decreased.

Field experiment

The integrated use of K (K30+OK30) was the most dominant treatment which performed far better than OK60 for various growth parameters as compared to its performance in pot trial (Table 4). Number of bolls per plant, average boll weight and K use efficiency in case of both CIM-506 and NIAB-78, coupled with seed cotton yield in case of NIAB-78, were highest in response of the integrated K nutrition from two different sources. Nonetheless, the number of bolls per plant and K use efficiency of NIBGE-2, besides the seed cotton yield of CIM-506, was highest at OK60. Moreover, the maximum average boll weight and seed cotton yield of NIBGE-2 was obtained in response to the inorganic K nutrition at 60 kg ha^{-1}. The data clearly demonstrated that the integrated K nutrition influenced the response of various growth parameters of cotton genotypes more than their K use efficiency. These results suggest that K use efficiency of cotton could be improved by the inclusion of organic K sources in its plant nutrition programs. Further examination of the data supported this premise by indicating that the K-enriched organic fertilizer was proved superior, at both levels of K. At lower application rate, K nutrition through

K-enriched organic fertilizer increased the number of bolls from 9-11%, average boll weight from 8 to 13% and seed cotton yield from 6-17% on overall basis. However, as compared to pot trial, under field condition, the K use efficiency of CIM-506 increased only slightly and decreased in case of NIAB-78. The genotype NIBGE-2 performed alike under both pot and field studies at lower K application rate. More or less similar results were noted for these parameters at higher K application rate. It was, however, highly interesting to note that K use efficiency increased with the increasing K application rate as against its decreasing trend at the lower K application rate. These results advocate that the use of organic K sources, especially at higher application rates, could be highly beneficial to enhance K use efficiency of cotton. Moreover, similar to the findings of pot trial, cotton genotypes performed better at higher application rates of K (60 kg ha^{-1}) as against the lower one (30 kg ha^{-1}) under field condition also, irrespective to the source of application. It was also worthy to note that as compared to the single application of K at 60 kg ha^{-1} from either source, the integrated use of K (K30+OK30) increased the number of bolls (3-14%), average boll weight (2-3%), seed cotton yield (7-15%) and K use efficiency (3-26%) more strongly under field condition than in pot trial. The increase in various parameters of each cotton genotype was different under field condition from pot trial (Table 4). Number of bolls per plant, in case of CIM-506 and NIAB-78, was 24.7 and 27.0 at K30 and increased to 32.3 (31%) and 34.3 (27%) at K30+OK30, respectively. In case of NIBGE-2, the number of bolls was lowest 32.7 at OK30 and increased to 37.7 (15%) at OK60. Similarly, average boll weight (g $boll^{-1}$), in case of CIM-506 and NIAB-78 was lowest, i.e. 5.2 and 5.9 at K30 and rose to 6.6 (27%) and 7.2 (29%) at K30 and K60, respectively. In case of NIBGE-2, lowest average boll weight (6.6) was recorded at K30 which increased to 7.2 (9%) at K60. Moreover, seed cotton yield (g $plant^{-1}$) in case of CIM-506 was 82.7 at K30 which further increased to 123.0 (49%) at OK60. In case of NIAB-78, minimum seed cotton yield of 97.7 was noted at K30 which reached to 147.0 at K30+OK30. NIBGE-2 produced lowest seed cotton yield of 121.7 at OK30 which increased to 148.3(22%) at K60. Although low (CIM-506) and medium (NIAB-78) K use efficient genotypes responded similarly to K nutrition, their response was more than two-fold in terms of increased seed cotton yield as compared to their K use efficient counterpart (NIBGE-2). K use efficiency of CIM-506 was 5.5 at K30 and rose to 7.1 (29%) at K30+OK30. In case of NIAB-78, the K use efficiency was 7.2 at OK30 which further increased to 9.6 (33%) at K30+OK30. The K use efficiency of NIBGE-2 was 9.2 at OK30 which reached to 13.0 at OK60.Under field conditions, the fiber quality traits of cotton (Table 5) increased in response to different K sources and their levels following more or less similar pattern, as was found in pot trial. However, the response of different quality parameters was more prominent in case of integrated K nutrition (K30+OK30) as compared to what was recorded in pot trial.

The integrated application of K from inorganic and organic sources, each applied at 30 kg ha^{-1}, proved to be the best treatment, followed by the application of K at 60 kg ha^{-1} as K-enriched organic fertilizer (OK60) for almost all the growth parameters and quality traits of cotton genotypes. Although the growth response of three selected cotton genotypes varied with nature of K sources, however, cotton genotypes showed similar order of efficiency against organic vs. inorganic K sources, i.e. NIBGE-2 > NIAB-78 > CIM-506 which may imply that genotypic variations are independent of the nature of K sources.

DISCUSSION

The results of present study depict the significance of K-enriched organic fertilizer in increasing the seed cotton yield and improving the K use efficiency and fiber quality of cotton. The integrated K application from inorganic and organic K sources each @ 30 kg K_2O ha^{-1} or the K application exclusively as K-enriched organic fertilizer @ 60 kg K_2O ha^{-1}offered highest response of cotton genotypes for various growth parameters. K-enriched organic fertilizer, irrespective of the rate of K application, performed either better or equal as compared to the inorganic K nutrition for all the parameters under study.

These results are in line with the early findings reporting the improved biomass and yield of a variety of crops by various types of nutrient-enriched organic fertilizers (Arshad et al., 2004; Ahmad et al., 2006; Asghar et al., 2006; Tahir et al., 2006; Ahmad et al., 2007; Arshad et al., 2007; Ahmad et al., 2008). Else,

the growth response of cotton genotypes was significantly ($p<0.05$) better to the higher application rate of K (60 kg ha^{-1}) as compared to the lower one (30 kg ha^{-1}), which again emphasized the importance of adequate K nutrition of cotton as has been advocated in the literature (Cassman et al., 1989; Makhdum et al., 2007; Zia-ul-hassan et al., 2011; Zia-ul-hassan et al., 2014).

The number of bolls and boll weight increased due to application of K-enriched organic fertilizer. Blaise (2006), while reporting the results of a 3-years study comparing the organic and inorganic (modern) methods of cultivation, stated that organic plots produced more seed cotton yield (additional 94 kg ha^{-1}) and increased number of bolls (37-71%). Earlier, Asghar et al. (2006) reported an increase in various growth parameters of radish by the application of N-enriched organic fertilizer. The improvement in various growth parameters by the application of N-enriched organic fertilizer was also reported for wheat (Arshad et al., 2007) and maize (Ahmad et al., 2008). Similarly, in these pot and field experiments the use of organic K fertilizer either single or integrated with chemical fertilizer improved cotton growth, yield and quality and resulted in better K use efficiency.

Since organic fertilizer products promote soil properties, the uptake of nutrients is enhanced due to their slow and gradual supply which ultimately promotes plant growth. Ahmad et al. (2008) reported that the application of enriched compost to soil increased its aggregate stability and water retention. They observed increased total uptake of N, P and K in maize in response to the integrated supply of enriched compost and N fertilizer. Similar results were reported by Blaise (2006) who observed in a 3-year study that the top soil (0.1 to 0.2 m) of organic plots had significantly better soil properties, i.e. carbon content, water-stable aggregates and mean weight diameter than the inorganic plots.

Moreover, the present study revealed that K-enriched organic fertilizer improved fiber quality traits of cotton genotypes more as compared to inorganic K nutrition which confirmed the early findings. Early findings (Blaise, 2006) reporting better fiber quality traits under organic method of cultivation vs. inorganic one, also support these results. Early studies elucidated that seed-cotton yield (Pervez et al. 2004a) and fiber quality traits (Pervez et al., 2004b) of four elite Pakistani cultivars were influenced by both the rates and sources (only inorganic, i.e. sulphate vs. muriate) of K. In a recent study involving same three cotton genotypes, it was observed that NIBGE-2 was the most K-use-efficient cotton genotype when supplied with potassium sulphate. Interestingly, the results of present study also demonstrated the same conclusion employing that source of K nutrition has no effect on the K-use-efficiency of cotton genotypes.

CONCLUSION

The present study concluded that the response of cotton genotypes did not differ with the source of K and cotton genotypes showed similar order under organic and inorganic K nutrition. These results may imply that the K-use-efficiency of cotton genotypes is independent of the nature of K sources.

ACKNOWLEDGEMENT

This study was a part of the PhD dissertation research of Zia-ul-hassan, funded by the Higher Education Commission of Pakistan under Indigenous PhD Scholarship Scheme.

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Table 1. Comparative nutrient content and carbon to nutrient ratios of raw and composted organic materials

Parameter	Raw organic material	Composted organic material	Remarks: changes due to composting
Carbon (g kg^{-1})	340.5 ± 5.0	220.0 ± 10.0	Decreased
Nitrogen (g kg^{-1})	12.8 ± 0.7	15.9 ± 1.4	Increased
Phosphorus (g kg^{-1})	4.0 ± 0.2	6.5 ± 0.9	Increased
Potassium (g kg^{-1})	13.0 ± 0.1	20.5 ± 1.5	Increased
Copper (mg kg^{-1})	1.11 ± 0.05	1.26 ± 0.08	Increased
Zinc (mg kg^{-1})	41.0 ± 4.0	48.5 ± 5.5	Increased
Manganese (mg kg^{-1})	39.5 ± 5.5	52.0 ± 3.0	Increased
Iron (mg kg^{-1})	505.0 ± 18.0	672.0 ± 38.0	Increased
C:N ratio	27.11 ± 0.99	17.17 ± 1.09	Decreased
C:P ratio	87.61 ± 4.28	34.29 ± 3.21	Decreased
C:K ratio	26.67 ± 1.67	10.75 ± 0.30	Decreased

Table 2. Number of bolls, boll weight, seed cotton yield and K use efficiency of selected cotton genotypes under single and integrated use of varying levels of inorganic and organic K sources in pot study.

K application (kg ha^{-1})		Number of bolls per plant^{-1}			Average boll weight (g boll^{-1})			Seed cotton yield (g plant^{-1})			K use efficiency (g^2 seed cotton mg^{-1} leaf K)		
SOP	OKF	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2
30	0	10.0g	12.3f	15.7bc	4.7f	5.1d-f	6.0c	11.9j	14.3i	19.3c-e	0.73i	0.90h	1.43ab
0	30	13.7ef	14.0de	15.3cd	5.0ef	5.5d	6.4bc	14.4i	15.7hi	18.8d-f	0.97gh	1.13d-f	1.30bc
30	30	15.7bc	16.3a-c	17.7a	5.4de	6.3bc	7.7a	17.6e-g	19.9b-d	23.3a	1.10e-g	1.23c-e	1.57a
60	0	14.0de	15.0c-e	16.3a-c	5.1d-f	6.1c	7.7a	16.6gh	18.8d-f	21.7ab	0.83hi	1.07fg	1.43ab
0	60	16.3a-c	17.0ab	17.3a	6.2bc	6.6b	7.8a	17.3f-h	20.9bc	21.0bc	1.07fg	1.27cd	1.37bc

SOP: Potassium sulphate, OKF: K-enriched organic fertilizer @ 300 kg ha-1

Note: Means followed by the similar letters are not significantly different at $P < 0.05$ on the basis of Tukey's HSD (honestly significant difference test).

Table 3. Fiber traits of selected cotton genotypes under single and integrated use of varying levels of inorganic and organic K sources in pot study.

K application (kg ha^{-1})		Lint percentage			Fiber uniformity ratio			Fiber length			Fiber fineness			Fiber strength		
		(%)			(%)			(mm)			(µg in^{-1})			(000 lb in^{-2})		
SOP	OKF	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2
30	0	36.3h	37.0gh	40.7b	45.0g	46.4ef	48.7b	25.2g	26.5d-f	27.1a-d	4.03f	4.27de	4.37c-e	91.7f	94.0e	97.0a-c
0	30	37.0gh	38.0fg	40.0b-d	46.3f	47.2d-f	47.4b-f	26.3f	26.4ef	26.9a-e	4.23e	4.40b-d	4.47a-c	94.0e	94.7de	95.7c-e
30	30	39.0c-f	39.7b-e	39.3b-f	47.2d-f	48.0b-d	48.5bc	26.8b-f	27.4ab	27.3ab	4.53ab	4.53ab	4.53ab	96.0b-d	97.0a-c	96.3b-d
60	0	38.3e-g	38.7d-f	43.0a	46.9d-f	47.9b-d	49.9a	26.3f	27.2a-c	27.4a	4.43a-c	4.47a-c	4.40b-d	95.3	97.0a-c	98.7a
0	60	39.0c-f	38.7d-f	40.3bc	47.3c-f	47.7b-e	48.0b-d	26.6c-f	26.9a-e	27.3ab	4.47a-c	4.57a	4.50a-c	96.7bc	95.7c-e	97.7ab

SOP: Potassium sulphate, OKF: K-enriched organic fertilizer @ 300 kg ha-1

Note: Means followed by the similar letters are not significantly different at $P < 0.05$ on the basis of Tukey's HSD (honestly significant difference test).

Table 4. Number of bolls, boll weight, seed cotton yield and K use efficiency of selected cotton genotypes under single and integrated use of varying levels of inorganic and organic K sources in field study.

K application (kg ha^{-1})		Number of bolls per plant^{-1}			Average boll weight (g boll^{-1})			Seed cotton yield (g plant^{-1})			K use efficiency (g^2 seed cotton mg^{-1} leaf K)		
SOP	OKF	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2
30	0	24.7h	27.0gh	33.3cd	5.2e	5.9d	6.6c	82.7g	97.7f	129.7bc	5.5i	7.4gh	10.2c
0	30	27.3fg	29.3ef	32.7cd	5.9d	6.4c	6.7bc	96.7f	104.0ef	121.7cd	5.6i	7.2gh	9.2de
30	30	32.3cd	34.3bc	36.7ab	6.6bc	6.7bc	7.0ab	122.7b-d	147.0a	145.7a	7.1gh	9.6cd	12.4ab
60	0	28.3fg	33.3cd	34.7bc	6.4c	6.6bc	7.2a	115.0de	133.0b	148.3a	6.6h	8.4ef	11.6b
0	60	31.0de	31.7d	37.7a	6.5c	6.5c	6.8bc	123.0b-d	127.7bc	146.3a	6.9gh	7.6fg	13.0a

SOP: Potassium sulphate, OKF: K-enriched organic fertilizer @ 300 kg ha-1

Note: Means followed by the similar letters are not significantly different at $P < 0.05$ on the basis of Tukey's HSD (honestly significant difference test).

Table 5. Fiber traits of selected cotton genotypes under single and integrated use of varying levels of inorganic and organic K sources in field study.

K application (kg ha^{-1})		Lint percentage (%)			Fiber uniformity ratio (%)			Fiber length (mm)			Fiber fineness (µg in^{-1})			Fiber strength (000 lb in^{-2})		
SOP	OKF	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2	CIM-506	NIAB-78	NIBGE-2
30	0	36.0g	37.7d-g	40.7a-c	45.3f	46.9de	47.1b-d	25.9h	27.4a-c	27.2a-d	4.10c	4.40b	4.47ab	93.0h	95.0fg	96.0d-f
0	30	37.3e-g	38.0d-g	36.3fg	45.7ef	46.7d-f	47.4b-d	26.3gh	26.5fg	27.0c-e	4.20c	4.40b	4.43ab	94.3g	95.0fg	96.3d-f
30	30	39.0b-e	39.7b-d	42.0a	46.9de	47.6b-d	48.5b	26.8d-f	27.3a-c	27.5a	4.50ab	4.50ab	4.53ab	96.7c-e	97.0b-d	98.3ab
60	0	38.3d-f	39.3b-e	41.0ab	46.5d-f	47.4b-d	51.5a	26.7e-g	27.4a-c	27.2a-d	4.40b	4.50ab	4.57a	95.0fg	97.3a-d	98.7a
0	60	39.0b-e	38.7c-e	39.7b-d	47.0cd	47.7b-d	48.3bc	26.8d-f	27.1b-e	27.4a-c	4.40b	4.43ab	4.47ab	97.3a-d	95.7e-g	97.7a-c

SOP: Potassium sulphate, OKF: K-enriched organic fertilizer @ 300 kg ha-1

Note: Means followed by the similar letters are not significantly different at $P < 0.05$ on the basis of Tukey's HSD (honestly significant difference test).

Potassium Fixation in Some Calcareous Soils of Iran

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Abstract
Potassium fixation influences the effectiveness of fertilization in soil-plant system. Therefore, understanding potassium fixation is fundamental for developing fertility management strategies. Potassium fixation in calcareous soils of Iran were investigated using 48 soil samples collected from different agricultural areas of Iran. The exchangeable potassium was determined after the application of 100 mg K/kg soil and 20 days of incubation at field capacity. Also, kinetics of K fixation at field capacity was studied during a period of 225 days of applying 200, 400 and 800mg K kg-1 soils. Results indicated fixation ranged from 0.0 to 36%, with the mean and the standard deviation of 12.5% and 9.5%, respectively. However, 44% of the soil samples fixed more than 15% of the added potassium. There was linear relationship between the amount of K fixation and K concentration in all reaction times. Evaluation of 6 kinetic models indicated that the best model for describing the data in all concentrations was power function equation. Constants a of the power function law, and R and C of the parabolic diffusion equation, were increased linearly with increasing concentration. Order equations could not describe K fixation properly, but the zero order equation described the kinetic data for the slow reaction (7200-57700min) properly, which its rate constant increased with K concentration.

Key words: potassium, fixation, calcareous soils

INTRODUCTION

Potassium exists in different forms of solution, exchangeable, fixed, and structural in the soils. These forms are in equilibrium or quasi-equilibrium with each other. One of the important processes that influence the availability of potassium for plants is fixation and release of potassium by soil minerals. This process plays important role in providing potassium to plants from fixed potassium and efficiency of applied fertilizer particularly in intensive agriculture. Therefore, understanding effective factors in potassium fixation is necessary for maximizing of potassium uptake from soil and fertilizer. Thermodynamic data only predicts the final state of system from primary non-equilibrium state while Kinetics studies present valuable information about the rate and mechanism of chemical reactions. The importance of potassium is well-known as an essential element for plants in agriculture and a dynamic ion in soils (Sparks and Huang, 1985). Kinetics studies of potassium in heterogeneous system are often valuable than thermodynamic studies because agricultural soils due to cultivation, fertilization and irrigation are almost non-equilibrium system. So, kinetics and exchange mechanism of potassium are very fundamental to understanding the chemistry of potassium in the soils (Huang, 2005; Sparks and Huang, 1985)

The kinetics of reaction between soluble, exchangeable, non-exchangeable, and structural phase of potassium severely affect the soil potassium chemistry. The rate and direction of these reactions determine that the added potassium will be washed to lower horizon, absorbed by plants, turned to insoluble form or released to available form. A lot of research about ion exchange with K is carried out, but only a few researches on kinetics of soil potassium can be seen in articles (Huang, 2005).

Bandyopadhyay and Bhattacharyay (1982) found that quick K fixation at the first day of wetting –drying cycle followed by slow fixation reaction for the next 4 days. Burns and Barber (1961) reported that the release of K from Indiana amended soil was very fast after wetting for 2-4 days and then declined. In

long-term greenhouse studies with aerobic and wet regimes, during 2 month (Attoe, 1947) to 3 years, the K fixation happened(Amberger et al., 1974; Grissinger and Jeffries, 1957). K fixation rate was determined by Olk et al. (1995) during 3 successive wetting and drying cycles in incubator. All rates were based on first order kinetics and there was a quick fixation phase at the first 2 days in each wetting-drying cycle. It continued with slower fixation and the constant fixation rate for both phase decreased in each successive cycle. Zang and Brown (2000) reported that during wetting and drying cycle, potassium concentration of soil solution increase while the volume of soil solution decrease but soluble potassium pools and extractable potassium with ammonium reduced. In a constant moisture, soluble K reduced during 16 days but its decline was not as much as wetting- drying moisture regime. Potassium fixation by soils showed a biphasic pattern in wetting- drying moisture regime – a quick fixation in the first 2 days after wetting that continued with slower fixation

Potassium fixation is controlled by diffusion (Sparks, 1987). When soil dry, labile potassium concentration increase extremely in a low volume of solution (Nye and Tinker.1977), which increase concentration gradient and control the fixation. Therefore, soil moisture significantly impact on fixation rate (Olk et al., 1995). Release of K from micas by cation exchange is strongly influenced by K ions activity. When the amount of K is lower than the critical level, interlayer K is released by other solution cations contrary and when the amount of K is more than the critical level, the expanding 2:1 mica sorbed K from solution. The critical level is highly dependent on mineral type, so that for muscovite is lower than trioctahedral (Scott and Smith.1966; Henderson et al., 1976). The nature and concentration of replaceable cations also affected the critical level of K in the solution (Rausell-Colom et al.,1965). The potassium fixation and the effect of concentration on kinetics of potassium fixation were investigated in this study.

MATERIALS AND METHODS

Forty eight soil samples were collected from different agricultural areas of Iran. These samples were selected on the basis of significant differences in general characteristics such as saturation present, field capacity moisture, pH, texture, calcium carbonate equivalent and exchangeable potassium. The samples were air dried and passed through a 2-mm sieve for use in this study. The potassium fixation in 48 soil samples were determined by adding 100 mg K/kg soil to 5g soil sample (two replicates) as a solution to get field capacity moisture. The samples were mixed thoroughly until the moisture become uniform and placed in an incubator at constant temperature of 25 C. At the same time, another samples was placed in the incubator with the same condition without adding K (blank). The exchangeable potassium were determined after 20 days. Effect of potassium concentration on kinetics of potassium fixation was studied in another experiment. Three soil samples were selected according to potassium fixation experiment and 5 g soil samples were transferred into plastic containers. Soil samples were reached to field capacity moisture with different concentration of K solution, so that the amounts of added potassium were 200, 400 and 800 mg K/kg soil. The container's lid was closed to keep the moisture at constant level. Then they were placed in an incubator at constant temperature of 25 C. the exchangeable potassium were determined 20 minutes, 8 hours, 1, 2, 3, 5, 9, 15, 25 and 40 days after adding potassium solution. Also exhalable potassium was determined after 225 days for 200 and 400 mg K/kg soil. In all above mentioned experiments, the exchangeable potassium was determined by using Knudsen et al. (1982) method. For this purpose, the soil samples were transferred to 50 ml centrifuge tubes and added 25 ml ammonium acetate. Then they were shacked 10 minutes at 125 rpm. The supernatant was filtered into 100 ml volumetric flask. This processes repeated 4 times and then it was brought to the volume with ammonium acetate solution. Potassium concentration was determined by flame photometer.

The kinetics and empirical equations, including the zero-order, first- order, second- order, power function, parabolic diffusion and Elovich equations were used to describe the kinetics of potassium fixation throughout the overall time of reaction. The linear forms of equations are presented in table 1.

