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Nutrient Management in Conservation Agriculture– A Special Focus on Smallholder Farmers of South Asia and Sub-Saharan Africa

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ABSTRACT

Conservation agriculture (CA) is promoted as an important crop and soil management practices for sustainable agriculture. The practice is particularly beneficial for addressing major soil and climatic constraints that limit crop productivity in smallholder farming system of South Asia (SA) as well as Sub-Saharan Africa (SSA). Along with three well established components of CA – minimum tillage; permanent organic soil cover; and diversified crop rotations,nutrient management is considered a key factor for the success of the practice. However, information on the role of plant nutrition in CA systems in South Asia and SSA is scattered and needs further integration. Present study aims to review data and information to give insights into the significance of nutrient management practices in CA systems. It describes nutrient use and dynamics and an assessment of the need for tailoring nutrient management practices and recommendations to CA systems. The review is based case scenarios from SA and Sub-Saharan Africa with relevant information to assess effects of nutrient management on increasing yield, nutrient use efficiency and profitability under CA.

Key words : Conservation Agriculture; Nutrient Stewardship, Sustainability, Fertilizer Use, Food Production, South Asia, Africa

Introduction

Conservation agriculture is defined as the cropping system management practice that promotes minimum soil disturbance, maintaining permanent soil cover and appropriate crop rotation leading to sustainable production systems. It is considered as a major way forward to make agriculture sustainable by protecting the soil (Dordass, 2015). The interest for conservation agriculture (CA) is increasing globally and the key drivers are water

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scarcity and labor costs associated with the conventional agricultural systems. The CA system has received attention for intensifying the system productivity, especially for small holder farmers of South Asia (Sapkota *et al.,* 2016) and Sub-Saharan Africa (Vanlauwe *et al.,* 2014). Support for promoting CA in Sub-Saharan Africa andSouth Asia is its success in broad acreage farms in various parts of the world (Bolliger *et al.,* 2006; Kassam *et al.,* 2009), with some adoption by smallholders (Vanlauwe *et al*., 2014; Add a reference from CIMMYT India). Among many reported benefits, CA often produced more stable and economically favorable yields, particularly in drought-prone regions, compared to conventional agriculture (Mitra *et al.,* 2019; Knowler and Bradshaw, 2007; Rusinamhodzi *et al.,* 2011).

Conservation agriculture was introduced to smallholder farmers by the Food and Agriculture Organization (FAO) as a part of their agricultural support programs to increase food security and productivity for these farmers (Jenrich, 2011). The success of conservation agriculture, however, depends on how well the component technologies, such as water, weed and nutrient management strategies, are developed to support crops under minimum or no tillage (Majumdar *et al.,* 2018). The three pillars of conservation agriculture - minimum tillage and soil disturbance; permanent organic soil cover; and diversified crop rotations have significant influence on the soil nutrient dynamics (Majumdar *et al,* .2018;Vanlauwe *et al.,* 2014). For example, when tillage is reduced, greater crop residues accumulate on the soil surface that minimizes wind and water erosion and reduces nutrient losses. Crop residues on the soil surface increase water infiltration and reduce evaporation losses, and lowers the surface temperature. At cooler soil temperatures, nutrient release from soil organic matter and other mineral fractions reduces, diffusion of nutrients to the plant roots slows down, affectingaccess to plant nutrients by the roots. In the absence of frequent tillage, mineralization is slowed and the release of plant nutrients declines, making fertilization more important in producing higher yields. At the initial years of adoption of no-till, the increased carbon (C) from the crop residues causes immobilization of soil N as microorganisms use soil N to maintain the C:N ratios during the decomposition process. With time, the breakdown of soil organic matter reaches a new equilibrium and the pool of potentially mineralizable N increases, resulting in more plant-available nitrate (NO_3)-N and ammonium (NH_4)-N. The P and K are generally less mobile in the soil, and may accumulate at the soil's surface (0-5 cm) in absence of tillage and soil mixing (Majumdar *et al.,* 2018). Considering its complexity as well as importance, nutrient management has been identified as the "fourth pillar" of conservation agriculture (Vanlauwe *et al.,* 2014).