Table1. Kinetics and empirical equations

Zero-order	$[K_f]_t = [K_f]_0 + kt$
First- order	$Ln[K_f]_t = Ln[K_f]_0 + kt$
Second- order	$1/[K_f]_t = 1/[K_f]_0 + kt$
Power function	$Ln[K_f]_t = Lna + bLnt$
Elovich	$[K_f]_t = (1/\beta_s)Ln(\alpha_s\beta_s) + (1/\beta_s)Ln(t)$
Parabolic diffusion	$[K_f]_t = Rt^{1/2} + C$

Where $[K_f]_t$ is the amount of potassium fixation at time of t, $[K_f]_0$ is the amount of potassium fixation at time t_0, a and b are constants of power function equation, α_s and β_s are Elovich equation constants , R is diffusion coefficient and c is equation constant.

$$[K_f]_t = [K_{add} + K_{in}] - K_t \qquad \text{Eq. 1}$$

Where:

$[K_f]_t$: Potassium fixation at time t (mg K/kg)
K_{add}: Added potassium (mg K/kg)
K_{in}: Initial extractable potassium with NH^{4+}(mg K/kg)
K_t: the extractable potassium with NH^{4+} at time t (mg K/kg)

The goodness of fit of the equations to the data was evaluated by using the correlation coefficient (r^2), probability (p) and standard error (SE) of linear regression analysis. The standard error of estimation was calculated as follows:

$$SE = [\Sigma (K_f - K_f^*)^2/(n-2)]^{1/2}$$

Where; K_f and K_f* are measured and calculated potassium fixation in the soil at time t respectively, and n is the number of measurements.

RESULTS AND DISCUSSION

Some characteristics of soils are given in table 2 Data for these factors indicated that the soils have great diversity in the mentioned characteristics and wide rage and relatively high standard deviation of the parameters also approved that.

Table 2. some characteristics of the soils studied

characteristic	unit	min	max	mean	*standard deviation*
Exchangeable potassium	mg/kg	76	899.5	326.2	173.9
Clay	mg/kg	92	480	252	105
pH		7.33	8.30	7.79	0.25
FC	mg/kg	72	398	247	715
SP	mg/kg	191	855	455	137

Wide range of clay percentage (9% to 48%), exchangeable potassium (76 to 900 mg/kg) along with numbers of soil sample (48 samples) which were selected randomly from different area, increase the possible presence of different kind of layer silicate minerals associated with fixation and release of potassium in soils. This diversity of soils makes the results generalizable to the field conditions.

Potassium fixation in the studied soil

The distribution of 48 studied soil based on potassium fixation percentage has shown in fig.1. potassium fixation according to the percentage of added potassium in different soils ranged from zero to 36% with

mean of 12.5% anf standard error of 9.47. This results revealed that 44% of soils fixed more than 15% of added potassium in field capacity moisture conditions.

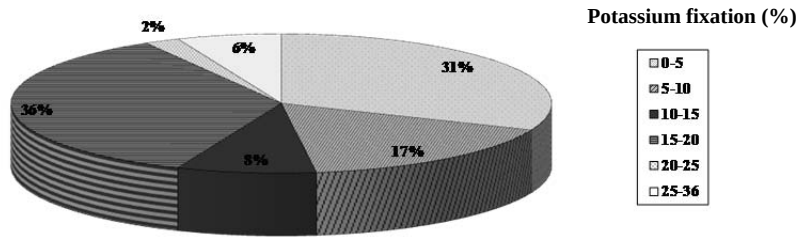

Fig 1.Potassium fixation status in soil samples

Effect of concentration on potassium fixation kinetics:
Some properties of 3 selected soils for this experiment is shown in table 3 and their main minerals are presented in table 4.

Table 3. some characteristics of selected soils

characteristic	unit	Soil No.		
		30	**11**	**9**
Texture		Sandy loam	Sandy loam	Sandy loam
Clay	%	14.6	18.6	14.8
FC	%	18.5	17.9	17.9
Exchangeable K	mg/kg	236.4	129.6	173.2
TNV	%	7.5	9.89	0.71
pH		7.8	7.9	7.6
OC	%	0.57	0.22	0.4

Table 4. Major clay minerals of soils used

Soil No.	Clay minerals
30	Montmorillonite- Vermiculite- mica (Illite)- Kaolinite- Chlorite- Quartz
11	Montmorillonite- mica (Illite)- Kaolinite - Quartz
9	mica (Illite)- Vermiculite- Montmorillonite- Chlorite- Kaolinite- Quartz

Effect of concentration on potassium fixation kinetics, was investigated by adding three different concentrations (200, 400 and 800 mg K/ kg soil) to the soil samples under constant field capacity

moisture. Kinetics of potassium fixation in different concentration has shown in fig 2 for soil No. 9. The concentration significantly increases the amount of potassium fixation. Potassium fixation was continued during the experiment. The rate of fixation at first 5 days was high and then gradually declined. The pattern of potassium fixation for two other soils was similar to soil No. 9.

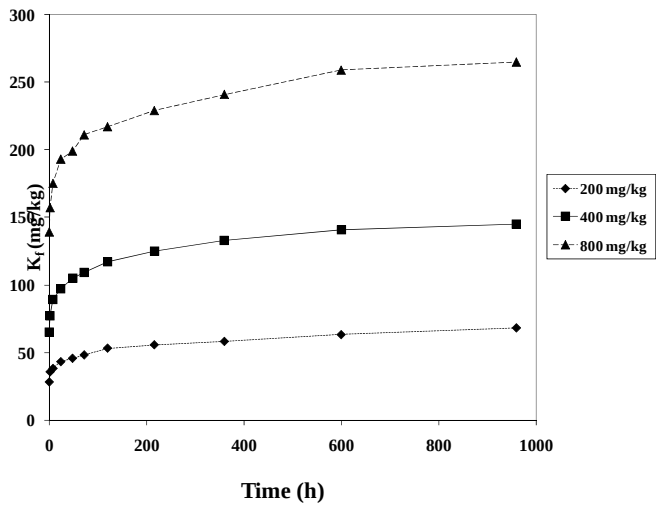

Fig 2. Kinetics of potassium fixation (soil No. 9)

Empirical and kinetics equations such as zero-order, first- order, second-order, power function, Elovich, and parabolic diffusion were fitted to potassium fixation data. According to the values of r^2, p and SE, the power function equation was best fitted to kinetics data. The values of these parameters for power function equation in soil No. 9 is presented in table 5.

Table. 5. The values of r2, p, and SE for zero- order fitted to potassium fixation kinetics in soil No. 9.

Soil No.	200ppm			400ppm			800ppm		
	r^2	p	SE	r^2	p	SE	r^2	p	SE
9	0.99	7.2E-10	4.0E-03	1.00	8.9E-12	2.3E-03	0.99	1.8E-10	2.6E-03
11	0.99	1.3E-10	6.3E-03	0.98	4.3E-09	5.9E-03	0.99	4.2E-10	3.7E-03
30	0.98	3.9E-09	6.8E-03	0.98	1.1E-08	6.9E-03	0.96	1.2E-07	6.6E-03

It seems that in heterogeneous system, number of Empirical and kinetics models can explain absorption data if correlation confident, probability and standard error were used to evaluate them (Chien and Clayton, 1980; Martin and Sparks,1983; Sparks, 1989; Aharoni et al., 1991). In heterogeneous system the order of kinetics equation does not have molecular concept and there is not a strong relationship between best equation and physicochemical, mineralogical property (Sparks, 2003). However, the parameters of selected model provides voluble means to compare the processes of absorption rate in different absorbent (Saha et al., 2004). The parameters of empirical models such as power function and Eluvich does not have physicochemical definition and cannot give the rate constant (Bolan et al., 1985). Parabolic diffusion equation can only be used to calculate the apparent diffusion coefficient.

According to correlation coefficient, probability, and standard error for multiple processes, only zero-order kinetics model fitted to the data in compare with first and second-order equations. Thus it explained potassium fixation in studied soils. The correlation coefficient, probability and standard error for zero order equation are shown in table 6. Furthermore, the zero order kinetics diagram of potassium fixation is shown in fig. 3.

Table 6. Reaction outputs after fitting zero-order kinetics equation on K fixation data in both fast and slow reaction in soil No. 9.

		Fast reaction				Slow reaction			
Soil No.	**Concentration (mg/kg)**	**r^2**	**p**	**SE**	**k**	**r^2**	**p**	**SE**	**k**
	200	0.81	5.6E-03	6.1E-04	2.8E-03	0.99	4.3E-04	1.7E-05	3.0E-04
9	400	0.75	1.2E-02	1.6E-03	6.2E-03	0.78	4.6E-02	1.4E-04	4.6E-04
	800	0.79	7.6E-03	2.3E-03	1.0E-02	0.90	1.4E-02	1.8E-04	9.2E-04
	200	0.85	3.1E-03	8.6E-04	4.6E-03	0.99	4.0E-04	2.3E-05	3.9E-04
11	400	0.67	2.5E-02	1.8E-03	5.8E-03	0.73	6.6E-02	2.4E-04	6.7E-04
	800	0.81	5.7E-03	2.9E-03	1.3E-02	0.82	3.3E-02	2.5E-04	9.4E-04
	200	0.89	1.3E-03	6.1E-04	3.9E-03	0.92	9.6E-03	5.2E-05	3.1E-04
30	400	0.66	2.6E-02	1.6E-03	5.0E-03	0.77	5.0E-02	1.3E-04	4.0E-04
	800	0.78	8.1E-03	1.7E-03	7.0E-03	0.86	2.2E-02	1.8E-04	7.6E-04

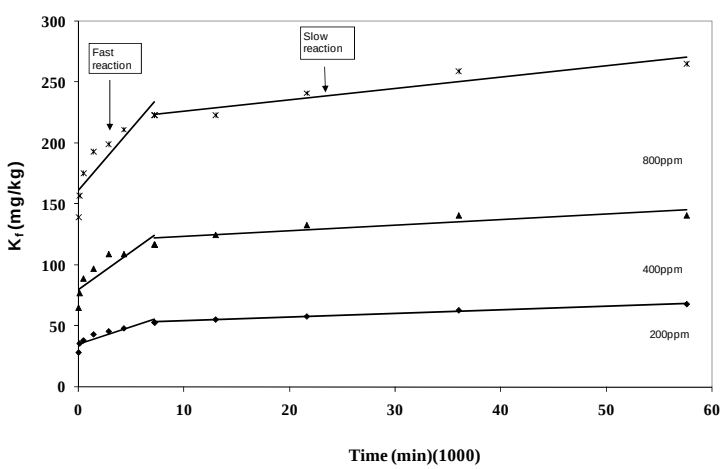

Fig 3. Fitting Zero-order equation to both fast and slow reaction of K fixation at different concentration

According to table 6 and fig. 3, rate constant increased with potassium concentration so that, rate constant of quick reaction for 800mg K/kg soil, is 2.7 and 1.8 fold of 200 and 400 mg K /kg soil. Similarly, this increase of rate constant for slow reaction was 2.3 and 1.8.

As it mentioned before, fixation is controlled by diffusion (Sparks, 1987) and with increasing the concentration of potassium, the potassium gradient which controls potassium fixation, increase and lead increase in potassium fixation rate. To check whether the capacity of these soils for potassium fixation is limited or not, some samples of these soils with 200 and 400 mg K/kg soil were incubated at 25° C for 225 days. Potassium fixation during this period is shown in fig. 4 for soil No.8. In two other soils, potassium fixation had the same pattern.

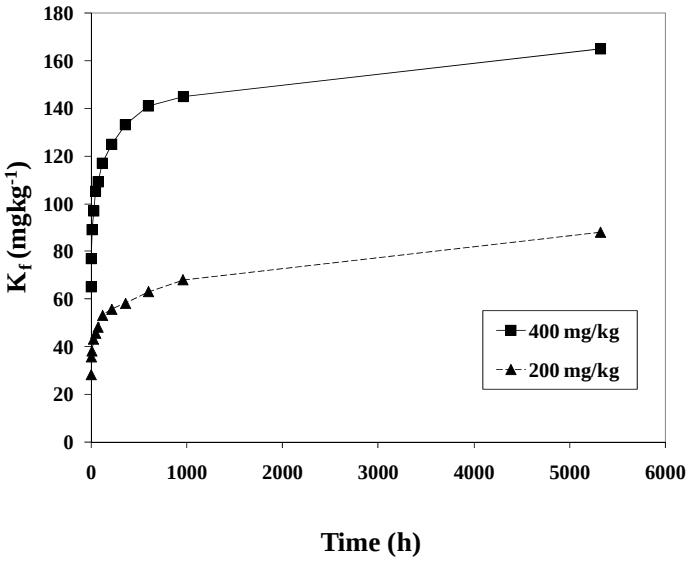

Fig. 4. Kinetics of potassium fixation (Soil No. 9)

Fig. 5 shows the potassium fixation in tree soils after 225 days. Table 7 shows the amount of potassium fixation in 20 min, 40 and 225 days of reaction time in soils.

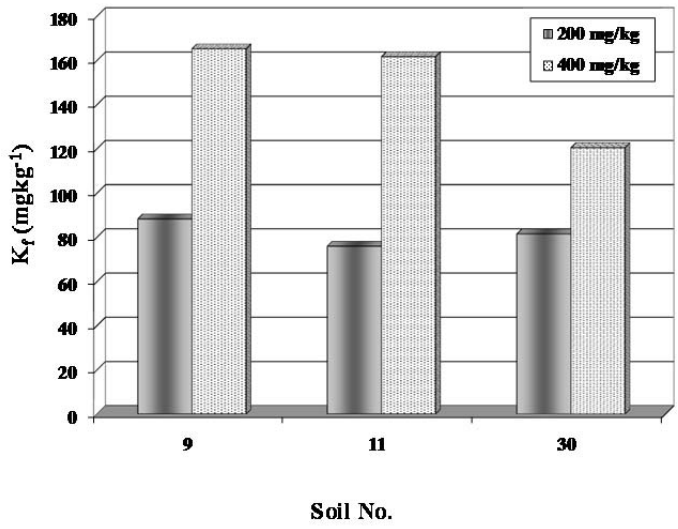

Fig. 5. Amount of potassium fixation after 225 days.

The results showed that, the capacity of potassium fixation in mentioned concentration is not limited and increase with concentration. Although at end of 225 days of reaction time the potassium fixation at 400mg K/kg soil was 1.8 times higher than 200mg K/kg soil (fig. 5). But this increase mainly related to the initial time of reaction (less than 40 days) and it seems that after this time, concentration does not have a significant impact in increasing the fixation, and rate constant after 40 days in these 2 concentration does not have any different with each other. According to table 7, for example, the potassium fixation after 225 days at 400 mg K/kg soil was 77 mg/kg more than 200 mgK/kg soil. The amount of this increase after 20 min and 40 days of reaction time was 37 and 73 mg/kg respectively. It means that in period of 6 month (40-225 days), the amount of fixation at 400 mgK/kg was only 4mg more than e 200 mgK/kg. Which indicates that gradual equilibrium among different forms of potassium and the stabilizing potassium fixation rate in different concentration after a certain period of starting the reaction(fig.6). This effect varied for different soils so that soil No.4, the impact of concentration after 40 days was more than the other soils.

Table 7. Amount of potassium fixation in 20 min, 40 and 225 days reaction time (mg/kg)

	225 days		40 days		20 minutes	
Soil No.	400 mg/kg	200 mg/kg	400 mg/kg	200 mg/kg	400 mg/kg	200 mg/kg
9	165.2	88.2	141.2	68.2	65.2	28.2
11	161.6	75.85	137.6	69.6	49.6	14.6
30	120.4	81.4	100.4	66.4	36.4	21.4

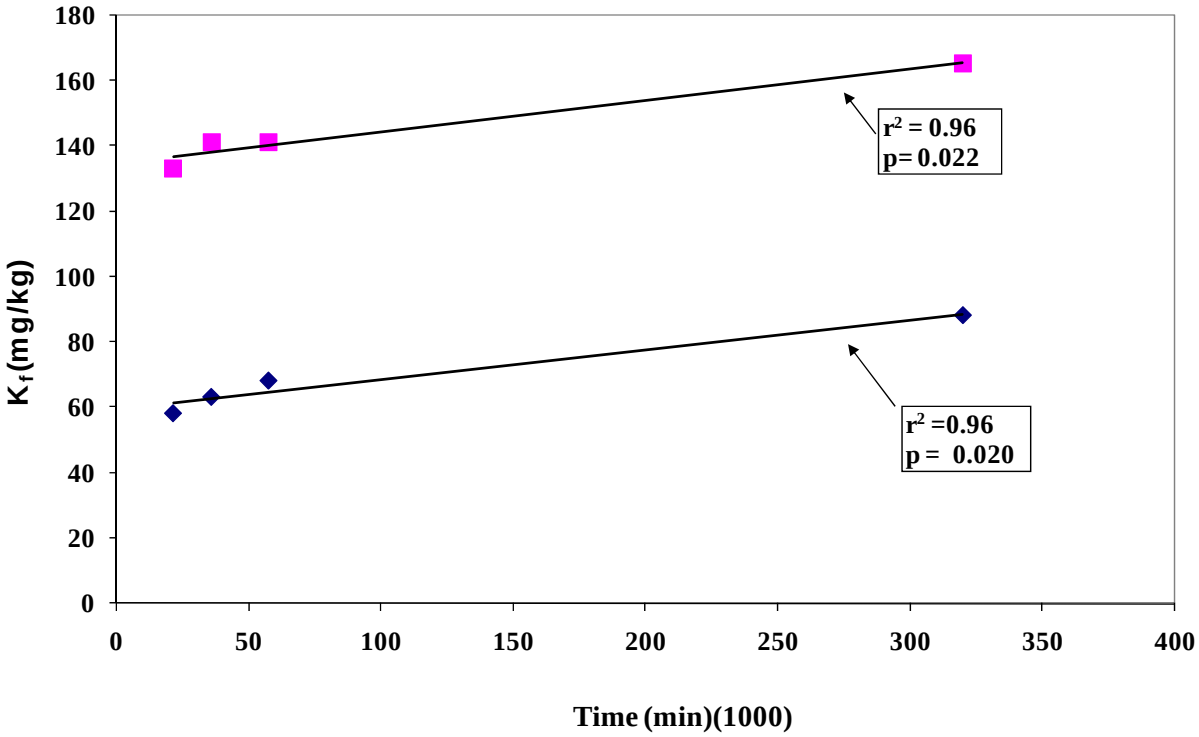

Fig. 6. Fitting Zero-order equation to slow reaction of K fixation at different concentration (15-225 days)

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Potassium Application is the Most Effective Countermeasure to Reduce Radioactive Cs Uptake by Plant

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Abstract

Subsequently after the Great East Japan Earthquake (March 11, 2011), tsunami damaged the TEPCO's Fukushima Dai-ichi Nuclear Power Plant (FDNPP). Which resulted a large amount of radioactive compounds (mainly ^{131}I, ^{134}Cs and ^{137}Cs) to the environment. Because of climate condition (wind direction, precipitation, etc.) and geographical feature a large area of eastern Japan, especially Fukushima prefecture, was suffered by these radioactive compounds. Remediation of crop field has been carried out mainly by top soil removal, but complete removal of radioactive compounds from the field is impossible. Which means farmers should introduce another countermeasure to mitigate the transfer of radioactive Cs from soil to harvest. Based on a large survey in 2011 of paddy field, it was demonstrated that soil exchangeable potassium level is the most critical parameter to regulate the radioactive Cs uptake from soil to brown rice (Kato et al. 2015). We have introduced the countermeasure to maintain the exchangeable potassium level more than 25 mgK_2O/100g soil during the growth. This countermeasure was successfully decrease the radioactivity of brown rice produced in the damaged paddy fields. Increasing the potassium level in the soil is also effective for other crops such as soybean, wheat, buckwheat, pasture, etc. Though this countermeasure has been carried out since 2012, one of the difficulties is that we do not have suitable method to evaluate the sufficient potassium level during the growth at the beginning of cultivation. So the potassium fertilizer was dressed uniformly. K-TPB method is alternative candidate to overcome this problem, and we have tested on different soils and confirmed that K-TPB method can be used to predict the potassium availability of the soil to mitigate the radioactive Cs transfer (Eguchi et al. 2015). Based on the observation of potassium availability by different types of mica, mica based potassium resource is also proposed.

The Role of Potassium for the Remediation of Radioactive Cesium Contaminated Agricultural Land – Fate Aftermath in Fukushima

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Abstract
Effect of radioactive compounds (^{131}I, ^{134}Cs and ^{137}Cs are in concern) to the agricultural products and agricultural field has been evaluated in Fukushima. Radioactive compounds were scattered and distributed based on wind, precipitation, geographical and geometrical factors from the FDNPP after East Japan Great Earthquake on March 11th, 2011. Evergreen plants (tea), winter crops (winter wheat, pasture) and orchard plants were directly contaminated by fall out. As in the case of paddy and upland crops, most of them are before the cultivation and only the soil surface was contaminated. The countermeasure was mainly dependent on how the plant and/or field was contaminated. Removal of attached radionuclides from the plant body was effective to reduce the harvest radioactivity and a large area of tea and fruit orchard were treated by mid place cutting and bark removal by high water pressure machine, respectively. On the other hand, in the case of grass land, as the transfer factor (radioactive Cs concentration in shoot / radioactive Cs concentration in soil) of pasture is relatively high, appropriate countermeasure (i.e. reversal tillage) was required. In paddy field and most of upland crop fields, regardless of top soil removal, it is required to mitigate the radioactive Cs transfer from soil to plant by maintain the exchangeable K level high during the growth (Kato et al. 2015). By these countermeasures, the radioactive Cs contamination the brown rice is greatly decreased (Table 1).

Introduction
As a large area has been contaminated and even after the decontamination process (e.g. top soil removal and reverse tillage), a sort of radioactivity still remains in the soil. To overcome this problem, the major countermeasure which has been taken to reduce the uptake of radioactive Cs (134Cs + 137Cs) is applying sufficient amount of potassium to the field. In 2011, after the FDNPP event, the urgent request to overcome the contaminated area in Fukushima prefecture and surrounding prefectures (e.g. Miyagi, Tochigi, Chiba, Gunma, Niigata prefectures). Based on the researches on rice plant which has been carried out about 50 years ago (Tensho et al. 1959 and related researches) and subsequent only few reports (e.g. Yonezawa and Mitsui 1965, Tsumura 1984), and researched by using global fallout data (Komamura et al. 2001), and Chernobyl event (Komamura et al. 2001, Tsukada et al. 2002), it is estimated that the higher transfer factor (radioactivity of Cs in brown rice / radioactivity of Cs of grown soil) is lower than 0.1 (Uchida et al. 2005). And the provisional limitation value for rice was 500 Bq/kg in 2011, it was allowed to plant rice in those paddy field lower than 5,000 Bq/kg in 2011.

Unfortunately in some monitoring sample of harvested brown rice exceeded the regulation value in 2011 (> 500 Bq/kg).

Materials and Methods
Detailed analytical information will be obtained in Kato et al. (2015) and Eguchi et al. (2015).

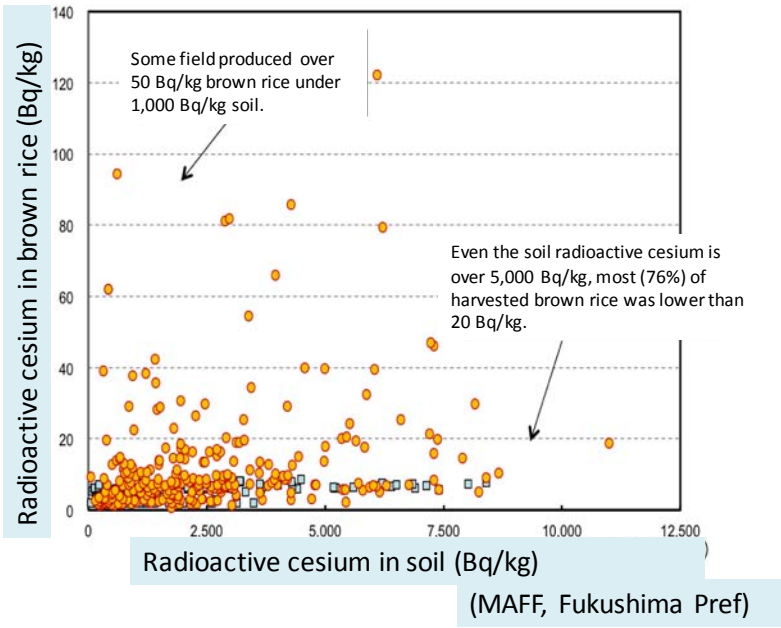


Fig. 1 Radioactive cesium concentration of soil and harvested brwon rice in Fukushima prefecture, cultivated outsider of Special Decontamination Area.

http://www.maff.go.jp/j/kanbo/joho/saigai/s_seisan_1.html

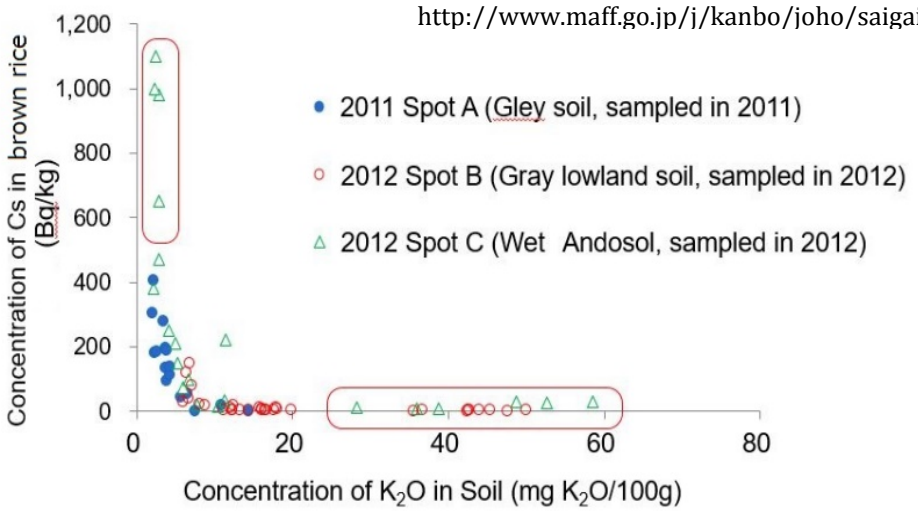
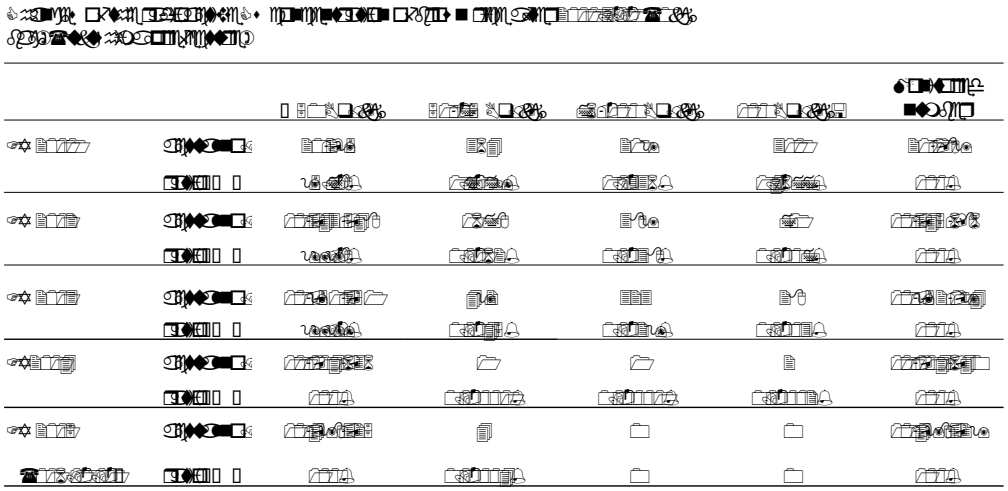


Fig. 2 The relationship between exchangeable potassium concentration in soil and radioactive Cs concentration in brown rice.

Results and Discussion

When the data were collected from many paddy field in Fukushima prefecture in 2011, and it was confirmed that there was no clear relationship between soil radioactive Cs concentration and brown rice radioactive Cs concentration (Fig. 1). As K fertilizer has been considered the plausible compounds to mitigate the transfer of cesium by its similar chemical characteristics. Several researchers have been reported the effectiveness of application of K application under K deficient soil (Lebmrechts 1993, Nisbet 1993, Smolders et al. 1997). We have plotted the relationship between soil Exchangeable K2O and radioactive Cs concentration (Fig. 2). Which shows a very clear negative relationship between them. Based on these data we have determined that maintaining 25mgK2O/100g soil throughout the growth stage is essential to keep the transfer factor lower than 0.01. As the standard value for brown rice radioactive Cs concentration was updated to 100 Bq/kg from 2012, this countermeasure has been introduced not only in the Fukushima prefecture but also surrounding prefectures as the official countermeasure to mitigate radioactive Cs from soil to brown rice. By applying this countermeasure, the ratio of exceeding standard value decreased dramatically and those brown rice produced in FY 2015 showed no sample which has higher than the value after more than 10 million all bags inspection for 30 kg brown rice bag (Table 1).

Table 1 Contamination level of brown rice produced in Fukushima prefecture after 2011.



However, additional application of K fertilizer and/or equivalent K resource (e.g. zeolite, manure, etc.) before the ordinary fertilization required additional labor for farmers and additional budget (ca. 15 billion JPY). It is because the exchangeable K2O by 1M ammonium acetate method is considered to underestimate the plant available K of soils especially where the soil is rich in mica (e.g. Jackson 1985), because non-exchangeable K in the mica interlayer is also plant-available (Sparks 1987). Alternatively tetraphenylboron (TPB) extraction method (precipitation of K with TPB is considered to mimic the process of K uptake by plant root) has been proposed (Fanning et al. 1989), which have the ability to elucidate the K supply from the mica to plant. Though rice plant is also considered to have the ability to utilize nonexhangeable K of mica (eg. Nanzyo et al. 1999), it is not clear the influence nonexchangeable K of mica on the radioactive Cs uptake by rice. Evaluation of plant-available K by TPB extraction was applied to paddy rice. By using different mica and KCl to the paddy field, rice plant was grown to obtain brown rice in pot experiment. Relationship between the transfer factor (TF) and exchangeable K was plotted in Fig. 3(a). The relationship is not consistent when different type of mica was applied. It is considered that the ability to supply K from mica to soil solution is different among different mica types. On the other hand, when the soil K level was evaluated by using TPB extraction, the relationship indicates a very clear negative relationship with TF (Fig. 3(b)).

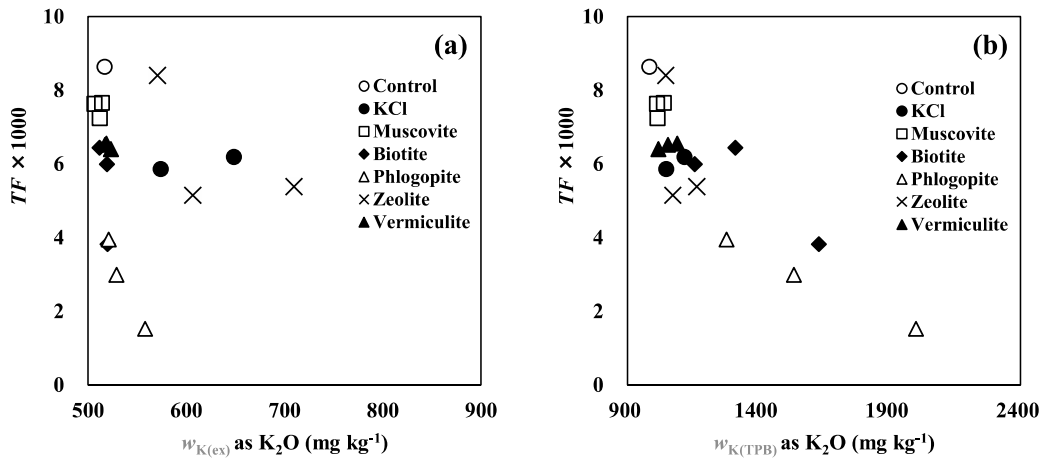


Fig. 3 Relationship between ^{137}Cs transfer factos for brown rice (TF) and (a) exchangeable K concentrations before planting and (b) sodium tetraphenylboron-extractable K concentrations before planting

Conclusion

After the East Japan Great Earthquake and subsequent Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plant accident, huge efforts have been paid for the countermeasure of the contaminated farmland. Besides the physical decontamination, far larger area is required to have mitigation of radioactive Cs transfer from soil to plant. K application is the most promising measure, but it is now coming to consider to apply it more efficiently in the meaning of labor and cost. In this study, TPB-extractable K concentration measured before planting was strongly negatively correlated with the ^{137}Cs TF, whereas exchangeable K concentration before planting was not correlated with the TF. Therefore, we conclude that TPB-extractable K is more reliable than exchangeable K as a basis of fertilizer recommendations for radiocesium-contaminated paddy fields.

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Acknowledgements

The data are collected by many researchers of NARO and Fukushima Agricultural Technology Center. The study is financially supported by MAFF, MEXT (KAKENHI) and NARO.

Regional Investigation of Soil Potassium Variability, a Study Case in Switzerland

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Abstract
Potassium (K) is a crucial element for plant nutrition but its availability in agricultural soils is influenced by many agro-environmental factors. In Switzerland, a soil monitoring network (FRIBO) was established in 1987 with 250 sites distributed over the whole of the canton of Fribourg, whose territory is shared between the Swiss Midlands and the Western Alp foothills. In this study area, diverse geological deposits, soil types and land uses are present, making the network interesting for assessing the relative contribution of environmental variables and land use management on soil properties. The aims of the present study were to (i) characterize the soil K status in the Fribourg canton according to four different extraction methods; (ii) analyse the spatial and temporal variability of soil K in relation to land use, soil type, soil parent material and topography; and (iii) analyse the implications for K fertilization management. The spatial distribution of total K was particularly influenced by soil types and soil parent materials while available K forms were significantly different among land uses. All K forms showed similar spatial regional patterns for all spatial interpolation methods, with areas dominated by permanent grassland and crops presenting higher values. However, these trends were less pronounced for the available K forms due to the prevalence of on-farm management practices for these K forms and their high temporal variability. This hypothesis was supported by spatial clustering of low and/or high K fertility status that could be related to local particular farming practices.

Response to Potassium Fertilization in Hybrid Rice-Maize Cropping System in Calcareous Soil of Eastern India

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Abstract

Potassium (K) is one of the 17 essential plant nutrient and plays a key role in many metabolic activities of the plant. Rice–maize systems are vital for meeting food requirements and improving food security for a large number of urban and rural poor of South Asia. In general, the small holder famers applied potassic fertilizers either insufficient or imbalanced, ignoring the extent of soil inherent potassium supplying capacity. Thus, to evaluate the response of K in hybrid rice-maize cropping system, field trials were conducted with treatments consisting of ample NPKSZn, omission plots comprised of (-)N, (-)P, (-)K, (-)S, (-)Zn and unfertilized check in randomized block design with three replications in calcareous soil in farmers' fields in Bihar (India). Application of balanced dose of potassic fertilizers along with other nutrients produced maximum yield both in hybrid and inbred crops. Omission of the potassium reduced the yield, but the reduction in yield was lesser than in the N and P omission plots. The percent decrease in hybrid rice-maize system grain yield due to omission of K varied from 5 to 15% at different farmers' fields depending upon the variation in soil inherent nutrient supplying capacity. The yield loss was greater in hybrid crops than inbred crops under fertilized plot that indicates higher demand of nutrients by the hybrids. The hybrid rice grain yield loss due to K omission was equivalent to economic loss of INR 4672 – 7773/ha with a mean of INR 5993/ha, while in hybrid maize it was 2547 – 22270/ha with a mean of INR 14847/ha. Return on investment (ROI) for K (i.e. rupees per rupee invested on K fertilizer) for rice ranged from 2.1 – 3.6 with a mean of 2.7 while for hybrid maize it varied from 0.5 – 4.0 with a mean of 2.7. The sustainable yield index (SYI) indicates that hybrid rice-maize cropping system was more sustainable in ample fertilized plot than the K omission plots. There was decline in availability of K in omitted plots while there was build up in available K in ample fertilized plots. The present findings indicate that there is a direct link between soil supplying capacity and K requirement by the different types of crops. Thus, adoption of hybrid crops with balanced application of K fertilization will be one of the tools for enhancing the food demand to feed the increasing populations and also helps in maintaining the soil fertility.

INTRODUCTION

Rice (*Oryza sativa* L.)-based cropping system has importance from the nutrient management point of view as because unlike most other crops rice is grown under anaerobic soil conditions; and the succeeding crops are grown under aerobic soil conditions (Salam et al. 2014). It is also an important crop in Bangladesh, Nepal and India in terms of both area and fertilizer use. In fact, rice based cropping system is the dominant system in South and Southeast Asia (Timsina and Connor 2001). Maize (*Zea mays* L.) has the highest genetic yield potential among cereals and is sometimes referred to as the 'queen of cereals' (Tollenaar and Lee 2006). It is the third most important cereal crop and cultivated in 160 countries on almost 150 million ha and contributes to 36% (78.2 million tonnes) in the total grain production of the world (McCann 2007; Parihar et al. 2011). India is ranked fifth among maize producing countries (FAO 2010). In India, maize is predominantly used for industries, only 25% of its production is used as human food (Jat et al. 2009).

Potassium (K) is one of the 17 essential plant nutrient and plays a key role in many metabolic activities of the plant. Plants need large quantities of K, as much as, or even more than nitrogen (Timsina et al. 2010). Plants deficient in K become susceptible to drought, excess water, high and low temperature, and to pests, diseases, and nematodes. It has been widely reported that most soils of South Asia have high K status due to continuing K additions from rainfall, irrigation water, and release from K-rich clay minerals (Dobermann et al. 1996). Rice–maize systems are vital for meeting food requirements and improving food security for a large number of urban and rural poor of South Asia. In general, the small holder famers applied potassic fertilizers either insufficient or imbalanced, ignoring the extent of soil inherent potassium supplying capacity. Thus, to evaluate the response of K in hybrid rice-maize cropping system, field trials were conducted in farmers' fields in Bihar (India).

METHODOLOGY

Field experiments were conducted in farmers' fields during 2013-14 and 2014-15 in calcareous soils of Bihar (India). The climate is sub-tropical, greatly influenced by hot-dry summer and cold winter. It falls in the region of south-west monsoon and generally monsoon starts from mid June and continued up to October. The mean average annual rainfall is 1240 mm out of which nearly 80-90 % is received between June to October. The day length varied from 10 hours 12 minutes to 13 hours 43 minutes. The initial properties of soil are presented in table 1.

The experiment was conducted in randomized block design to assess the contribution of nutrients to yield of hybrid rice (*Oryza sativa* L.) and maize (*Zea mays* L.) through omission plot technique. During *kharif* seasons (wet season) (2013 and 2014), two varieties of rice *viz.* hybrid rice (Arize 6444) and inbred rice (Rajshree) was grown, while during *rabi* (winter season) (2013-14 and 2014-15) two verities of maize *viz.* hybrid maize (DKC9081) and inbred maize (Laxmi) was grown (Table 2). Nine treatment combinations (Table 2) plots were taken to conduct the trials. The net plot size was 100 m^2. In hybrid rice (Arize 6444) the ample fertilizer was applied by fixing the yield target at 7 t ha^{-1} ($N:P_2O_5:K_2O$, 175:70:80) and in local rice (Rajshree) at 5 t ha^{-1} ($N:P_2O_5:K_2O$, 125:50:60), while in hybrid maize (DKC 9081) at yield target of 10 t ha^{-1} ($N:P_2O_5:K_2O$, 210:140:200) and in local maize (Laxmi) at yield target of 6 t ha^{-1} ($N:P_2O_5:K_2O$, 150:70:120) through urea (46% N), triple super phosphate (46% P_2O_5) and muriate of potash (60% K_2O). The sulphur was applied at 30 kg ha^{-1} through bentonite-S (90% S) and Zn at 3 kg ha^{-1} through Zn-EDTA (12% Zn) in both rice and maize as per treatment combinations (Table 3). The impact of nutrient omission was studied only in hybrid crops, while, the inbred crop was grown to compare the yield gap in between inbred and hybrid crop with ample fertilization and also to compare the nutrient mining by these two varieties.

Grain and straw samples were drawn from each treatment plot after recording yields. Each plant sample was washed in acidified detergent solution and finally rinsed three times in deionized water. These samples were dried in a forced-air circulation oven at 65°C. These samples were pulverized in wiring blender, which was cleaned with a hairbrush after grinding each sample, and digested in di-acid (9:4 v/v) of nitric acid (HNO_3)/perchloric acid ($HClO_4$). Following the digestion, volume of digests was made up to 50 mL using distilled water. The nutrient concentration in plant samples were determined by the methods as described by Tondon (1984).

Initial soil samples (0-15 cm) as well as after harvest of maize crop, were drawn with stainless steel tube auger. The soils were air dried and ground to pass through a 2-mm stainless steel sieve. The different soil parameters were determined by standard methods described in table 1.

RESULT AND DISCUSSION

Effect of Potassium on System Productivity and Sustainable Yield Index

Nutrient management showed significant effect on rice and maize yield. Omission of the nutrient decreased the yield and N was the most limiting nutrient followed by P, K, S and Zn (Table 4). The grain yield of hybrid rice-maize cropping system in terms of rice equivalent yield (REY) was maximum (14.1 t/ha) in ample fertilized plot and minimum in unfertilized check (6.5 t/ha). The nutrient response i.e. decrease in system yield was maximum in unfertilized plot followed by N, P, K, S and Zn omitted plot. The system yield of inbred variety was lower than the hybrid variety. The decrease in REY due to omission of K varied from about 5 to 15 percent with an average of 11 percent over ample fertilized plot. The decrease in yield due to omission of the nutrients depends on the soil environment during growing period of a crop.

Balanced fertilization (NPKSZn) exhibited maximum sustainability yield index (SYI) for both hybrid and inbred crops in the system (Table 4). The SYI for hybrid crops was lower than the inbred crop in unfertilized plot. Omission of K decreased the sustainability yield index (SYI) while it was maximum both for hybrid and inbred crops in ample fertilized plot and minimum in unfertilized and N omitted plot. The findings showed that application of balanced nutrition will be more sustainable for both hybrid and inbred crops. Bhattacharya et al. (2008) also found that treatments without adequate supply of nutrients through mineral fertilizers resulted in lower SYI compared with those treatments received recommended dose of mineral fertilizers.

Potassium Concentration and Its Uptake

The nutrient concentration in grain and straw/stover and uptake by the rice and maize crops decreased in respective nutrient omitted and unfertilized plot over ample fertilized plot. Maximum decrease in nutrient uptake was recorded in N omission followed by P, K, S and Zn in rice-maize cropping system. Omission of potassium (K) decreased the respective nutrient concentration in both grain and straw/stover. The concentration of N, P, K, S and Zn in inbred crop was lower than the hybrid crops in ample fertilized plots. The potassium concentration in hybrid rice and maize grain varied from 0.138 to 0.206 and 0.532 to 0.574 percent with an average concentration of 0.160 and 0.551 percent, respectively. The total potassium uptake by hybrid rice and maize varied from 49.7 to 94.8and 134.0 to 158.7 kg/ha with a mean of 76.8 and 147.3 kg/ha, respectively. The decrease in total potassium uptake by hybrid rice and maize in K omitted plots was 22.7 and 27.2 percent, respectively over ample fertilized plot (Fig 1). Highest nutrient concentration and uptake in ample fertilized plot was attributed to the higher available nutrients and possibly more proliferation of root system with balanced fertilization leading to higher absorption of nutrients from soil. The K uptake by hybrid rice and maize grain showed positive relationship with grain yield in K omitted plot (Fig 2 and 3). This indicates that the K plays an important role in crop production.

Economics of Potassium Fertilization

The hybrid rice grain yield loss due to K omission was equivalent to economic loss of INR 4672 – 7773/ha with a mean of INR 5993/ha, while in hybrid maize it was 2547 – 22270/ha with a mean of INR 14847/ha. Return on investment (ROI) for K (i.e. rupees per rupee invested on K fertilizer) for rice ranged from 2.1 – 3.6 with a mean of 2.7 while for hybrid maize it varied from 0.5 – 4.0 with a mean of 2.7.

Impact on Potassium Status in Post Harvest Soil

Application of balanced nutrients based on target yields in both hybrid and inbred crops improves the availability of potassium in post harvest soil (Fig 4). There was a decline in available potassium status in potassium omitted and unfertilized plots. The decrease in available K was more pronounced in K omitted plot than the unfertilized plot that might be due to more K uptake in K omitted plot (Fig 4). Also the decrease in available K status in unfertilized plots was more in hybrid grown plot than the inbred crops indicating that the hybrid crops (higher yield potential) mines more K nutrients from soil than the inbred

crop (lower yield potential). In general, the decline in the availability of nutrients in post harvest soil was more in respective nutrient omission plot than the unfertilized check that might be due to more yields in nutrient omission plot than the unfertilized plot and thus mines more nutrients from nutrient omission plot than the unfertilized plot. A given soil has a specific inherent nutrient supplying capacity (Chuan et al. 2013), but the capacity is crop specific because of the variation in crops' biological demand and uptake ability. Root biological differences and nutrient solubilizing power of different crop species have a great role in helping the crop to adapt under nutrient stress conditions and in absorption of soil nutrients.

CONCLUSIONS

At present, the area under rice-maize cropping system is much less compared to rice-rice, rice-wheat or maize-wheat systems, but is increasing rapidly since past few years. The increase is very rapid in Bangladesh, Nepal, and Eastern as well as in Southern India. Although the yield potential of hybrid crops is more but in general, a farmers could not achieved it. There is potential to reduce yield gaps through nutrient management. The demand of K by the hybrid rice and maize is very high than the inbred verities. High K demand is associated with high extraction or uptake of K nutrients from soils leading to declining fertility unless the extracted nutrients are replenished from external sources. This study highlighted for better nutrient management as per crop requirements to reduce yield gaps and also to evaluate the impact of the nutrient omission in crop production.