The importance of nutrient management in CA systems was well articulated in a recent article (Vanlauwe*et al.* 2014) where the authors argued that a fourth principle of CA– the appropriate use of fertilizer–is required to enhance both crop productivity and produce sufficient crop residues to ensure soil cover under smallholder conditions in Sub-Saharan Africa. An understanding of how nutrients move and react in the soil is necessary for proper fertilizer management in reduced tillage systems. However, studies on nutrient dynamics in CA systems are limited, and fertilizer recommendations developed for conventionally tilled systems are generally used for crops grown under conservation agriculture practices. Kassam and Friedrich (2009) suggested that conventional soil analysis data might not necessarily be a valid basis of fertilizer recommendations for CA, since the available soil volume and the mobility of nutrients through soil biological activities tend to be higher than in tillage-based systems against which the existing recommendations have been calibrated. The authors also suggested that the nutrients and their cycles must be managed more at the system or crop mix level in a fully established CA system so that fertilization is not strictly crop specific, rather nutrients are provided at the most convenient time during the crop rotation to maximize benefit. Vanlauwe*et al.*(2014) proposed fertilizer application as a separate principle for CA in contrast to other agronomic practices, including planting time, spacing, and weeding regime, because fertilizer is essential for CA to work, whilst the sub-optimal implementation of other crop management practices do not lead to the failure of CA as such. They suggested that without acknowledging this fourth principle, i.e. nutrient management, the chance of success for CA, especially in smallholder farms, is limited.

2. Nutrient dynamics and management in conservation agriculture

Nutrient management in CA systems is a complex issue as it involves several interconnected mechanisms (Majumdar *et al.*2018). Therefore, the subject needs attention from researchers'point of view for successful adoption of conservation agriculture practices at the farm level. In general, four important chemical and biochemical processes, often working simultaneously, are involved in influencing the dynamics of a nutrient in the soil system (Majumdar *et al.*2018). These are: mineralization-immobilization, sorption-desorption, dissolution-precipitation and oxidation-reduction; and most of the dynamic behavior of soil nutrients can be explained by one or a combination of these processes. Among these, the mineralization-immobilization and sorption-desorption seem to play more dominant roles in governing the source-sink interactions characterizing the nutrient dynamics. The three key elements of CA systems, minimum disturbance, residue retention and legume in crop rotation, are expected to influence the above-mentioned chemical and biochemical processes considerably. The changes in physical and biological properties of the soil associated with CA practices are expected to modify the direction and kinetics of the chemical and biochemical processes leading to altered nutrient dynamics in the soil. We intend to correlate the altered bio-physical properties of soils under CA practices and their expected influence on the chemical and biochemical processes in the soil to highlight the nutrient dynamics under such systems, particularly for the macronutrients.

Mineralization is the transformation of nutrients from an organic to an inorganic state while immobilization is the reverse process. Both the processes are biochemical in nature and are bound to the activities of the heterotrophic biomass. These two processes significantly influence the dynamics of several nutrients, namely nitrogen (N), phosphorus (P), sulphur (S) and micronutrients. Both mineralization and immobilization have fundamental functions in the universal N cycle. Both the processes are linked to the heterotrophic sub-cycle (Campbell, 1978) that is characterized by mineralization, energy dissipation from organic matter. The functioning of the sub-cycle is dependent on this mineralized N where invariably a part of it is immobilized by the heterotrophic organisms involved in the sub-cycle. These two opposing processes result in net mineralization or net immobilization depending on the difference in rate with net mineralization being the normal and dominating reaction. Such continuous process of transfer of mineralized N into organic products of synthesis and of immobilized N back into inorganic decay products is defined as MIT (mineralization-immobilization turnover) (Campbell, 1978).