Application of balanced dose of fertilizers yielded maximum in both hybrid as well as inbred crops. Omission of the nutrients reduced the yield, and N was most limiting nutrient followed by P, K, Zn and S. The hybrid rice and maize yielded 34 and 37.5 percent more grain yield, respectively than the inbred crop with ample fertilization based on target yield. The hybrid and inbred rice-maize cropping system was more sustainable in ample fertilized plot than the respective nutrient omission and unfertilized plots. Also, hybrid crop mines more K than the inbred crops. The available K was found to decline more in K omitted plots and unfertilized plots, while a build up was recorded in ample fertilized plot. Thus, the study on K omission helps a crop grower about the understanding role of K, its deficiency symptoms and balanced K nutrition. Adoption of hybrid crops with balanced nutrients will be one of the tools to feed the increasing populations with enhancing the food demand and also helps in maintaining the soil fertility. However, further research is needed at different locations to determine and optimize the K nutrient demands by the hybrid crops for getting sustainable yield and maintaining soil fertility.

ACKNOWLEDGEMENTS

The financial support of International Plant Nutrition Institute (IPNI)-South Asia Program for conducting the project is thankfully acknowledged. The authors are also thankful to the selected farmers for their keen interest and cooperation during conducting the trials. The technical and administrative support of Dr. Rajendra Prasad Central Agricultural University, Bihar, India in close monitoring and smooth running of the research is thankfully acknowledged. The authors would also like to thank Dr. A. M. Johnston, Retd. Vice President, IPNI, Asia, Africa and Middle East Group for his kind interactions and guidance during the execution of field trial.

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Table 1. Initial soil (0-15 cm) properties of famers' fields

Sl. No.	Variables	Range	Mean	Reference/method
1.	pH (1:2, soil : water)	7.43 – 8.15	7.87	Glass electrodes pH meter (Jackson, 1973)
2.	EC (dS/m) at 25^0C	0.21 – 0.72	0.34	Conductivity Bridge (Jackson, 1973)
3.	Organic carbon (%)	0.42 – 0.80	0.58	Walkley and Black (1934)
4.	Available N (kg/ha)	190.4 – 285.8	223.8	Alkaline permagnate method Subbaih and Asija (1956)
5.	Available P (kg/ha)	12.4 – 56.6	24.2	Olsen's method (Olsen's *et al.* 1954)
6.	Available K_2O (kg/ha)	110.9 – 239.7	188.3	Flame Photometer (Jackson, 1973)
7.	Available S (mg/kg)	8.4 – 35.9	16.4	0.15 % Calcium chloride Method (Williams and Stienbers.,1959)
8.	Available Zn (mg/kg)	0.38 – 2.16	1.09	Lindsay and Norvell (1978)

Table 2. Treatments details

S. No.	Treatments	Crop/Variety		Code
		Kharif rice	Rabi maize	
1	N+ P+ K+ S+ Zn	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_1
2	P+ K+ S+ Zn (-N)	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_2
3	N+ K+ S+ Zn (-P)	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_3
4	N+ P+ S+ Zn (-K)	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_4
5	N+ P+ K+ Zn (-S)	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_5
6	N+ P+ K+ S (-Zn).	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_6
7	Inbred variety under unfertilized check	Inbred (Rajshree)	Inbred (Laxmi)	T_7
8	Inbred variety under ample fertilization	Inbred (Rajshree)	Inbred (Laxmi)	T_8
9	Hybrid rice under unfertilized check	Hybrid (Arize-6444)	Hybrid (DKC-9081)	T_9

Table 3. Fertilizer dose and time of application

Yield target (t/ha)	N (kg/ha): 3 splits				Total P_2O_5 (kg/ha) basal	K_2O (kg/ha): 2 splits		
	Total N	Basal N	Active tillering	Panicle initiation		Total K_2O	Basal	Panicle initiation
Rice								
5 (Inbred rice)	125	55	35	35	50	60	30	30
7 (hybrid rice)	175	75	50	50	70	80	40	40
Maize								
Yield target (t/ha)	Total N	Basal N	At V6	At V10	Total P_2O_5 (kg/ha) basal	Total K_2O	Basal	At V10
6 (Inbred maize)	150	50	50	50	70	120	60	60
10 (hybrid maize)	210	70	70	70	140	200	100	100

V6 and V10, six and ten leaf stage in maize, respectively.

Table 4. Rice equivalent yield (REY), standard deviation (SD), sustainable yield index (SYI) and percent decrease in REY over ample fertilization (T_1) in nutrient omission trial

Treatment	REY (t/ha)			SYI	Percent Decrease		
	Min	Max	Average		Min	Max	Average
T_1	13.2	14.9	14.1	0.91	-	-	-
T_2	6.9	8.4	7.7	0.49	40.2	52.1	45.0
T_3	11.5	13.3	12.2	0.78	7.9	17.4	13.5
T_4	11.8	13.6	12.5	0.80	4.8	15.1	11.1
T_5	11.8	13.7	12.7	0.82	5.2	12.4	9.6
T_6	12.5	13.8	13.1	0.85	4.0	11.0	7.0
T_7	3.5	5.5	4.3	0.37	40.6	57.7	51.4
T_8	7.7	10.2	8.8	0.79	-	-	-
T_9	5.2	7.6	6.5	0.37	45.2	64.9	54.0
LSD ($p \leq 0.05$)	-	-	0.38	-	-	-	-

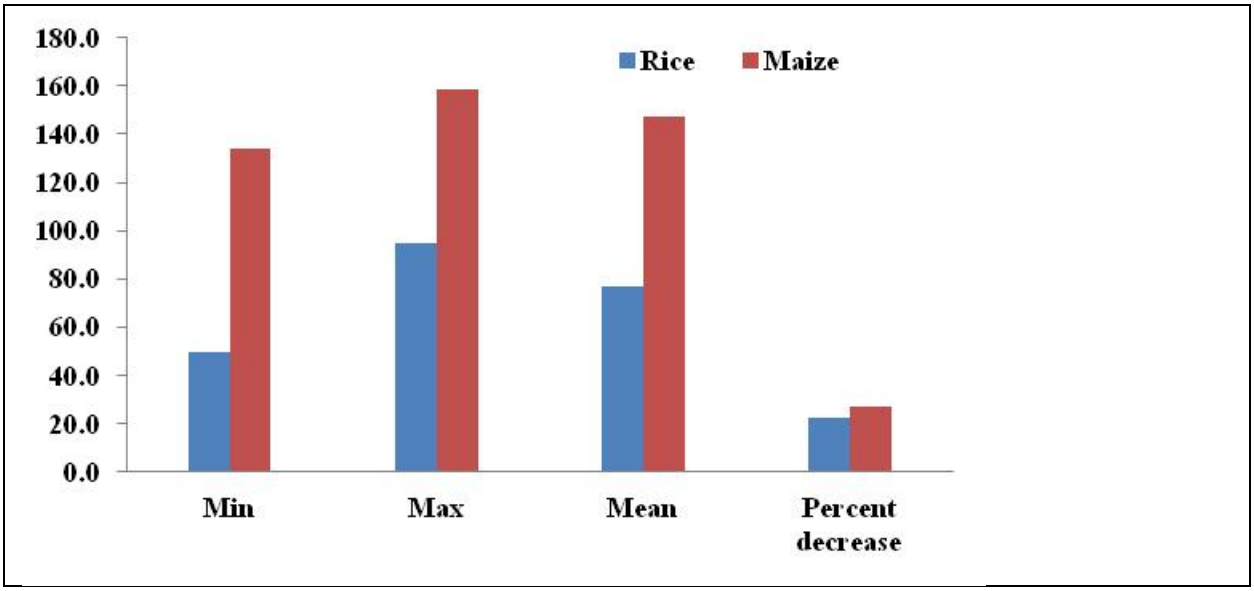

Fig 1. Total potassium uptake (kg/ha) in K omitted plot and percent decrease over ample fertilized (NPKSZn) plot by hybrid rice and maize under nutrient omission trial

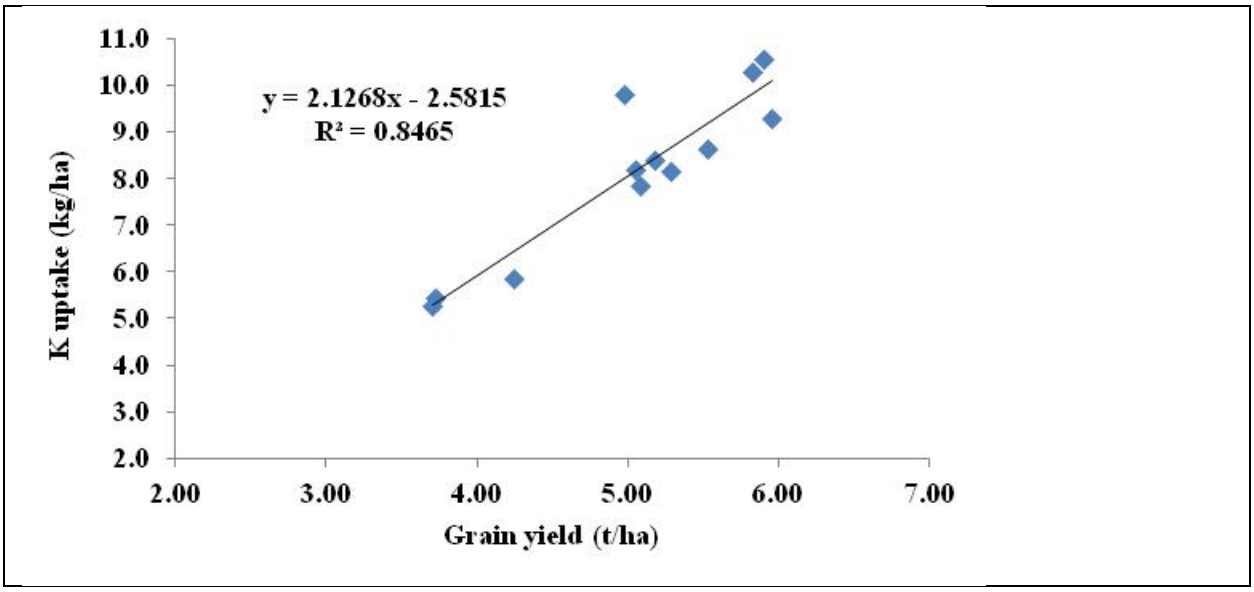

Fig 2. Relationship between potassium uptake by hybrid rice grain and grain yield in K omitted plot

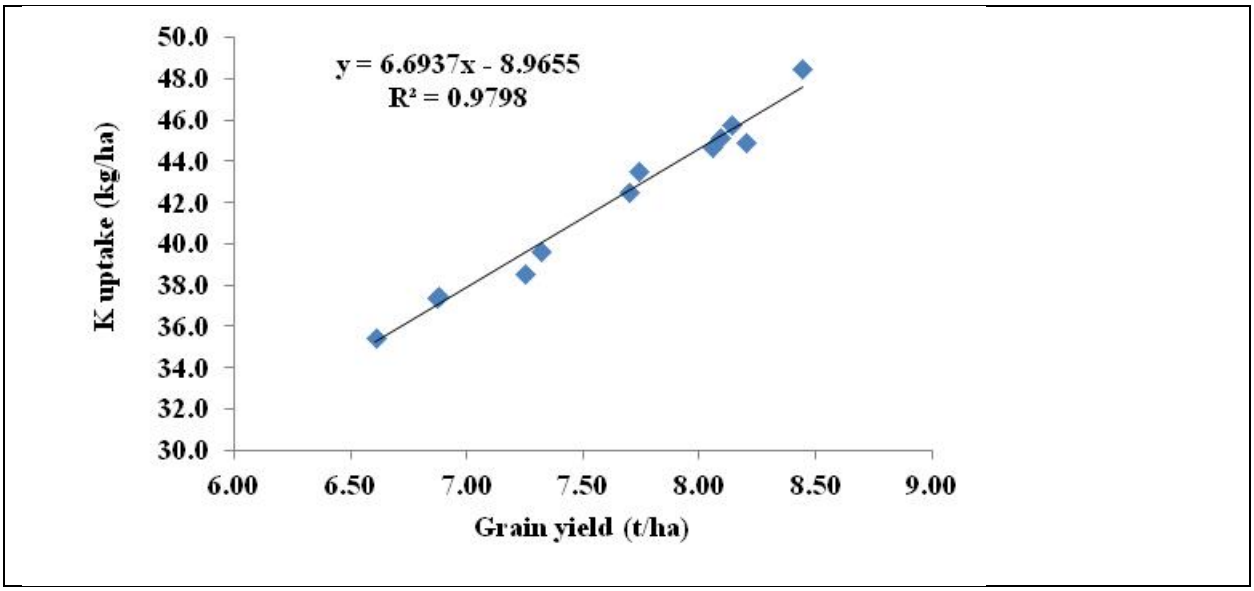

Fig 3. Relationship between potassium uptake by hybrid maize grain and grain yield in K omitted plot

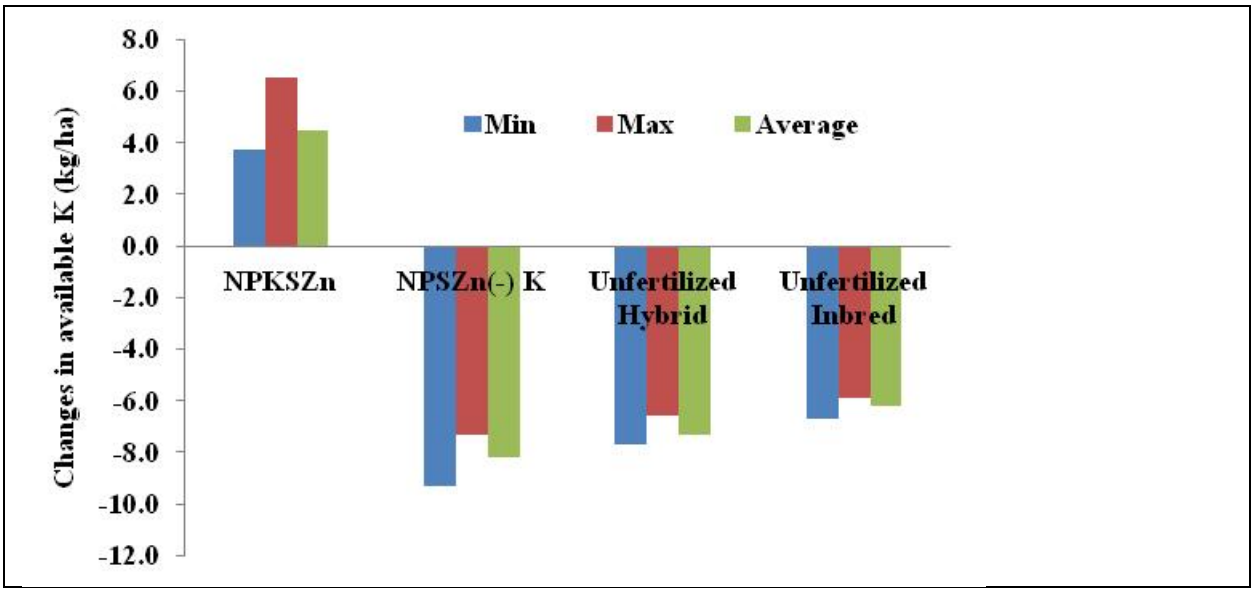

Fig 4. Changes in available potassium in post harvest soil (0-15 cm) nutrient omission trial

Potassium and Phosphorus Fertilization in a Long-term Rice and Soybean Rotation

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Abstract
An experiment with rice and soybean was conducted for seven years in Missouri (USA) to determine how quickly farmers need to build up soil test levels in low P and K fertility fields. The crops were rotated annually between two fields. Plots received phosphorus (P) and potassium (K) fertilizer to increase soil Bray-1P and ammonium acetate extractable K in one, four, or eight year buildup programs. In most years, soybean and rice yields from plots receiving P and K fertilizer treatments were significantly greater than yields from untreated checks. Tow soil test P and K target levels were tested. The soil test target for rice using University of Missouri recommendations was 22% lower for P and 36% lower for K than the soybean target. Averaged across buildup programs, rice produced significantly greater yields using the soybean P and K targets than the rice P and K targets. No difference in yield was found between slow and fast P and K buildup programs. Farmers can prolong buildup of soil test P and K over four to eight years without yield losses.

INTRODUCTION

Rice and soybean are important crops on farms near the Mississippi River in the Delta counties of Missouri, Arkansas, Mississippi, and Louisiana. In the region, farmers typically do not grow rice more than two consecutive years in fields without rotating with another crop. Alternating rice cropping with a legume such as soybean helps soil microbes decompose the rice residue faster by lower the carbon nitrogen ratio. Both rice and soybean benefit from rotating to disrupt disease and weed pest cycles.

Annual P and K fertilizer application rates by farmers in rice and soybean fields usually follow soil test recommendations from public or private laboratories. State universities in the U.S.A. conduct fertilizer rates field trials to calibrate soil test levels with yield responses. Most labs use a single extraction solution such as Mehlich-3 for both P and K testing (Thomas, 1982). The University of Missouri Soil Test Lab uses Bray-1 (Bray and Kurtz, 1945) to extract P and ammonium acetate (Brown & Rodriguez, 1983).

Fertilizer recommendations consider the probability of producing higher crop yields from an additional increment of fertilizer at a given soil test level. University of Missouri recommendations have three components- soil test target, annual crop removal, and buildup. Each crop has a recommended P and K soil test target for optimum yields (Buchholz, 2004). Soil test target level is the amount of extractable nutrient found in a soil at the critical point where applying more fertilizer is not likely to increase crop yields. Crop removal is the amount of nutrient contained in harvested forage, grain, or fiber. For estimating crop removal, the laboratory requires the grower to enter a yield goal on a submission form with the soil sample. Build-up is the additional fertilizer needed above crop removal to increase low- and medium-testing soil P and K to the target fertility level for crop production.

MATERIALS AND METHODS

A long-term field evaluation was initiated in 2004 in two adjoining fields with the same initial soil fertility at Glennonville, Missouri. The experiment was originally planned to last through 2011, eight years, but ended one year short in 2010. The objective of the study was to evaluate effects of P and K build-up programs and soil test targets on rice and soybean yields using equations in the University of

Missouri (MU) fertilizer recommendation program. Soybean and rice were fertilized using both soybean and rice target levels in the recommendation program.

The test was conducted on a Dewitt silt loam (fine, smectitic, thermic Typic Albaqualf) soil which is poorly-drained with a silty clay loam subsoil. The Dewitt soil contains smectite clay in the subsoil with secondary amounts of illite and kaolinite. The experimental design was a randomized complete block with four replications. Rice and soybean were alternated between the adjoining fields to maintain the annual soybean-rice rotation. Crop residues were incorporated each year with a disk and field cultivator. Both crops were planted in one or the other field each year. The plan for the eight year trial was for each field to be planted four years in rice and four years in soybean. Rice were drill seeded (19-cm row spacing) at a rate of 330 seeds m^{-2}. Soybean were drill seeded with the same row spacing at a rate of 53 seeds m^{-2}.

Soil test P and K were monitored each spring by collecting 0 to 15-cm composite soil samples from each plot prior to fertilizer application and analyzed for Bray-1 P and ammonium acetate-extractable K at the MU- Delta Center Soil Laboratory at Portageville, Missouri. Soil potassium was extracted in 1N ammonium acetate and measured with a Perkin-Elmer AAS. Phosphorus was measured colorimetrically using Bray-1 extraction solution. Initial soil test levels in the fields averaged 32 kg Bray-1 P ha^{-1} and 184 kg ammonium acetate-extractable K ha^{-1}. Cation exchange capacity (CEC) was 9.8 meq/100g soil and organic matter content was 2.0%.

Fertilizer treatments used in the experiment were an untreated check (N only in the rice rotation), and 1-year, 4-year, and 8-year P and K build-up programs with treatments including soybean and rice soil targets (Table 1). The treatments were designed so that at the end of eight years, the total amount of fertilizer applied to each plot were equal for buildups within the two target groups. We were not able to finish the last year of the eight year buildup treatment. Triple super phosphate (0-46-0) and muriate of potash (0-0-60) were used as P & K sources. The amount of fertilizer applied included the prescribed buildup plus crop removal. In the 1-year build treatment, all of the buildup P and K was applied in 2004. For the remainder of the study, these plots received only P and K amounts to off-set annual crop removal. The amount of crop removal depended on whether soybean or rice was planted in the crop rotation. Because two fields were used, both soybean and rice were grown each year. In the 4-year build treatment, the buildup P and K was divided between 2004, 2005, 2006, and 2007. After 2007, only crop removal P and K was applied in these plots. Urea was applied 168 kg N ha^{-1} on rice before flooding at V4 to V5 growth stage with no additional N at midseason.

Four decades earlier in Missouri, T.R. Fisher (1974) applied incremental amounts of P_2O_5 and K_2O fertilizer on soils to vary extractable soil P and K values and developed equations for the relationship. Shown below are Fisher's empirical equations currently used to calculate University of Missouri recommendations for P and K build-up programs

$$\text{Build-up } P_2O_5 = \frac{110(X_d^{1/2} - X_o^{1/2})}{\text{Years}} \qquad \text{Build-up K2O} = \frac{75.5(X_d^{1/2} - X_o^{1/2})}{\text{Years}}$$

X_d = desired target soil test level in kg P or K per ha
X_o = observed soil test level in kg P or K per ha
Years = desired time period for build-up

Due to the fractional exponents in the buildup equations, a field with low initial soil test K or P level will be recommended to receive more fertilizer to increase extractable amounts to the next kg ha^{-1} unit compared to a soil with medium or high initial K or P test levels.

The University of Missouri soil Bray-1 P target for soybean is 50 kg P ha^{-1}. The P target for rice was 39 kg kg P ha^{-1}. Target ammonium acetate-extractable kg K ha^{-1} for soybean is 246.4 + (5.6 x CEC) and K target for rice was 140+ (5.6 x CEC). The soil CEC of the test field was 9.8 so the calculated K target was 301 kg K ha^{-1} for soybean and 195 kg K ha^{-1} for rice.

Generally, soybean removes more K each year than rice. For the test fields, we selected a 7,056 kg ha^{-1} yield goal for rice and 3,024 kg ha^{-1} yield goal for soybean. Current MU recommendations estimate rice nutrient removal at 6.5 g P_2O_5 kg^{-1} and 4.0 g K_2O kg^{-1} of rough rice. For soybean, the nutrient removal is 14.0 g P_2O_5 kg^{-1} and 24 g K_2O kg^{-1} of soybean grain. Calculated crop removal fertilizer in the build-up treatments based on yield goals was 46 kg P_2O_5 and 28 kg K_2O per year for rice and 42 kg P_2O_5 and 73 kg K_2O per year for soybean.

Soil samples collected in April 2008, before applying fertilizer that spring, showed that Bray-1 extractable P levels were above P target levels for soybean (50 kg P ha^{-1}) and rice (39 kg P ha^{-1}) in plots with 1-year and 4-year buildup programs. At that point, these programs were complete and the plots received only maintenance crop removal fertilizer for the duration of the test. Soil P levels in the 8-year buildup program plots were below target levels. However, the P levels were higher than the untreated check (N only in rice) and on track to be above target levels after four more buildup applications in the program. Soil P levels in the check plots were below the initial 32 kg P ha^{-1} measured in 2004.

All of the buildup soil test P levels measured above the targets in 2010. Crop removal should have reduced P in the untreated checks. However, in 2010, the untreated check, was 16 kg ha^{-1} higher than it had been in 2008. In 2004, before the first fertilizer was applied, the plots tested 184 kg K ha^{-1}. The April 2008 samples showed that the soil test K in check plots declined 9 kg K ha^{-1}. Although soil test K in fertilized plots were significantly higher than the untreated check plots after 2004, K levels in check plots showed a continued decline in 2010. None of the buildup treatments reached the soybean target of 301 kg K ha^{-1}. Although numerical differences in soil K were observed, soil test K levels were not significantly different between target treatments.

Sixty percent of the time, check plots, without any P and K fertilizer, produced significantly less soybean or rice grain than fertilizer treated plots (Tables 2 and 3). No significant difference in soybean or rice yields was found between buildup programs (one, four, or eight years). Response to P and K targets was different from what we expected. Soybean yields were not greatly affected by fertilizing for the lower rice P and K soil target. Rice was impacted more than soybean by using the rice P and K target. Averaged across years and buildup programs, soybean yields were 3,290 kg ha^{-1} with the soybean P and K target compared to 3,229 kg ha^{-1} with the rice target. Rice yields averaged 9,319 kg ha^{-1} with the soybean P and K target compared to 8,799 kg ha^{-1} with the rice target (6% less).

Rice yield, averaged across years and treatments, was 8,852 kg ha^{-1}compared to the initial yield goal of 7,056 kg ha^{-1} (20% higher than planned). Soybean yield, averaged across years and treatments, was 3,200 kg ha^{-1} compared to the initial yield goal of 3,024 kg ha^{-1} (5% higher than planned). More K was removed by the rice and soybean grain than anticipated which contributed to the soil test shortfall for the soybean K targets in 2010. When T.R. Fisher developed the P and K buildup equations in Missouri four decades ago, rice was not an important crop in the state. Although his research is still valid today, calibration research is needed on other soils, including DeWitt silt loam, used in rice and soybean production.

SUMMARY

A soybean-rice rotation field experiment, conducted over a seven year period, found no justification for recommending lower soil test P and K target levels for rice than soybean. Changes are being made in the University of Missouri soil test recommendation program to set the targets for rice to the soybean targets.

No yield advantage was found from using short buildup programs (one or four years) compared to an eight year buildup program. Farmers should have the option to build up soil test levels to the target in one year if they have the financial resources to pay a large fertilizer bill or stretch the P and K build up over four or eight years without negatively impacting crop yields. In this study, rice or soybean yield losses were not observed from spreading out P and K build up in the eight year program.

More research is needed to model the relationship between available soil K, clay minerals, and fluctuating soil moisture and temperature. Considering the fluctuations in K soil test levels that we observed over years, growers should soil sampled as often as possible (2 or 3 year increments) to have any accurate assessment of P and K levels. Sampling on the same month each time will provide more uniform results but year-to-year differences in temperature and rainfall before sampling are inevitable.

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Table 1. Planned annual fertilizer application rates based on soil tests for soil P and K build-up programs in adjoining fields of Dewitt silt loam soil at the Missouri Rice Research Farm at Glennonville, Missouri.

Fertilizer	Soil Target†			Year 1‡		Years 2, 3, 4		Years 5, 6, 7, 8	
Program	P	K	N	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
	extractable		---------- fertilizer kg ha^{-1} ----------						
Soybean rotation season									
Check	-	-	0	0	0	0	0	0	0
1-year build	50§	301	0	217¶	376	43	73	43	73
4-year build	50	301	0	86	149	86	149	43	73
8-year build	50	301	0	64	111	64	111	64	111
1-year build	39#	195	0	120	105	43	73	43	73
4-year build	39	195	0	62	81	62	81	43	73
8-year build	39	195	0	52	76	52	76	52	76
Rice rotation season									
Check	-	-	168	0	0	0	0	0	0
1-year build	50	301	168	221	333	46	28	46	28
4-year build	50	301	168	90	104	90	104	46	28
8-year build	50	301	168	67	66	67	66	67	66
1-year build	39	195	168	123	60	46	28	46	28
4-year build	39	195	168	65	36	65	36	46	28
8-year build	39	195	168	56	32	56	32	56	32

† Soil samples were tested with Bray 1-P and ammonium acetate K extraction methods. Initial soil test levels in the fields averaged 32 kg P ha^{-1} and 184 kg K ha^{-1}.

‡ 2004 was the first year of the experiment.

§ Soybean soil test P and K targets for soil with 9.8 meq/100g soil CEC.

¶ Fertilizer rate is buildup plus crop removal.

Rice soil test P and K targets for soil with 9.8 meq/100g soil CEC.

Table 2. Soybean yield response to potassium and phosphorus fertilizer rates based on soil test build-up time and soil test target levels from University of Missouri recommendations for soybean and rice.

Build-up time	Soil test PK target	2004	2005	2006	2007	2008	2009	2010†	Mean
		----------soybean yield, kg ha^{-1}----------							
check	N only fertilizer	2,688 b‡	2,621 c	3,494 b	2,016 b	2,125 a	4,099 a	-	2,841 b
1 year	soybean §	3,494 a	3,629 a	4,234 a	2,621 a	2,016 a	4,032 a	-	3,338 a
4 year		3,427 a	3,091 b	4,009 a	2,352 ab	1,855 a	4,906 a	-	3,273 a
8 year		3,448 a	2,957 bc	4,135 a	2,554 a	1,949 a	4,502 a	-	3,258 a
1 year	rice¶	3,562 a	3,158 ab	3,830 ab	2,150 b	1,814 a	4,704 a	-	3,203 a
4 year		3,533 a	3,293 ab	3,696 b	2,419 ab	1,882 a	4,099 a	-	3,154 a
8 year		3,427 a	3,494 ab	3,822 ab	2,822 a	1,921 a	4,502 a	-	3,331 a

†Soybean yields in 2010 are not reported because of pod shattering before harvest.
‡Soybean yield values within columns followed by the same letter were not significantly different at the 0.05 level.
§ Fertilizer was applied to soybean plots based on soybean P and K soil targets. University of Missouri recommended at least 50 kg Bray-1 P ha^{-1} and 301 kg ammonium acetate-extractable K ha^{-1} for soybean.
¶ Fertilizer was applied to soybean plots based on rice P and K soil targets. University of Missouri recommended at least 39 kg Bray-1 P ha^{-1} and 195 kg ammonium acetate-extractable K ha^{-1} for rice.

Table 3. Rice yield response to potassium and phosphorus fertilizer rates based on soil test build-up time and soil test target levels based on University of Missouri recommendations for soybean and rice.

Build-up time	Soil test PK target	2004	2005	2006	2007	2008	2009	2010	Mean
		----------rice yield, kg ha^{-1}----------							
check	N only fertilizer	8,467 b	7,157 a	6,602 a	9,526 b	6,098 b	6,955 b	8,467 a	7,610 c
1 year	soybean ‡	9,677 a	8,064 a	6,703 a	13,558 a	7,308 a	8,014 a	12,449 a	9,396 a
4 year		9,727 a	8,117 a	6,854 a	13,507 a	6,955 a	8,114 a	13,558 a	9,547 a
8 year		9,425 a	8,014 a	7,610 a	12,146 a	7,560 a	8,064 a	10,289 a	9,015 a
1 year	rice §	8,669 ab	7,510 a	7,207 a	13,810 a	7,106 ab	7,337 ab	10,312 a	8,850 ab
4 year		8,568 ab	8,127 a	7,560 a	12,600 a	7,056 ab	7,510 ab	9,929 a	8,764 b
8 year		8,316 b	7,812 a	6,754 a	13,709 a	6,854 ab	7,358 ab	10,685 a	8,784 b

† Rice yield values within columns followed by the same letter were not significantly different at the 0.05 level.
‡ Fertilizer was applied to rice plots based on soybean P and K soil targets. University of Missouri recommended at least 50 kg Bray-1 P ha^{-1} and 301 kg ammonium acetate-extractable K ha^{-1} for soybean.
§ Fertilizer was applied fertilizer to rice plots based on rice P and K soil targets. University of Missouri recommended at least 39 kg Bray-1 P ha^{-1} and 195 kg ammonium acetate-extractable K ha^{-1} for rice.

The Effects of Potassium Deficiency and Osmotic Stress on the ROS-antioxidant Balance and Whole Genome Transcriptional Response of Barley

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Abstract

Potassium (K) is the most abundant inorganic cation in plants playing a vital role in photosynthesis related processes and osmoregulation. Studies report that there is a high risk of photo-oxidative damage under drought stress conditions which can be mitigated by adequate potassium supply. However, how the oxidative balance in the plants will be negatively affected under combined potassium and drought stress conditions is still under question. Moreover, there is limited knowledge available on the interactive effects of these combined stresses on plant transcriptomic responses.

In the present work, the dynamics of Reactive Oxygen Species (ROS) and antioxidant activities of barley to two K levels (low: 0.08 mM K and adequate: 0.8 mM K) and drought condition induced by polyethylene glycol (PEG) in the nutrient solution, have been studied. Based on the observed ROS response, whole genomic response of the plants at a selected time in the experiment was studied by using Massive Analysis of CDNA Ends (MACE).

The results showed that low K supply raised the targeted ROS (H_2O_2 and O_2^-) concentrations up to several folds. However, when low K treated plants were exposed additionally to PEG induced osmotic stress, a considerable increase in ROS concentrations was observed. In line with increased ROS concentrations, the activities of antioxidant enzymes altered significantly being higher under combined stress treatment.

Whole genome expression profiling results showed that plants treated with PEG and the ones exposed to combined stress (low K +PEG) are urged to reduce the light capture capacity via suppression of chlorophyll a-b binding proteins. At the same time, the genes involved in abscisic acid (ABA) biosynthesis were upregulated. These measures, though sufficient in aiding the plants to survive the drought stress, leaded to significant yield loss due to limitations occurred to the photosynthetic apparatus.

Keyword: ROS, Antioxidant activity, Genomic response, Potassium deficiency, barley

Available Potassium in Arable Soils in Mazandaran and its Relationship with Soil Texture and Rainfall

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Abstract
Potassium is one of the important nutrients and is vital for plants growth. Spatial variability of soil potassium is very essential for its management and proper utilization of K fertilizers. Likewise soil Intrinsic factors such as soil particles (especially clay and sand), climatic factors such as rainfall can affect the available potassium for plants. Rainfall may leach available potassium and is considered to be one of the important factors on distribution of available K in the region. Spatial distribution of available K indicated that area with high annual rainfall had lower amount of available potassium. Available K was significantly negatively correlated with soil sand portion (r= .377). Spatial structure analysis was done with GS^+ version 5.1 (Gamma design software) and the maps drown with ArcGIS (version 9.2). Rainfall interpolation was done with Inverse Distance Method (IDW).

Keywords: available potassium, annual rainfall, ordinary kriging, inverse distance weighting, ArcGIS

INTRODUCTION

Proper management of soil nutrients is important for meeting the needs of ever increasing population of the word without deteriorating the environment. Surveys and maps illustrating the geographic distribution of soil nutrient availability would provide guidance for proper management of nutrients in soils, and are necessary for a better understanding of the nature and extent of nutrient deficiencies and toxicities in plants, livestock and humans (Liu et al. 2008). Mapping soil K availability is relevant because potassium is the second largest plant nutrient (Bernardi et al., 2002). Plant nutrient mapping has been used at the farm level as part of precision agriculture (Bernardi et al., 2002). Soil agrochemical properties are affected from large amount of soil processes, which are working together but their activity and interaction vary both in time and space. Peck and Melsted (1973) suggest that existing of seasonal variability of soil test results are going to change because of factors affecting the nutrient uptake by plants and nutrient replenishment of soil solution (sorption, desorption, water transport, soil microbial activity, soil pH, CEC). Analysis and interpolation of spatial variability properties of soil is an important factor in site specific management (Yasrebi et al. 2009). With increasing of sand percent, because of low exchangeable sites, large pores and high drainage, potassium leaching is high which decreases the concentration of soluble K (Jalali and Rowell, 1999). Prado et al., (2008) indicated that sandy soils generally contain low k due to low nutrient retention capacity and high leaching. Geostatistic combined with geographic information system (GIS) have proven to be useful in the predicting the spatial distribution of soil properties that are very spatially dependent in fields having a limited number of soil samples. The interpolation technique that usually used is kriging (Yost et al, 1982, Cambardella et al. 1994). Spatial prediction technique, also known as spatial interpolation technique, differ from classical modeling approaches in that they incorporate information on the geographic position of the sample data points (Cressie, 1993). Geostatistical analyses provide quantitative information about spatial variability, which is a principal requirement for Site Specific Crop Management (SSCM). SSCM is a fundamental component of precision agriculture (PA), which embodies a holistic farm management strategy where farm operator can adjust input use and cultivation methods, including seed, fertilizer, pesticide and water application, variety selection, planting, tillage and harvesting, to match varying soil, crop and other attributes (Robert, 1999). To account for the spatial variability of rainfall, conventional techniques such as Thiessen polygons, the isohyetal method, and inverse distance weighting (IDW) were used for interpolation of

rainfall data until the late 1980s (Goovaerts,1997 and Phillips et al, 1992). One of the important inputs for a water resources study is rainfall. Choosing improper interpolation methods may result in extensive errors. Geostatistical methods may also fail to be used, in case of insufficient data (Rahimi Bondarabadi and Saghafian, 2007). Weber and Englund, (1994) have used Coefficient of Variation (CV) as an indicator of accuracy of inverse distance method (IDW) and explain using high powers (most notably p= 4) are most accurate for data with low CV_s (less than 25%) and least accurate for data with Higher CV_s.

MATERIAL AND METHODS

This study was conducted in Mazandaran province in north of Iran and bounded east longitude 51°0′-54°0′ and north latitude 36°0′-37°0′ with the total area of 5645 km^2. Average annual precipitation is 881 mm. Soil sample were collected from 953 locations in 2-km regular grid. Some points, which fell on road, buildings and inaccessible, were not sampled. All samples georeferenced using GPS system. All soil samples were taken at depths of 0-15 cm then air dried and passed through 2 mm sieve then stored in plastic bags prior to chemical analysis. Available K was extracted with NH_4OAC 1N and determined by flame atomic absorption spectrometry. Organic matter was determined using oxidation method (Walkly and Black, 1939) and soil particles (Clay, Sand and Silt) were determined with hydrometry method.

Statistical analysis

Outliers were removed from data set with method of (4 S.D ± mean) and the data which were out of this range, were deleted (Chan et al,1994). Distribution of soil properties tested with kolmogrov- smironove (K-S) statistic and logarithm transformation were done for the parameters in non normal distribution (Liu et al, 2004). In numerous data transformation methods, logarithmic transformation is widely applied (Webster and Oliver, 2001). Descriptive statistics, including mean, median, range, standard deviation (SD), skewness, kurtosis and coefficient of variance (CV) as an indicator of heterogeneity were determined for data set. Pearson correlation coefficients (r) were employed to identify the relationship between soil potassium and dependent variables (soil chemical attributes such as Clay, Sand, Silt and O.C) and climatic attribute such as annual Rainfall. Statistical analysis was carried out in SPSS 17.

Geostatistical analysis

Semivariogram is modeled using several models such as Gaussian, spherical and exponential. The models are fitted to the semivariogram data (Oliver, 1987, Isaaks and Srivastava, 1989) and the best fitted model was selected. Nugget variance (C_0), range (A) and Sill ($C + C_0$) are Basic spatial parameters of the semivarigram. The nugget/sill ratio can be regarded as a criterion to classify the spatial dependence of soil properties. If the ratio is less than 25%, the variable has strong spatial dependence, between 25 and 75%, the variable has moderate spatial dependence and greater than 75%, the variable show only weak spatial dependence. The spatial variability of soil properties may be affected by intrinsic (soil formation factors, such as soil parent material) and extrinsic factors (soil management practices such as fertilization). Usually, strong spatial dependence of soil properties can be attributed to intrinsic factors, and weak spatial dependence can be attributed to extrinsic factors (Cambardalla et al, 1994, Shi et al, 2008).

Inverse Distance Weighting (IDW):

All interpolation methods have been developed based on the theory that points closer to each other, have more correlations and similarities than those farther. In IDW method, it is assumed substantially that the rate of correlations and similarities between neighbors is proportional to the distance between them that can be defined as a distance reverse function of every point from neighboring points. It is necessary radius and the related power to the distance reverse function is considered as important problem in this method. The main factor affecting the accuracy of inverse distance interpolation is the value of the power parameter (Isaak and Srivastava, 1989 and Yasrebi et al, 2009).

Kriging

Among the geostatistical technique, kriging is a linear interpolation procedure that provides a best linear unbiased estimation for quantities which vary in space. Kriging estimates are calculated as weighted sums of the adjacent sampled concentrations. That is, if appear to be highly continuous in space, the points closer to those estimated receive higher weights than those farther away (Criese, 1990).

RESULTS

Descriptive statistics of soil parameters were listed in table 1. Soil available K in this area was in range of 12-895.1 with the mean of 219.5 mg kg^{-1}. O.C was in range of 0.2-5.2 with the mean of 1.94 (%) and Clay, Silt and Sand were in range of 4-70, 6-72 and 2-78 with the mean of 35.23, 43.14 and 21.25 percent respectively. Then outliers were removed from data set and Distribution of soil properties tested with kolmogrov- smironove (K-S) statistic and indicated that soil K, Sand and OC have non normal distribution. To avoid result distributions and low level of significance, log transformation performed on these parameters and the data of these parameters become fitted normal distribution. The frequency distribution histograms for K, Sand and OC before and after transformation are shown in fig.1. It can be seen that K, Sand and OC fitted normal distribution after logarithmic transformation. To obtain the valuable information, the spearman nonparametric correlation coefficients were calculated between soil properties (available K, Clay, Silt, Sand, organic carbon (OC)) and rainfall. Results were shown in table 2. Available K was significantly positively correlated with Clay with (r= .377) and negatively correlated with sand and annual rainfall respectively with (r= .304 and r= .094) in significant level of ($p< 0.01$). Prado et al. (2008) were reported the negative correlation between soil Sand and soil available K. Coefficient of variation (CV) for all of variables is shown in table 1. Soil clay and silt had medium variation (15< EC< 35) and available K, soil sand and OC had high variation (CV>35%).

Table1. Descriptive statistics of soil properties

Soil properties	unit	mean	median	range	S.D	Skewness	Kurtosis	CV(%)
available K	($mgkg^{-1}$)	219.5	179.03	12-895.1	151.78	1.36	1.78	69.15
Ln of available K	($mgkg^{-1}$)	5.17	5.19	2.48-6.80	.68	-.047	.46	
(OC)	(%)	1.94	1.81	.2-5.2	.74	.97	1.75	38.14
Ln of OC	(%)	.59	.59	-3.89-1.65	.42	-1.76	14.79	
Clay	(%)	35.23	35	4-70	11.94	.1	-.134	33.89
Silt	(%)	43.14	44	6-72	9.58	-.79	1.95	22.20
Ln of Silt	(%)	3.73	3.78	1.79-4.28	.29	-2.86	12.95	
Sand	(%)	21.25	18	2-78	12.94	1.53	2.81	60.89
Ln of Sand	(%)	2.89	2.89	.69-4.36	.58	-.131	.238	

Table 2. Correlation coefficient

	K (mg\kg)	OC (%)	Clay (%)	Silt (%)	Sand (%)	Rain (mm)
K (mg\kg)	1					
OC (%)	-.043	1				
Clay (%)	.377**	.138**	1			
Silt (%)	-.054	.021	-.254**	1		
Sand (%)	-.304**	-.133**	-.722**	-.472**	1	
Rain (mm)	-.094**	.109**	-.187**	-.111**	.253**	1

In order to identify the possible structure of different soil properties, semivariograms were calculated and the best models with highest R^2 (R square) and lowest RSS (residual some of square) that describe these spatial structures were identified. The semivariograms of available k and soil parameters were shown in fig 2 and the geostatistical model parameters were shown in table 3. The best fitted semivariogram models of available K were Gaussian and for soil sand, clay and OC were exponential. The range of K was 3.93 and the range of other soil parameter such as O.C, Sand and Clay and Sand were 33, 97, 73.9

km respectively. The nugget/sill ratio for available K and soil Sand, Clay and OC were 30.56, 45.09, 48.95 and 48.96 respectively and they had moderate spatial dependency and intrinsic factors such as (soil formation and parent material,…) and extrinsic factors such as (rainfall and, fertilizers, …) affecting spatial dependency of these parameter. Wollenhaupt et al. (1994) relate soil available P, K and Mg to the properties with medium spatial variability.