It is well established that due to less surface evaporation (surface cover) and better infiltration of rainfall (better soil aggregation), there is usually 15-25%extra available moisture during the growing season with no-till as compared to conventional tillage. Besides the perceivable advantage of extra moisture during the growing season, particularly in arid and semi-arid regions, this also opens up the possibility of N losses from the system through leaching and gaseous losses. There are several reports from Kentucky, USA, (Thomas *et al.,* 1973; McMahon and Thomas, 1976; Tyler and Thomas, 1977) comparing NO_3^- – N movement in no-till corn as compared to conventional tillage that showed loss of NO_3^- below 90 cm depth of the soil and attributed that to lower surface evaporation and deep penetration of water and NO_3^- through large pores, facilitated by better aggregation in the wetter no-tilled soil. This led researchers to speculate that more fertilizer N will be required for optimum no-till corn production than for conventionally tilled corn. The additional nitrogen is expected to compensate for high risk of leaching losses of NO_3^- – N and for lower rate of mineralization of residual soil N in the Kentucky soil. Long-term yield results from one such study (Blevins *et al.*, 1980) showed higher yield response in no-till corn, particularly at the first incremental N use and may reflect greater mineralization of residual soil N in conventional tillage.

The impact of residue retention on nutrient dynamics and subsequent yield of wheat was revealed by a nutrient omission study in Northwestern India (Kumar *et al.*, 2012). Nitrogen, P or K responses in the contrasting tillage practices, estimated by subtracting the omission plot yields from the ample treatment yield. The effect of differential residue management, such as full retention of residues from the previous rice crop, partial retention of rice residue (anchored rice stubbles), and complete removal/burning of residues within CA on the yield of wheat was estimated (Figure 1). Higher yields were observed for ample NPK, P omission and K omission when the full residue of the previous rice crop was retained and no tillage was done. The N omission plot yield was higher under complete removal of rice residue. Higher availability of nutrients from retained residues in the ample NPK and P or K omission plots probably increased yields, while greater immobilisation of N in the full residue retained plots caused yield decline in the N omission plots.