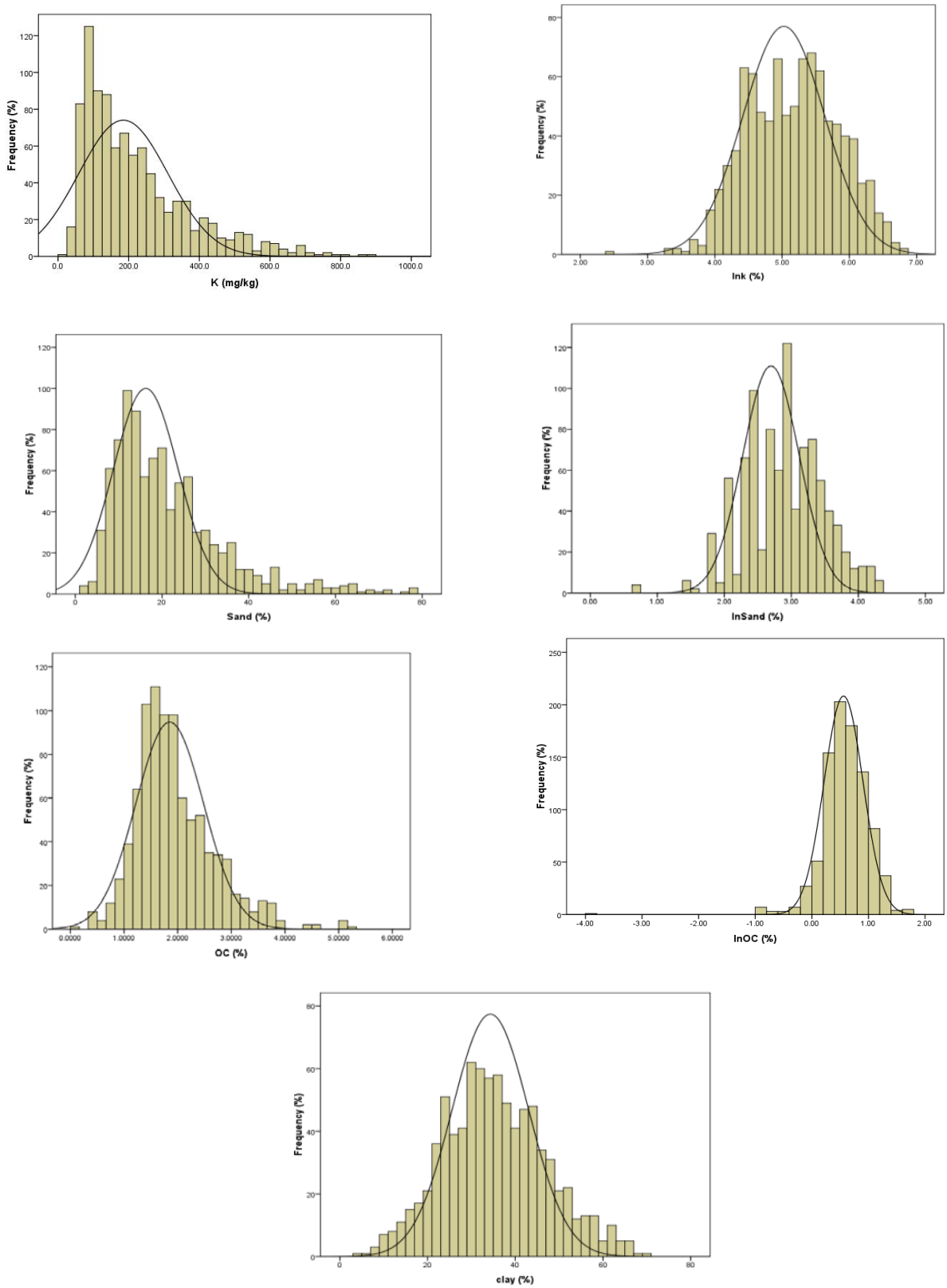

Fig1. Histograms of soil parameters

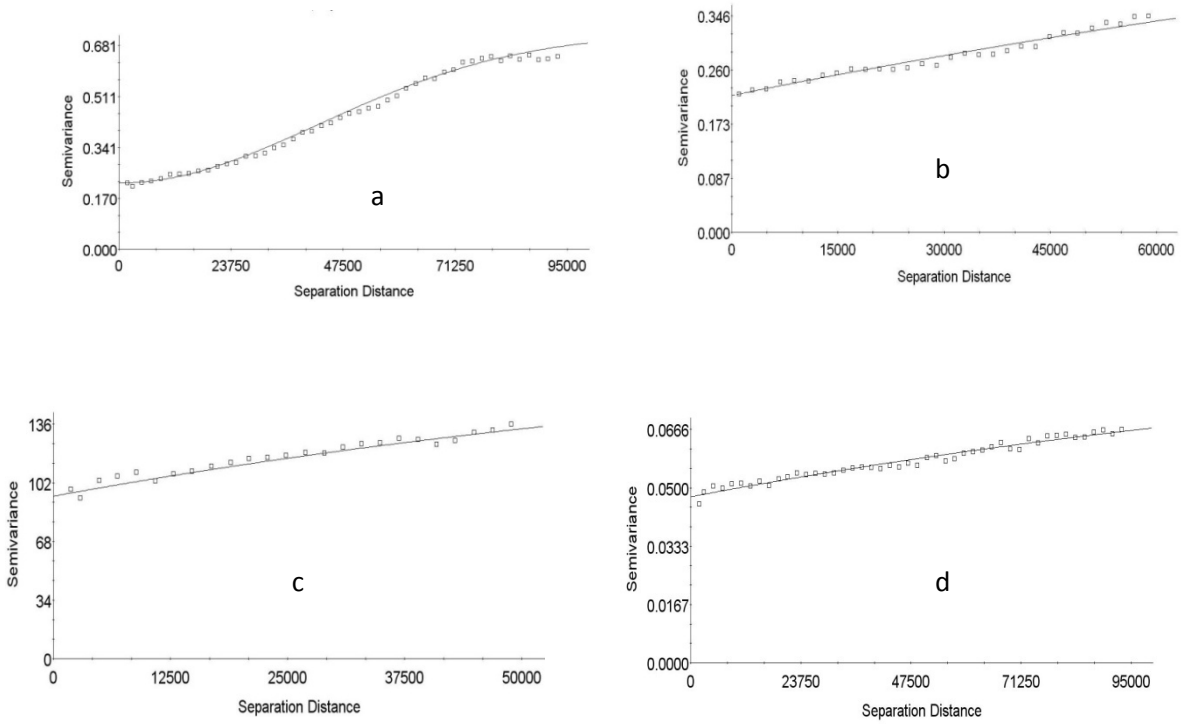

Fig2. Semivariograms of a: available potassium, b: sand, C: Clay and d: organic carbon

Table 3. The best fitted variogram models and their parameters

variable	model	C_0	$C + C_0$	EA	R2	RSS	$\frac{C_0}{C+C_0} \times 100$	Spatial structure
K	Gaussian	.22	.72	3923	.99	8.73×10^{-3}	30.56	M
Sand	Exponential	.23	.51	33000	.95	4.46×10^{-3}	45.09	M
Clay	Exponential	94	192	97000	.96	183	48.95	M
OC	Exponential	.047	.096	73900	.96	4.91×10^{-5}	48.96	M

Information for mapping the rainfall in Mazandaran province was collected from 7 synoptic stations (table 4). Due to few numbers of synoptic stations and the amount of information, IDW methods were used for interpolation of rainfall in the study area. Indicating of Kravchenko, 2003 and Whelan et al, 1996 IDW may be use for small data sets for which variogram parameters are not known and for the data sets with large distances between the grid points. Coefficient of variance of annual rainfall was higher than 25% (CV= 31.66) (table.5) and regarded with Weber and Englund (1994), IDW with low powers had been used to interpolation of rainfall. In this study IDW with power = 2 was performed.

Available K in the western parts of study area was in the medium range (60-120 mg/kg) (fig, 2-a). This area approximately had high amount of rainfall (> 1000 mm) (fig. 2-b) and medium to high amount of Sand (> 30%) (fig. 3-a). In the eastern parts of study area available K was high (> 240 mg kg-1) and in regarded to spatial distribution maps of rainfall and Sand, this area have low amount of Sand (< 30 %)

and mean annual rainfall was lower than 880 mm. These results confirmed Jalali and Rowell (1999) which indicated with increasing of sand percent, due to low exchangeable sites, large pores and good drainage, potassium leaching is high and concentration of soluble K decreases significantly.

Spatial variability map of soil Clay (fig. 4-b) shows that the western area that located between upland and sea, small particles such as Clay can be leached to the sea or to the sub soil by rainfall or irrigation. Clay amount in this area was low and contrarily sand percent was high. In the eastern areas with wider area between mountains and sea there are more time for small particles to depositing therefore Clay percent was greater than 30 percent and the amount of Sand was low.

Table 4. Information of Synoptic stations

Synoptic station	X	Y	elevation (m)	Rain (mm)
Amol	52°23	36°28	23.7	702.6
Babolsar	52°39	36°43	-21	894.4
Ramsar	50°40	36°54	-20	1217.8
Gharakhil Ghemshahr	52°46	36°27	14.7	738.7
Sari	53°00	36°33	23	789.2
Siahbisheh	51°18	36°15	1855.4	531.02
Noshahr	51°308	36°39	-20.9	1293.5

Table5. Descriptive statistics of rainfall

Soil properties	unit	mean	median	range	S.D	Skewness	Kurtosis	CV(%)
Annual rainfall	mm	881.03	789.2	531.2-1293.5	278.91	0.6	-0.9	31.66

Table 6. Potassium classification

K (mg kg^{-1})	K content
0–30	very low
30–60	low
60–120	medium
120–240	high
> 240	very high

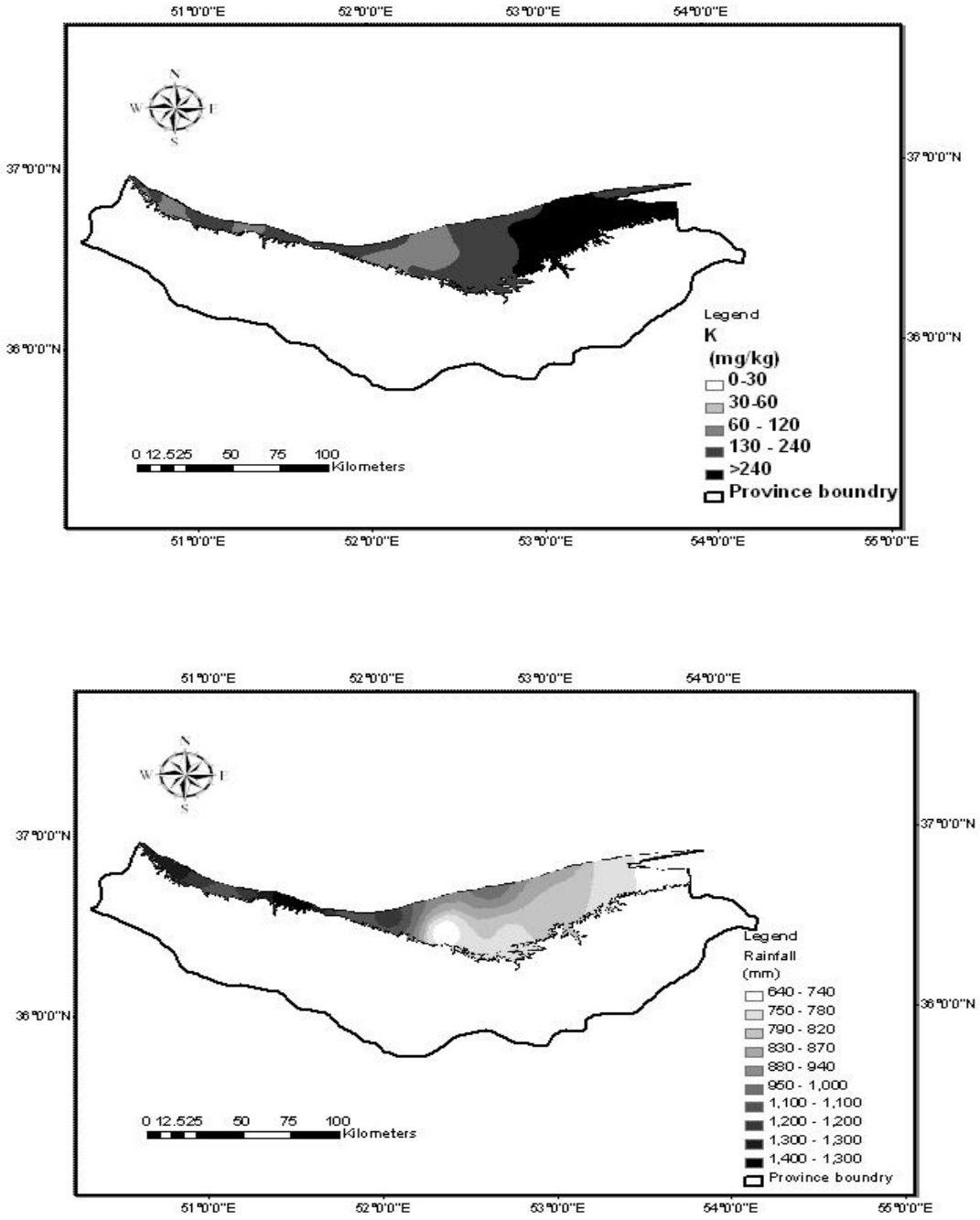

Fig 3. Filled contour maps produced by a: ordinary Kriging of soil available potassium and b: Inverse distance weighting of annual rainfall

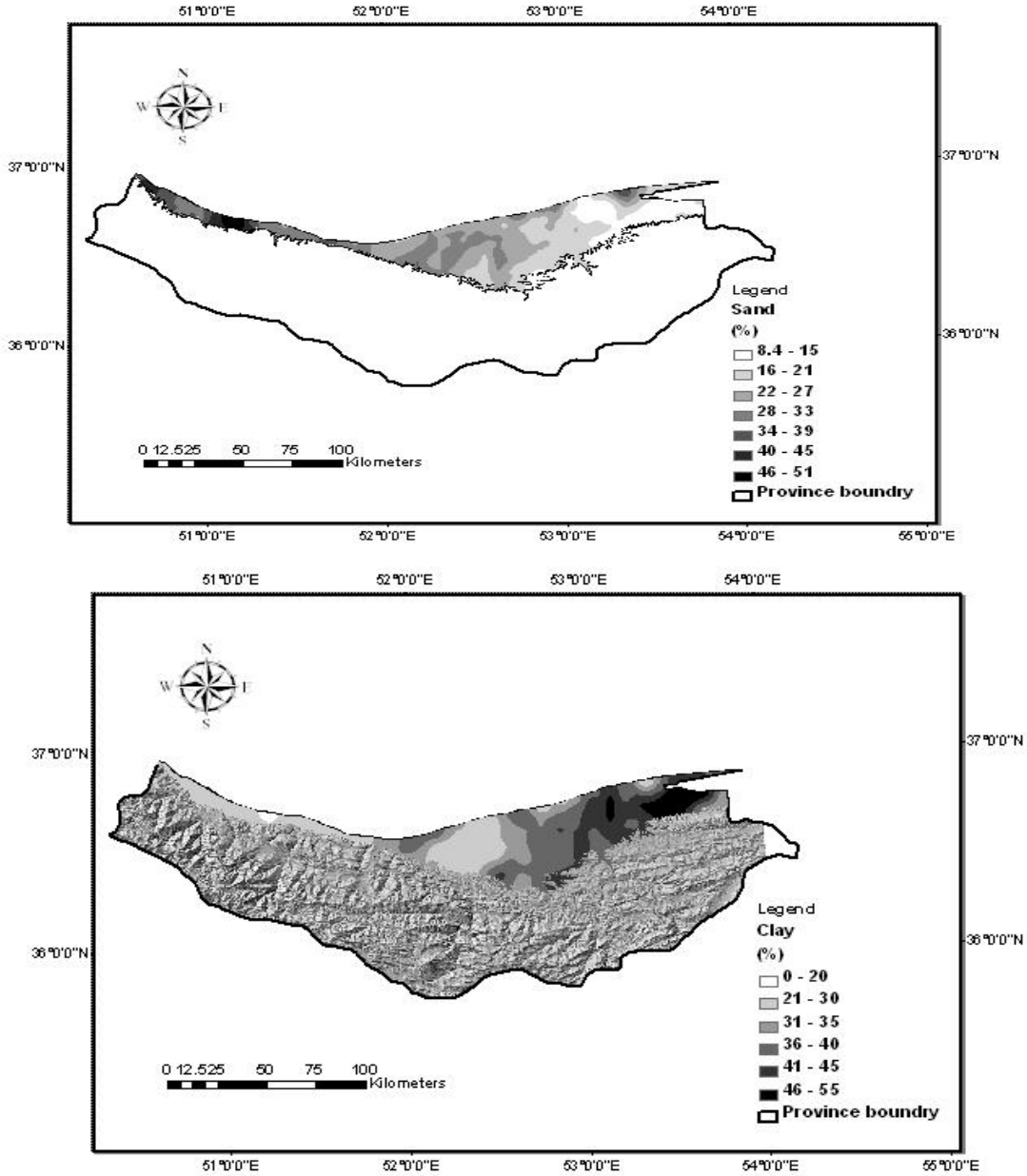

Fig4. Filled contour maps produced by ordinary Kriging of a: sand and b: clay

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Comparative Study on Proteome Changes in Response to Potassium Deficiency and Drought in *Triticum aestivum* Roots

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Abstract
Potassium deficiency in crop production is commonly reported and causes limitations to yield formation worldwide. In plants, potassium is the most abundant cation and constitutes up to 6 % of plant dry weight, which indicates its essential importance for plant physiology. Besides potassium deficiency, drought causes high yield losses of crops such as wheat. More than 50 % of wheat cultivated land is prone periodically to drought; however wheat demand and consumption is rising and requires increasing yields, indicating the indispensability to understand adaptive mechanisms in response to these abiotic stresses. The root system is the first plant organ that senses drought and potassium deficiency and accordingly, a complex physiological regulatory network is induced. Proteome analysis is a powerful tool to study large-scale plant responses to various stress conditions and comparative proteome studies allow identification of key proteins involved in stress adaptation. This study aimed at investigating changes in the protein expression pattern of wheat roots in response to potassium deficiency and drought. Wheat plants were grown hydroponically with potassium deficiency and PEG-induced short-term drought stress (4 days) was applied before flowering phase. Proteins were extracted from root material and separated by SDS-PAGE. Proteomic results clearly showed that general plant defence mechanisms are triggered. In total, 19 spots were identified as differentially expressed proteins which could be classified into 6 different categories namely i) antioxidation and detoxification, ii) carbohydrate and energy metabolism, iii) protein synthesis, folding and degradation, iv) defence-related protein, v) ion transport, and vi) signalling. As far as we are aware, the present study is the first revealing protein alterations under potassium deficiency and drought in wheat roots. Thus, this study provides a useful leverage point for further research that aims at developing tolerant and high productive wheat varieties.

Changes in Root Morphological Parameters in Response to Varied Potassium Supply

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Abstract

There are several important physiological and morphological alterations occurring in crop plants when exposed to low supply of potassium (K). Probably, a major driving factor behind these changes is the impairment in biosynthesis, transport and utilization of photosynthates. Reduction in carbohydrate partitioning into roots as a result of impaired phloem loading of assimilates is a well-documented phenomenon in plants with low K supply. Consequently, root growth is often much earlier affected than shoot growth leading to greater shoot to root biomass ratio. There is, however, very little published evidence about the impact of K deficiency on root morphological parameters such as root architecture (root branches), root surface area, root length, root volume, and number of root tips and their relation to sugar concentrations in the roots. In this study, WinRHIZO software has been used to monitor changes in in root architecture and morphological parameters in young wheat seedlings under 4 different K application rates (e.g., very low, low, medium and adequate) over time. Among the root parameters studied, the number of root forks and root length were the most sensitive root morphological parameters to low K supply. A short-term resupply of K to low K plants resulted in significant improvements in root parameters.

Effect of Different Potassium Management Practices on Growth, Yield and Economics of Maize (Zea mays L.)

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Abstract

A field experiment was conducted during *kharif* season of 2014 and 2015 in sandy loam soils of Zonal Agricultural and Horticultural Research Station, Navile Shivamogga under rainfed situation to study the effect of different potassium management practices on growth, yield and economics of maize. soils of experimental sites were low in available nitrogen (194 kg ha-1), high in avialable phosphorus (64 kg ha^{-1}) and medium in available potassium (244 kg ha^{-1}).Among different potassium management practices, application of 60 kg K_2O in two splits along with foliar fertilization of potassium sulphate at 60 DAS has recorded higher leaf area, LAI and LAD at later stages of crop growth. The highest grain yield of 7693 kg ha^{-1} was obtained with application of 60 kg K_2O ha^{-1} in two split doses (basal+30 days after sowing) along with foliar fertilization of potassium sulphate (0:0:50) at 60 DAS. It was closely followed by the application of 40 kg K_2O ha^{-1} in split doses along with foliar fertilization of potassium sulphate (0:0:50) at 60 DAS (7620 kg ha^{-1}). Higher gross returns (Rs. 1,01,730 ha^{-1}) and net returns (Rs. 64,897 ha^{-1}) were recorded with application of 60 kg K_2O ha^{-1} in two splits along with foliar fertilization of potassium sulphate (0:0:50) at 60 DAS. However, higher BC ratio (2.77) was recorded with application of 40 kg K_2O ha^{-1} in two splits along with foliar fertilization of potassium sulphate (0:0:50) at 60 DAS.

Effect of Potassium Fertilization on the Yield and Thousand Berry Mass of Gooseberry (Ribes grassularia L.)

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Abstract

The gooseberry production and consumption in the world is slowly, but steadily growing. This is because, in addition to the standard range of fruits, supports the variety of our diet. The semi-ripe berries are rich in valuable fruit acids, a part of which contains the fully ripened fruits as well. The ripe berries contain about 1% by weight of sucrose, in addition to 3-3.5% glucose and fructose content of the same amount, resulting a typical pleasantly sour-sweet taste. In addition to the consumption of fresh fruit, compotes and jams are to be used for making it. Economic benefits is, that the berries are to be harvested and may be sold in late spring - early summer period, so that farmers receive financial income in a short period of time.

The gooseberry requires an adequate plant nutrient supply. Nevertheless, the gooseberry is mainly grown in the northeastern region of Hungary, mostly in acidic sandy soils, poor in nutrient supply. For these soils the very low potassium content is characteristic, that is why this nutrient in the right gooseberry plantations with great care should be taken of.

As the berry fruits generally, gooseberry is also susceptible to large amounts of chloride ion. Another problem is that the large dosage of potassium fertilizer deteriorates magnesium availability in the soil. These factors makes the of appropriate potassium supply of gooseberry not an easy task.

In a randomized, four-repetition small plots (20 m^2 $parcel^{-1}$) experiments, different doses were delivered out of potassium fertilizers, both of chloride and sulfate form. The treatment set up using “Patentkali” was a variant in which the addition of magnesium sulfate, potassium sulfate is contained in the fertilizer, to test whether the treatment with magnesium in combination with the impact of the test parameters. In the experiment, a total of 32 plots were set up. To enhance the reliability of the results, the experiments were carried out in two consecutive years.

Besides the crop mass and thousand berries mass, the potassium and magnesium content of leaves were also determined. The measurement data were evaluated by ANOVA. On our poster the results will be demonstrated.

Silt as K Source for Crops in Tropical Soils

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Abstract
The original soil exchangeable potassium (K) concentrations are at or above critical levels in many Brazilian Cerrado (savanna) soils. Hence, many cropped areas have been fertilized with low K rates, below crop requirements, but yields have not decreased as expected. In these areas, topsoil exchangeable K analyses have shown no decrease, or even some increase. The aim of this study was to evaluate exchangeable and non-exchangeable K forms in soils under different uses and managements in the Vale do Araguaia region of Mato Grosso state, Brazil. Soil samples were taken from 91 sites at depths of 0-20 cm and 20-40 cm, in areas under grain crops, pasture and native vegetation (Cerrado or forest). Silt content ranged from 12 to 175 g kg^{-1} and clay from 90 to 595 g kg^{-1}, and the predominant clays were kaolinite, hematite, goethite and gibbsite. Under pasture, the soils had high levels of exchangeable K in the 0-20 cm layer and high levels of non-exchangeable K from 20 to 40 cm. This can be a result of the absorption of non-exchangeable K by grasses, the main cultivated species, by recycling K to the exchangeable fraction in the topsoil. There was a positive relationship between silt and non-exchangeable K contents. Ratios of exchangeable to non-exchangeable K were over 3 in soils with silt above 70 g kg^{-1}, in which non-exchangeable K was over 100 mg dm^{-3}. Cover crops growing in soils rich in silt take up non-exchangeable K and exchangeable K from deeper layers, which is recycled to the soil as exchangeable K upon plant residue mineralization, which may have been responsible for the maintenance or increase in exchangeable K levels in the 0-20 cm layer in areas where low K rates have been used for grain production.

Keywords: Cerrado soils; Exchangeable K; Vale do Araguaia

INTRODUCTION

More than 90% of the potassium contained in soils is in the structural fraction linked to the material of origin, represented as total K (Coelho & Vilagia, 1988). According to Raji (1991), the main mineral compounds with K are feldspar, potash and mica. The presence of the ionic form of K from this material of origin is due to mineralization, through weathering or “geological reaction of the decomposition of rocks” (Kerbauy, 2013; Kampf et al., 2009). The vermiculites, like micas, contain K between the layers, and in smectites, reduction of iron content facilitates the fixation of K (Curi et al., 2005). The 2:1 feldspars, depending on chemical variations, can form potassium, sodium-calcium and barium minerals. A main characteristic of alkaline feldspars is the large quantities of K or Na and dearth of Ca (Melo et al., 2009). Potassium fractions considered as having low solubility, linked to the mineral of origin, such as the interlayer K or non-exchangeable K, can be a source of K for plants. The action of the rhizosphere can deplete the K present in phlogopite minerals, transforming them into vermiculite (Hinsinger & Jaillard, 1993; Gomers et al., 2005).

As the mineralogy, the soil silt content can be correlated with the levels of K (Medeiros et al., 2014). In this regard, Silva et al. (2008) reported that the silt fraction contains large reserves of non-exchangeable K.

Mato Grosso state is the Brazil's largest producer of grain crops, and the Vale do Araguaia region, in the state's northeast, is an agricultural frontier region that accounts for more than 16% of the state's soybean output (IMEA, 2015). This region contains highly varied soil classes, but three stand out: Dark-Red Latosol (Oxisoil); Red-Yellow Latosol (Oxisol); and Plinthosol (Plinthaquox) and Red-Yellow Argisol (Ultisols) (IBGE, 2014; SEPLAN, 2014). Few studies have been conducted to investigate the influence of production system or silt content in the soil on the potassium nutrition of crops, especially in soils with high concentrations of non-exchangeable K, characteristic of this region of Mato Grosso state. In this region, some areas are fertilized with insufficient K rates to replenish the quantity taken up by the crops, but no declines have been observed in yields or levels of exchangeable K in the arable layer (0-20 cm depth). The objective of this study was to assess the forms of exchangeable and non-exchangeable K in soils under different management systems and uses, as well as the relationship with the soil mineralogy.

MATERIAL AND METHODS

Studied region was the Vale do Araguaia (Araguaia Valley - Figure 1), which basically contains four soil classes: Dark-Red Latosol (Oxisoil); Red-Yellow Latosol (Oxisol); and Plinthosol (Plinthaquox) and Red-Yellow Argisol (Ultisols) (IBGE, 2014; SEPLAN, 2014). The predominant clay minerals are kaolinite, hematite, goethite and gibbsite, except in the Plinthosol, where hematite is absent (Ker, 1997; Galvão et al., 2007). Soil samples were collected from 91 sites (Table 1). Each collection point was geographically referenced with a GPS device. Soil samples were collected in areas cultivated with soybeans, in a line transversal to the rows, at depths of 0-20 cm and 20-40 cm. At each depth, a portion of soil with thickness of 5 cm and width 50 cm was collected, within a 50 cm wide part of the planted row. Soil samples were also collected in areas of pasture and native vegetation (Cerrado or forest). Cropped areas were chosen for contrast regarding the use before planting soybeans: corn, millet, *Urochloa* (Brachiaria) or fallow (Table 1).

Exchangeable K in the soil was extracted with Mehlich-1 solution. The non-exchangeable K was extracted with a hot solution of HNO_3 and the quantity was determined by subtraction from the exchangeable K value (Rouse & Bertranson, 1949).

The descriptive data on the levels of K were analyzed and the correlations were determined by multiple regression analysis, with a predictive model for the K extractable in HNO_3 based on soil chemistry analysis. The progressive matrices technique was used.

RESULTS AND DISCUSSION

The silt content in the top layer (0-20 cm) varied from 12 to 175 g kg^{-1}, while the organic matter content ranged from 7 to 54 g kg^{-1} and the exchangeable potassium concentration varied from 9.5 to 319 mg dm^{-3}. According to Oliveira Junior et al. (2010), in general the critical level of K in the soil is considered to range from 31 to 51 mg dm^{-3}. In turn, the levels of non-exchangeable K varied from 0.01 to 403 mg dm^{-3} in the top layer. At the depth of 20-40 cm, large amplitudes of the forms of K were observed. The exchangeable K presented a minimum value of 5.0 mg dm^{-3} and maximum of 191.50 mg dm^{-3}, while the non-exchangeable K ranged from 0.78 mg dm^{-3} to 339.13 mg dm^{-3}.

Therefore, the soils in the Vale do Araguaia region presented high levels of non-exchangeable K, but in some cases the concentration of non-exchangeable K was up to 2.39 times more than that of exchangeable K in the top layer, and up to 5.52 times more in the 20-40 cm layer. As can be seen in Figure 2, the slope of the line is steeper in the 20-40 cm layer than in the 0-20 cm layer (2.04 and 1.7 respectively).

Therefore, at the depth of 20-40 cm, twice as much K was extracted in HNO_3 in relation to the exchangeable K.

At sites 24, 32, 41, 42, 43, 64 and 66, the levels of K in HNO_3 were high even though the levels of exchangeable K were low (Figure 2).

Sites 41 and 66 had been cultivated with soybeans for longer than four years, with cover of *U. ruziziensis* between crops. Besides this, these sites had not received potassium fertilization in the past three crops. Nevertheless, the levels of K were above the critical threshold. In these cases, the content of non-exchangeable K was high at both depths. Site 42 is a native Cerrado area, with low exchangeable K and high non-exchangeable K levels at both depths.

Sample 43 came from an area cultivated with pasture for more than 15 years that had never received any fertilization. In the top layer the level of exchangeable K was higher than that of non-exchangeable K, but at the depth of 20-40 cm the content of non-exchangeable K was greater than that of exchangeable K (Figure 2). According to Mielniczuk (2005), the straw from dried cover plants that are efficient in absorbing potassium releases the mineral to the soil, creating different levels from the surface to the lower levels of the profile.

Sample 32 came from a field cultivated with soybeans, without potassium fertilization on the two previous crops. Even with this management, the content of exchangeable K was above the critical level. Nevertheless, the level of non-exchangeable K was low in the top layer (0-20 cm). These results indicate a tendency for transformation of non-exchangeable K to exchangeable K. This is supported by the fact that the soil in the forested areas on this same property (sample 32) presented high non-exchangeable K and low exchangeable K in both layers sampled (Figure 2).

The areas with pastures (sites 43 and 66) presented the same tendency, in which the concentration of exchangeable K was high in the 0-20 cm layer and that of non-exchangeable K was low at the 20-40 cm depth. It can be stated that Brachiaria extracts potassium from the non-exchangeable fraction and transfers it to the exchangeable fraction of the higher soil layers. The highest concentration of Brachiaria roots was found in the 0-20 cm layer. These roots are responsible for depletion of non-exchangeable K and its transformation into exchangeable K (Hissinger et al., 1993; Gomers et al., 2005), and the deposition of exchangeable K occurs from senescence of the plants with the action of rain, causing this K to be deposited on the soil surface (Rosolem et al., 2006). This can be explained because Brachiaria extracts a large amount of K and exports very little, and because of the form of the K^+ ions in the plant, where it is not part of any cell constituent. Then it is rapidly leached from the dried grass after senescence and deposited in the soil. This increases the fraction of exchangeable K in the surface layer. Besides this, livestock activity also exports very little K from the system, as reported by Vilela et al (2007). Garcia et al. (2008) identified absorption of the non-exchangeable K fraction by Brachiaria grown together with corn, because the non-exchangeable K in the soil declined in the parts covered with Brachiaria and the exchangeable K increased. Calonego et al. (2005) found that the release of K from dried grass cover occurs in rising quantities after drying, due to the loss of turgescence of the cells.

Cultivated areas with Brachiaria between crops and soybeans in the summer presented distinct results: at site 24 the exchangeable K was higher than the non-exchangeable K while at site 41 the exchangeable K was lower than the non-exchangeable K. The area of site 24 received K fertilization all years, while that of site 41 did not. This indicates that the plants only access the less soluble source when there is no addition of readily available sources. Growing of cover plants in the winter, without fertilization, causes depletion of the non-exchangeable forms of K, with corresponding enrichment of the solution in the soil, a pattern than is more pronounced in plants with high extraction capacity, such as grasses (Benites et al., 2010).

There was a positive and significant correlation (at 1%) between the levels of silt and non-exchangeable K (Table 2), at both depths, such that the higher the silt content, the greater the concentration of non-exchangeable K. Similar results were reported by Medeiros et al. (2014) and Silva et al. (2008), indicating that the silt fraction contains large reserves of non-exchangeable K.

The levels of non-exchangeable K were only higher than 120 mg dm^{-3} in the soils with silt concentration greater than 70 g kg^{-1} (Figure 4). Hence, it can be inferred that in this region, non-exchangeable K will only be found in soil with silt content higher than 7% (70 g kg^{-1}).

The highest levels of non-exchangeable K observed were 339.1 mg dm^{-3}, with silt content of 100 g kg^{-1} (sample 18), and 203.1 mg dm^{-3}, with silt content of 150 g kg^{-1} (sample 41). According to Melo et al. (2003) reported higher quantities of total K in sand and silt fractions, while Castilho et al. (2002) concluded that the silt fraction, in the majority of soils studied, was the main source of K.

Samples 2, 21, 39 and 88 contained high silt contents (Figure 3), but the levels of non-exchangeable K were low. The soils in samples 2, 21 and 88 were reddish, indicating a high quantity of iron oxide, which is an excellent cementing agent of silt in clay. This may have hampered the dispersion during analysis of the silt and can generate a functional silt. As pointed out by Melo et al. (2000, 2003), it can be hard to analyze the silt in soils with high concentrations of iron oxide, particularly because of the cementing effect in Latosols. Sample 39 might have come from a soil with low silt content, because soils under native Cerrado vegetation in the study region typically have low levels of non-exchangeable K. Therefore, the material of origin might have been poor in potassium.

Figure 4 shows the ratio between non-exchangeable K and exchangeable K in relation to the levels of silt. It can be seen that the levels or silt are correlated with higher levels of non-exchangeable K in these samples.

The samples with silt contents higher than 70 g kg^{-1} corresponded to the highest ratios between non-exchangeable K and exchangeable K. All of these ratios were higher than 3 (Figure 4). The highest ratios between non-exchangeable K and exchangeable K were found in the samples from sites 41, 42 and 64, all of which were in the range of 5. In these cases, the silt contents were higher than 100 g kg^{-1} (Figure 4).

Brazilian soils generally have high levels of non-exchangeable K, with ratios between non-exchangeable and exchangeable K ranging from 1 to 3 (Benites et al., 2010).

Figure 5 shows a multiple regression of the variables observed K in HNO_3 and the expected level, based on two variables: level of silt and level of exchangeable K. To estimate the concentration of K extracted in HNO_3 in the top layer (0-20 cm), the following equation can be used (1):

(1) $$K\ HNO_3 = -31.7746 + 1.6980\ \text{exchangeable K} + 0.2635\ \text{silt}\ (R^2=0.82)$$

Equation (1) explains 82% of the variation of the levels of K extracted in HNO_3. The equation is highly significant, with an estimated error of 28. Using this equation with the concentrations of exchangeable K and silt (parameters routinely analyzed in soil laboratories), it is possible to estimate the content of K that would be extracted in HNO_3.

Figure 5 was plotted with data from the soil samples collected at the 91 sites in the Vale do Araguaia region. Note that only three data points are outside the 95% confidence interval. Therefore, equation (1) can be used for this region to predict the content of K that would be extracted in HNO_3, since analysis using this extractant is more difficult and expensive than determining the content of exchangeable K (Mehlich-1).

CONCLUSIONS

The levels of silt were directly correlated with the levels of non-exchangeable K and based on the values of exchangeable K and the silt concentration, the levels of non-exchangeable K (extractable in HNO_3) can be estimated.

Forage species used as cover between crops or as pasture in silt-rich soils absorb exchangeable K and non-exchangeable K from the subsoil, recycling K to the arable layer with mineralization of residues. This can explain the maintenance or even increase in the levels of K in the surface layers, even without application of potassium fertilizer.

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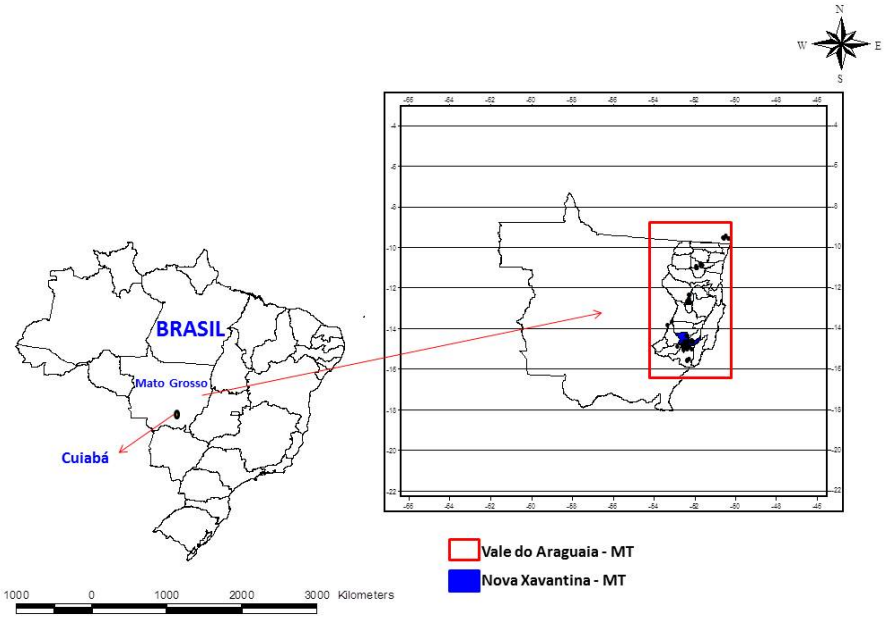

Figure 1. Map indicating the region where the soil samples were collected.

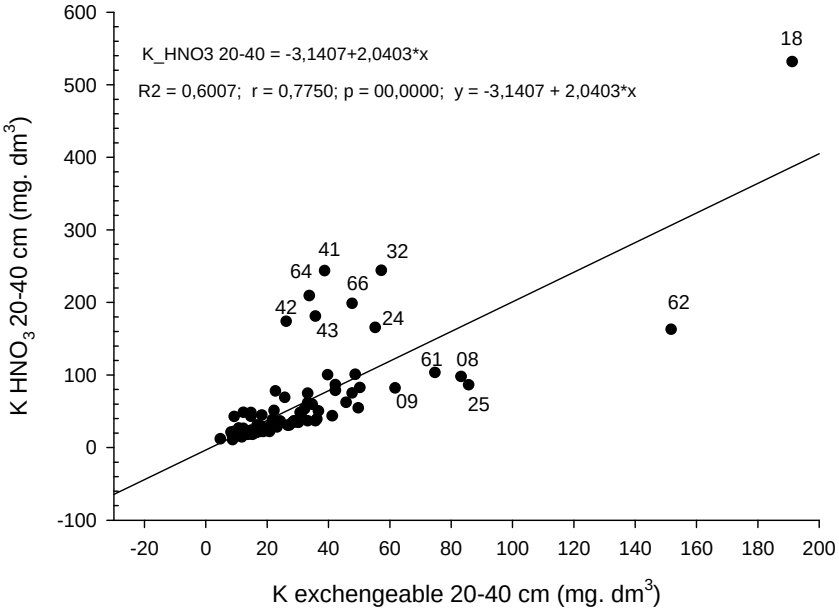

Figure 2. Relation of levels of exchangeable K and K extracted in nitric acid (HNO_3) at the depth of 20-40 cm at the 91 collection sites in the Vale do Araguaia region.

Table 1. Simple pairwise linear correlation coefficients between the levels of exchangeable K, non-exchangeable K and silt in the two soil layers (0-20 cm and 20-40 cm).

Variable	Non-exch K (0-20cm)	Exch K (20-40 cm)	Non-exch K (20-40 cm)	Silt (0-20 cm)	Silt (20-40 cm)
Exchangeable K (0-20 cm)	0.66*	0.77*	0.58*	0.12	0.20
Non-exchangeable K (0-20 cm)		0.66*	0.95*	0.28*	0.35*
Exchangeable K (20-40 cm)			0.53*	0.10	0.13
Non-exchangeable K (20-40 cm)				0.26	0.39*

*significant at the level 1% of probability.

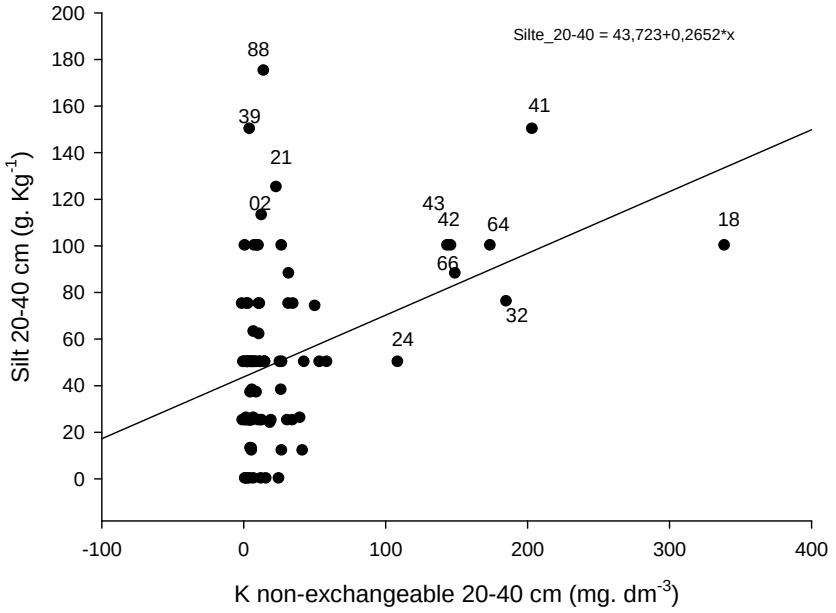

Figure 3. Relation between levels of non-exchangeable K and silt in the 20-40 cm layer in soil samples from the 91 collection sites in the Vale do Araguaia region.

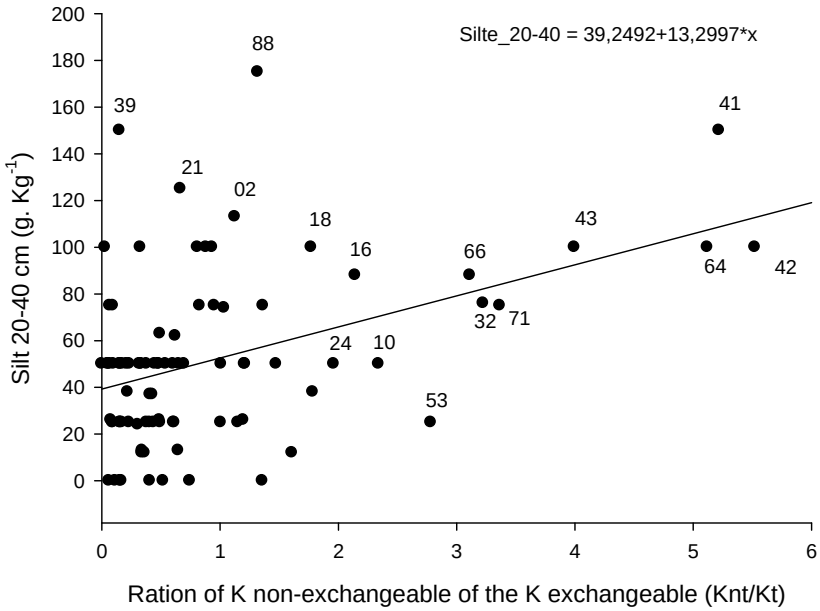

Figure 4. Ratio between levels of non-exchangeable K and exchangeable K in relation to silt levels in the 20-40 cm layer in samples from 91 sites in the Vale do Araguaia region.

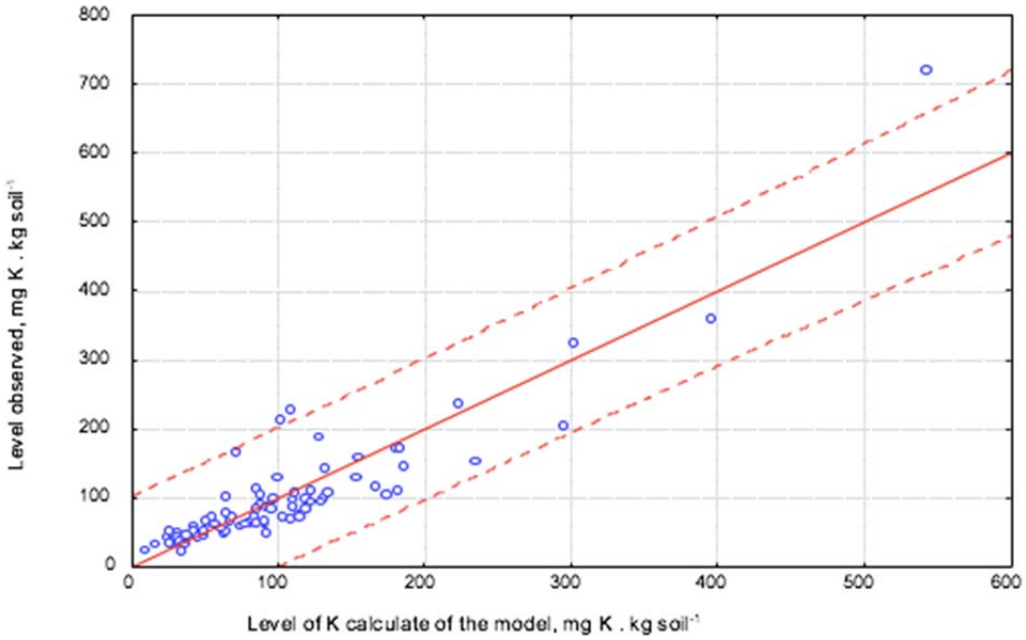

Figure 5. Multiple regression of K extracted in nitric acid (HNO3), generated by the observed levels of exchangeable K and silt in the soil samples from the 91 sites in the Vale do Araguaia region.

Productivity of Aerobic Rice Growth System can be Enhanced by Potassium Fertilization

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Abstract

Direct seeded aerobic rice production system has been developed and adopted as an alternative for medium-grain rice in many parts of the world, whereas efforts for aerobic basmati rice production are still in infancy. Among two major constraints for aerobic rice, weeds are progressively being eliminated to great extent through introduction of new herbicides, however, the issue of panicle sterility is still elusive. As potassium (K) deficiency produce sterile pollen in different crops, therefore possible K deficiency in aerobic production system may cause panicle sterility in rice. Therefore, it was hypothesized that K application may yield better by decreasing panicle sterility of basmati rice under aerobic conditions. Pot and field experiments conducted with no K fertilization, K fertilization at the rate of 90 and 180 kg ha^{-1} indicated that application of K fertilizer at 180 kg ha^{-1} can significantly increase the rice grain yield due to decrease in number of un-filled grains. The improvement in yield was more pronounced in Basmati 515 than Super Basmati. Economic analysis shows that benefit cost ratio was more for Basmati-515, and for K fertilization at the rate of 90 kg ha^{-1} when grown aerobically. However, net benefit of K fertilization was increased from all K application levels and both cultivars as well. As K fertilization decreased the panicle sterility and improved the rice yield therefore, for better yield and well adaptability of aerobic rice production, appropriate K fertilization is suggested for economical rice production.

Potassium Use Efficiency of Cotton as Affected by Application Methods

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Abstract
The potassium (K) fertilization is vital to attain potential yield with adequate lint quality of cotton. The proposed study was conducted to quantify the impact of K application approaches on K use efficiency of cotton. The two years' field trials were conducted in alkaline soils under arid environment at Central Cotton Research Institute, Multan, Pakistan during the year 2013 and 2014. The treatments were comprised of control (no K application), four foliar sprays of 2% KNO_3, basal application (100 kg K_2O ha^{-1}), basal application (200 kg K_2O ha^{-1}), combine K application (100 kg K_2O ha^{-1} + four foliar sprays of 2% KNO_3) and combine application (200 kg K_2O ha^{-1} + four foliar sprays of 2% KNO_3). The treatments were arranged according to randomized complete block design (RCBD) with four replications. The same treatments were allocated to plots during both the years. The K uptake was improved from 23.1 to 30.5 in leaves, 20.9 to 39.2 in stalk, 39.6 to 56.9 in fruits and 83.5 to 126.5 kg ha^{-1} in total dry matter in various treatments. The highest total plant biomass (754.9 g m^{-2}) was recorded with combined application of 200 kg K_2O ha^{-1} along with four foliar sprays of 2% KNO_3. The agronomic K use efficiency (increase in seed cotton yield (kg)/kg of K_2O fertilizer) was 3.81 and 2.85 with basal dose application of 100 and 200 Kg K_2O ha^{-1}, respectively which was improved to 7.75 and 4.77, respectively with four supplemental foliar sprays. The maximum agronomic K use efficiency was recorded when 100 kg K_2O per ha was supplemented with four foliar sprays, although total seed cotton yield was highest in 200 kg K_2O per ha supplemented with four foliar applications. Therefore, it is suggested that basal dose of 100 kg K_2O application with foliar application is more economical.

INTRODUCTION

Cotton is an important fiber and industrial crop sharing a large proportion of foreign exchange in Pakistan. Potassium is an important nutrient which contributes to productivity and quality through its positive impacts on yield attributes and fiber traits. It has been estimated that cotton consumed 23% of total fertilizer but it was limited to only for nitrogen and phosphorus without potassium (Anon 2007). The imbalance use of NPK fertilizers may be referred an additional factor of potassium deficiency. Likewise, other cotton growing countries, the soils of the Pakistan has been characterized as potassium deficit (Zia-ul-hassan et al. 2014). The proportion of potassium deficit soils of Pakistan is continuously increasing (Akhtar et al. 2003) and potassium depletion rate has been estimated 18 kg ha^{-1} $year^{-1}$ (NARC, 2003). Like other crops, cotton is relatively inefficient in potassium absorption from soil (Cassman et al. 1989). The daily potassium requirement for cotton has been estimated up to 3-5 kg K ha^{-1} day^{-1} (Ashfaq, Hussain & Athar 2015). To produce a lint yield of 2500 kg ha^{-1}, it would require 150 kg K ha^{-1} which equals to nitrogen (Silvertooth 2007). Despite very high potassium requirement coupled with soil depletion, we are fertilizing cotton with very low potassium i.e. <1.0 kg K_2O ha^{-1} (Nawaz et al. 2006). This might be among the important causes of stagnant cotton yield during last decade. The cotton demand for potassium is also high for conventional cultivars but transgenic cotton is more susceptible to potassium deficiency (Yukui et al. 2009). The cotton grown with insufficient potassium supply terminate growth earlier (Pettigrew 2008) and produce low seed cotton yield with poor quality fibers (Pettigrew, Meredith & Young 2005). Generally, potassium fertilizers are soil applied where a remarkable portion became unavailable to plants due to fixation with clay minerals (Ali et al. 2005). The foliar application is an effective way of feeding

plants with restricted root growth and adverse soil conditions (Howard et al. 2000). It is very important for correcting potassium deficiency during peak bloom season due to rapid uptake. The nutrients applied on leaves are translocated to various plant parts which results in higher yield. The cotton is very responsive to potassium supply and seed cotton yield was improved up to 40% under irrigated conditions (Coker, Oosterhuis & Brown 2009). The cost of potassium fertilizers is increasing (NFDC, 2005) and farmers of resource poor countries exclude potassium from their fertilizer programs. Thus, such issues compel the researchers to elaborate the application methods impacts on potassium uptake and utilization efficiency.

MATERIALS AND METHODS

The experiment was conducted at agronomic research area of Central Cotton Research Institute, Multan during crop season 2013-14. The soil of the experimental area was alkaline with poor fertility profile and climate is very hot in summer and cold in winter. The field was kept fallow during winter season and treatments were allocated to same plot both the years. The soil was well prepared with deep ploughing followed by planking and general cultivation and beds formation. The treatments were comprised of control (without K application), four foliar sprays of 2% KNO_3, basal application (100 kg K_2O ha^{-1}), basal application (200 kg K_2O ha^{-1}), combine K application (100 kg K_2O ha^{-1} + four foliar sprays of 2% KNO_3) and combine application (200 kg K_2O ha^{-1} + four foliar sprays of 2% KNO_3). The foliar sprays were repeated on 30, 45, 60 and 75 days after planting. The net plot size was 20ft × 45ft, consisting of eight rows of cotton. The basal dose of potassium in form of potassium sulfate (50% K_2O and 18% S) was surface broadcasted and incorporated to designated plots during last operation of seed bed preparation. The treatments were laid out according to Randomized Complete Block Design (RCBD) having four repeats. The delinted seed at the rate of 15 kg ha^{-1} was dibbled at 22.5 cm on moist beds in 75 cm wider rows during 3rd week of April in both the years. The recommended dose of phosphorus and 1/3 of nitrogen was soil incorporated with last cultivation. The remaining nitrogen was splitted in two parts at flowering and peak boll setting stage. The crop was furrow irrigated at 12-15days interval and last irrigation was applied during mid-October. General cultivation and plant protection practices were kept normal and uniform for all the treatments. The two plants from each plot was harvested from soil surface and separated into leaves, stalk and fruits to determine the dry matter partitioning. It was followed by oven drying till constant weight at two consecutive weighing was obtained. The potassium agronomic use efficiency (AEK) was determined using following equation

$$AEK\ (kg\ kg^{-1}\ potash) = \frac{Seed\ cotton\ yield\ (SCY)\ of\ fertilized\ plot - SCY\ of\ control\ plot}{Fertilizer\ applied}$$

The plant parts were weighed, grinded and potassium contents were measured following standard procedure. The fully opened bolls were picked manually and weighted on plot basis to record seed cotton yield. The data on yield, potassium uptake by various plant parts and potassium use efficiency was subjected to analysis of variance technique (ANOVA) using Statistix 8.1 and the significance of means was evaluated at 5% probability levels using least significance test (LSD) (Steel, Torrie & Dickey 1997).

RESULTS AND DISCUSSION

The mean of two years' results presented in Table 1 indicate that potassium uptake was significantly affected by various potassium fertilizer treatments. The minimum potassium uptake was recorded in plots where no potassium was added and it was followed by plots sprayed with 2% KNO_3 only. But the differences between these two treatments were non-significant. The combination of basal dose and foliar application produced significantly higher values for potassium content of various plant parts against their full dose basal application. This happened because foliar application enhanced the efficiency of soil applied potassium (Muhammad 2016). However, the increasing trend for potassium uptake was consistent in various plant parts. The total potassium uptake, dry matter accumulation and allocation to reproductive parts of plants was increased from 2.87% to 51.31%, 2.58% to 22.88% and 2.02% to 43.68%,

respectively against various potassium application treatments. The enhanced dry matter production and translocation to reproductive organs of cotton with adequate potassium nutrition is confirmation of the results of the Makhdum, Pervez, & Ashraf (2007). The growth response to soil applied and foliar potassium application was persistent for all recorded above ground plant parts. It was indicated from Table 1 that almost half of the total plant potassium was allocated to fruits (bur, lint and seed) which showed that potassium fertilizing is necessary for cotton from flowering through peak boll setting period.

It is clear from Table 2 that potassium uptake has been major factor of biomass production irrespective of application methods and rates. More dry matter allocation to fruits was translated by higher seed cotton yield. Significant yield improvement in cotton with potassium input has already been documented in literature (Aneela, Muhammad & Akhtar 2003). The soil application when supplemented with foliar supply increases leaf mass and seed cotton yield attributes to produce higher yield (Dewdar 2013 and Keshava et al. 2013). The yield benefit of 20-30% with four foliar sprays of 2% KNO_3 over unfertilized plots has also been reported by Knowles, Hipp & Langston (1995). While, the crop grown without potassium supply are not good in physiological and yield traits to produce high yield. Because more potassium uptake and reproductive dry matter was achieved at 200 kg K_2O ha^{-1} supplemented with 2% foliar sprays which resulted 38.4%, 32.4%, 20.0%, 12.5% and 5.5% higher seed cotton yield over T_1, T_2, T_3, T_4 and T_5, respectively (Fig 1). The significant yield increase with potassium fertilization has been reported by Kaleem et al. (2009). The yield improvement with potassium application might be result from changes in number of bolls, seed and lint mass. The poor seed cotton yield in control treatment is because of early maturity of crop.

The agronomic potassium use efficiency (seed cotton yield/fertilizer applied) was improved from 3.81 to 7.75 and 2.85 to 4.77 (kg kg^{-1}) with foliar application of 2% KNO_3 at 100 and 200 kg K_2O ha^{-1} (Figure 1). The potassium utilization was higher at lower potassium rate than higher dose. It is evident that 3.81 kg seed cotton per kg potassium was obtained at 100 which decreased up to 2.85 kg at 200 kg K_2O ha^{-1}. The same trend was consistent for their combined application. The reduced agronomic use efficiency of potassium at higher fertilization rate is in accordance with Yang et al. (2016). However, unutilized proportion of potassium would not pollute the ground water rather it will contribute to succeeding crop due to less leaching losses.

In conclusion, the potassium application rates improved the seed cotton yield and potassium uptake over control plots. The potassium uptake and dry matter production was improved with foliar application of 2% KNO_3 under low (100 kg) and high (200 kg) potassium rates. The agronomic potassium use efficiency was greater at lower application rate (100 kg K_2O ha^{-1}) and decreased with further potassium supply. Therefore, combined application of soil and foliar applied potassium is recommended for general cultivation.

ACKNOWLEDGEMENT
The authors greatly acknowledge the research grant provided by International Potash Institute (IPI), Switzerland.

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Table 1: Potassium distribution in various plant parts as influenced by K fertilizer applications and application methods

Treatments	**L-K-U** (kg ha^{-1})	**S-K-U** (kg ha^{-1})	**F-K-U** (kg ha^{-1})	**T-K-U** (kg ha^{-1})
Control	23.1 c	20.9 d	39.6 d	83.6 e
4 FAs of 2% KNO_3	23.6 c	22.1 cd	40.4 cd	86.0 e
100 kg K_2O ha^{-1}	25.0 bc	26.4 c	44.2 c	95.5 d
200 kg K_2O ha^{-1}	27.0 b	33.2 b	50.0 b	110.2 c
100 kg K_2O ha^{-1} & 4 FAs of 2% KNO_3	30.2 a	37.0 ab	50.3 b	117.4 b
200 kg K_2O ha^{-1} & 4 FAs of 2% KNO_3	30.5 a	39.2 a	56.9 a	126.5 a
LSD	2.85	4.45	4.51	6.68

The means denoted by various letter in column differed significantly at 5% probability level using LSD.
4 FAs= Four foliar applications, L-K-U=leaf K uptake, S-K-U= stalk K uptake, F-K-U=fruit K uptake, T-K-U=total K uptake

Table 2: Dry matter partitioning and potassium use efficiency as influenced by potassium applications and application methods

Treatments	**LDM** (g m^{-2})	**SDM** (g m^{-2})	**FDM** (g m^{-2})	**TDM** (g m^{-2})	**K-use efficiency** (kg kg^{-1} K_2O)
Control	128.9 c	159.4 d	326.0 d	614.3 d	-
4 FAs of 2% KNO_3	132.0 c	163.1 cd	335.1 cd	630.2 d	-
100 kg K_2O ha^{-1}	143.8 bc	171.9 bcd	350.5 bc	666.2 c	3.81
200 kg K_2O ha^{-1}	157.3 ab	179.1 bc	369.9 ab	706.3 b	2.85
100 kg K_2O ha^{-1} & 4 FAs of 2% KNO_3	158.9 ab	185.1 ab	375.5 a	719.5 b	7.75
200 kg K_2O ha^{-1} & 4 FAs of 2% KNO_3	170.4 a	198.5 a	386.0 a	754.9 a	4.77
LSD	17.63	18.06	23.31	25.76	

The means denoted by various letter in column differed significantly at 5% probability level using LSD.
4 FAs= Four foliar applications, LDM=leaf dry matter, SDM= stalk dry matter, FDM= fruit dry matter, TDM= total dry matter

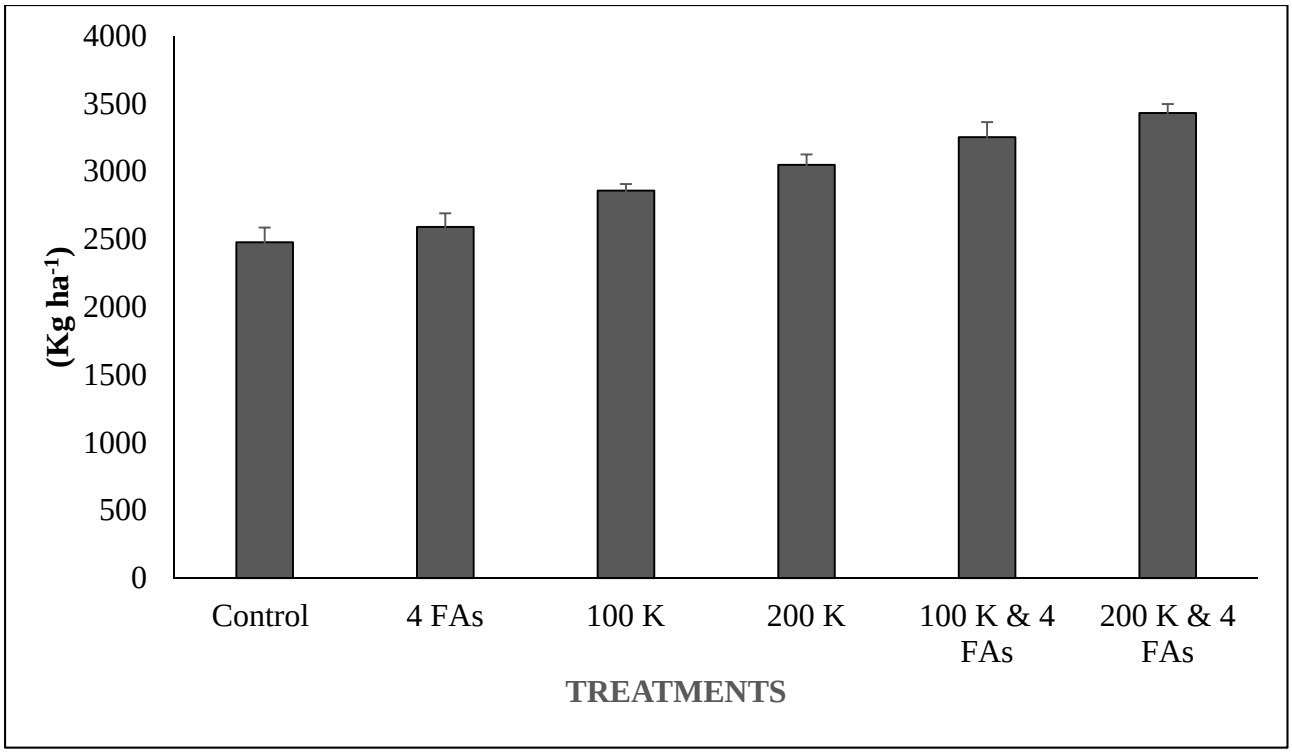

Figure 1: Effect of different levels of potassium fertilizers and fertilizer application methods on seed-cotton yield. Colum's are mean of two years and each year data had three replications for each treatment. Bars represent standard error. 4 FAs= Four foliar applications, 100 K= 100 kg K_2O ha^{-1} as K_2SO_4, 200 K= 200 kg K_2O ha^{-1} as K_2SO_4.

Effects of Biochar Application on Soil Potassium Dynamics and Crop Responses in Two Contrasting Soils

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Abstract

Soil amendment with biochar is evaluated globally as a means to improve soil fertility and agricultural productivity. However, there is limited understanding about the effects of biochar application on soil K dynamics. The aim of this study was to elucidate the role of biochar application in soil K status with the hypothesis that biochar application could facilitate soil K release and thus plant K uptake through the improvement of soil environment.

Within a winter wheat-maize rotation, plants were grown in two contrasting soils, namely yellow-brown soil (pH 5.7, silty clay, hydro-mica and kaolinite dominated) and fluvo-aquic soil (pH 7.8, sandy loam, smectite and hydro-mica dominated). In each soil, plants were applied with 0 (CK), 5 (B1), 10 (B2) and 25 g kg^{-1} (B3) biochar as soil amendment and K source.

In the first growing season, biochar enhanced wheat K uptake. Across treatments, K uptake in yellow-brown soil was higher than that in fluvo-aquic soil. Along with biochar rate, K uptake derived from water soluble K (WS-K) increased, while the contribution from exchangable K (E-K) declined in both soils. The changes in non-exchangable K (NE-K) was relatively small in yellow-brown soil. In fluvo-aquic soil, however, it contributed 44.6% and 28.9% of wheat K uptake in CK and B1, but showed a significant increase in B3 treatment, indicating K fixation.

In the second season, maize grown in fluvo-aquic soil had higher K uptake in CK, B1 and B2 treatments due to more NEK release. But K uptake was higher in yellow-brown soil in B3 treatment because of more K supply from WS-K. After two seasons of culture, biochar application significantly enhanced soil K buffer power, especially the case in B3 treatment, due to improved CEC. Along with biochar application rate, an obvious increase in soil pH was detected in yellow-brown soil (+0.10, +0.40 and +0.54 units, respectively), but it was only the case in B3 treatment in fluvo-aquic soil (+ 0.14 units). Moreover, soil organic matter content was greatly improved, while bulk weight was reduced, the effect of which was more pronouced in fluvo-aquic soil than in yellow-brown soil. Biochar application greatly promoted silicate bateria development in both soils, with the abandance in fluvo-aquic soil ca. 2-fold higher than that in yellow-brown soil across treatments.

According to our results, biochar affected soil K dynamics and plant K uptake mainly through the within-carried K that acted directly as a K source. We did not found evidence that biochar facilitated NE-K release through two seasons of culture. However, some soil properties such as organic matter content and silicate bacteria development have been greatly improved. With more growing seasons, the effects of biochar on NE-K release might therefore be more obvious when K becomes the main limiting factor. It was concluded that biochar could be serve as a soil amendment and feasible K sourse, but the effects may differ depending on soil properties, which should be taken into consideration in terms of plant K nutrition.

Impact of Potassium on the Abundance and Distribution of Antioxidants in Tomato Fruits

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Abstract
The tomato fruit is the most important vegetable. Their fruits are consumed fresh and processed and contain high amounts of antioxidants like phenolics and carotenoids (1). Potassium (K) as macronutrient of plants, is essential for several physiological functions such as translocation of assimilates, activation of enzymes, and stomata regulation (3). However, findings on water and lipid soluble antioxidants are contradictory (2, 4) indicating that the knowledge about the K-effects on secondary plant metabolism is limited.

We propose that K has a positive influence on antioxidant metabolism in tomato fruits. Therefore, we performed two pot experiments (outdoor and greenhouse) with high and low K fertilization application and different tomato cultivars. The results of the outdoor experiment showed that the ripening stage had a significant influence on the carotenoid content and on single phenolic compounds. The carotenoid content was only partly determined by the K fertilization. Therefore, in the greenhouse experiment we wanted to know which tissues of tomato fruit are changed by K. We harvested it at breaker and full ripe stages and separated the fruit tissues into peel, flesh and kernels. There were significant differences and interactions between the tomato fruit tissues and ripening stages but no change among the K fertilization levels in lycopene concentrations. However, concentrations in □-carotene and single phenolic compounds varied significantly among K fertilization levels, fruit tissue and ripening stages. The phenolic acids were mainly positively, and the later in metabolism appearing flavonoids were mainly negatively affected. High K-fertilization lead to significant higher K content in all tested tomato cultivars.

In the two experiments there were mainly the water-soluble phenolic compounds affected by the K fertilization in a fruit tissue and ripening stage specific manner. Impact of K fertilization on the lipid-soluble carotenoids was negligible in relation to a high tissue and ripening stage effect.

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Comparison of Ammonium Lactate Extraction and Electroultrafiltration Data for Avaiable Potassium on Different Soil Types

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Abstract
The aim of this study was to compare electroultrafiltration available potassium (K_{EUF}) from arable horizon (0-30 cm) of nine different soil types with ammonium lactate method (K_{AL}), which is frequently used analytical method for determining the accessibility of nutrients and it is a common method used for issuing fertilizer recommendations. In total, 90 soil samples from agricultural sites in eastern Croatia were analyzed using standard physico-chemical soil properties methods and simultaneously analyzed by both methods to determine soil available potassium. The analyzed soils were extremely heterogeneous with a wide range of determined values. Exchangeable acidity (pH_{KCl}) of investigated soils ranged from 3.69 to 7.91, organic matter content ranged from 1.20 to 5.40 % and clay content from 1.83 to 52.42 %. In relation to K_{AL} method (180.13 mg K/kg) as the standard method, K_{EUF} method (104.28 mg K/kg) extracts 42.11 % less on average of available potassium. In relation to standard method, on average K_{EUF} extracts 9.62 % less potassium on fluvisol, 35.39 % on luvic stagnosol, 39.58 % on stagnosols, 40.03 % on luvisol, 43.16 % on gleysols, 44.75 % on endogleyic stagnosols, 48.50 % on humic glaysols and 50.15 % less available potassium on eutric cambisol. Comparison of analyzed extraction methods of potassium from the soil is of high precision (r^2=0.92), and most reliable comparison was on stagnosol (r^2=0.98), followed by: gleysols (r^2=0.95), luvisol (r^2=0.94), endogleyic stagnosol (r^2=0.90), luvic stagnosol (r^2=0.87), fluvisol (r^2=0.83), humic gleysol (r^2=0.83), eutric cambisol (r^2=0.79) and stagnic gleysol (r^2=0.75) Extremely significant statistical correlation between different extractive methods for determining available potassium in the soil indicates that any of the methods can be used to accurately predict the concentration of potassium in all soil types.

Keywords: extraction methods, soil available potassium, soil types