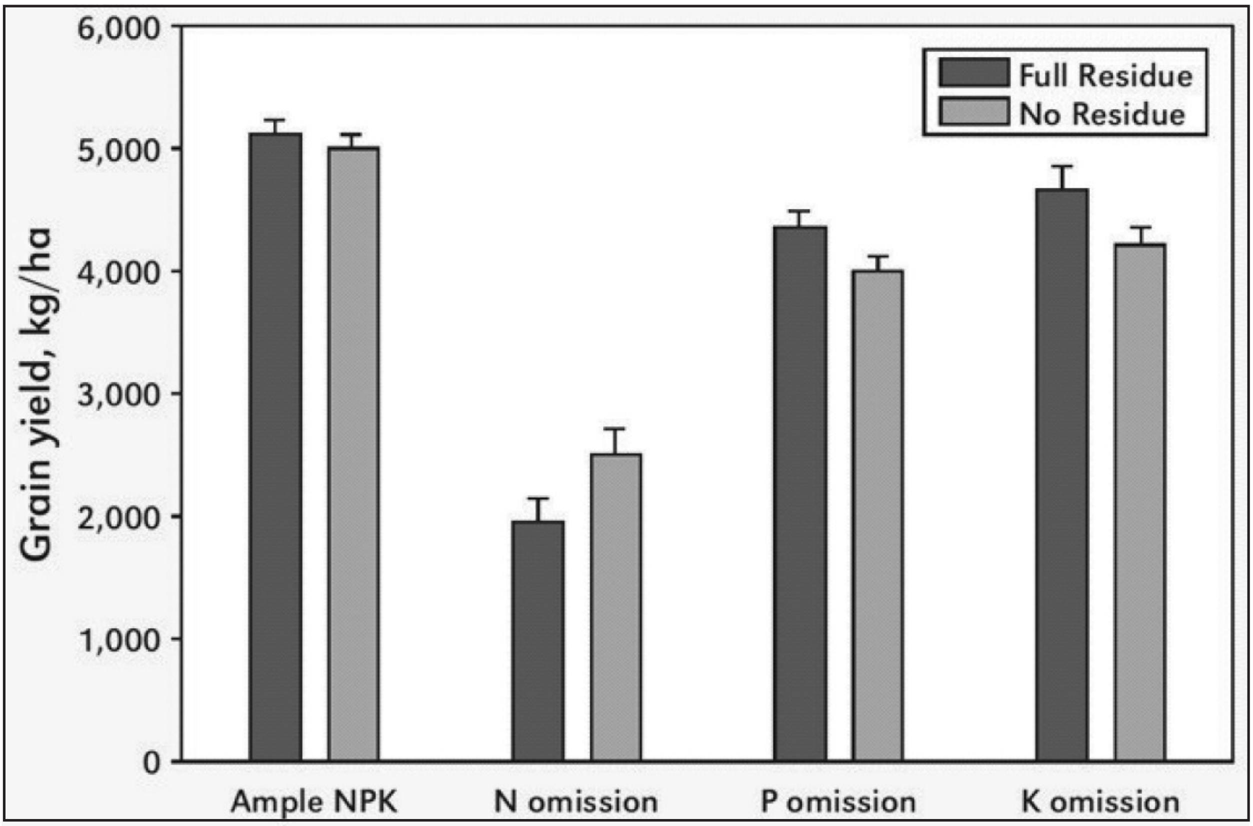

Figure 1. Effect of residue management on wheat grain yield under no-till. The bars represent the standard error.

Jat *et al.* (2011) reported several advantages of conservation agriculture in cereal systems of South Asia. For example, minimum disturbance of optimum porous soil architecture may optimize proportions of respiration gases in the rooting-zone; moderate organic-matter oxidation;favor water movement, retention and release at all scales; limit re-exposure of weed seeds and their germination. The permanent cover of sufficient organic matter over the soil surface could buffer against severe impact of solar radiation and rainfall; provide substrate for soil organisms' activity; improve cation-exchange capacity for nutrient capture, retention and slow-release; and smothering of weeds. Crop rotations that include legumes disrupt life cycles of pest and diseases; promote biological N-fixation; and increase organic-matter addition at all depths reached.

3. Nutrient management strategies for conservation agriculture

The issue and challenges of nutrient management under CA system is a global phenomenon and therefore can be addressed with global nutrient management concepts. Such concepts and their integration with CA system aredescribed below.

3.1. 4R Nutrient Stewardship

The 4R Nutrient Stewardship is a concept based on the principles of balanced fertilization that advocates application of the required nutrients to the plants in a balanced manner, keeping into account the native nutrient availability in soils and the nutrient requirement of the crop (IPNI, 2012). The 4R Nutrient Stewardship Principles of applying the right source of plant nutrients at the right rate, at the right time, and in the right place is at the core of the balanced fertilization approach. The source, rate, time and place essentially define fertilizer application in any context, be it at the broad acreage farms where sophisticated machinery is used for precision application of nutrients or in smallholder systems where fertilizer is manually mixed and applied by farmers in their small fields. The detailed principles along with the concept of 4R Nutrient Stewardship is described in previous volume of the journal (Dutta *et al.,* 2015).

Principles Supporting Practices:

Specific scientific principles guide the development of practices determining right source, rate, time, and place of fertilizer application. A few examples of the key principles and practices are shown in Table 1 and Figure 2. The principles are the same globally, but how they are put into practice varies locally depending on specific soil, crop, climate, weather, economic, and social conditions.

The four "rights" provide a simple checklist to assess whether a given crop has been fertilized properly. Asking "Was the crop given the right source of nutrients at the right rate, time, and place?" helps farmers and advisers to identify opportuni-ties for improvement in fertilizing each specific crop in each specific field, that are expected outcomes associated with applying fertilizer best management practices (FBMPs).

Source, Rate, Time and Place is interconnected and synergistic in nutrient management, and none of the four can be right when any one of them is wrong. It is possible that for a given situation there is more than one right com-bination, but when one of the four changes, the others may as well. The 4Rs must work in synchrony with each other and with the cropping system and management environ-ment.

The 4R framework is based on long-understood principles (Thorup and

Table 1. Examples of key scientific principles and associated practices

	The Four Rights (4Rs)		
Source	**Rate**	**Time**	**Place**
Examples of key scientific principles • Ensure balanced supply of nutrients	• Suit soil properties • Assess nutrient supply from all sources • Assess plant demand	• Assess dynamics of crop uptake and soil supply • Determine timing of loss risk	• Recognize crop rooting patterns • Manage spatial variability
Examples of practical choices • Commercial Fertilizer • Livestock manure	• Compost • Crop residue • Test soils for nutrients • Calculate economics	• Balance crop removal • Pre-plant • At planting • At flowering	• At fruiting • Broadcast • Band/drill/inject • Variable-rate application

Source : IPNI (2012)

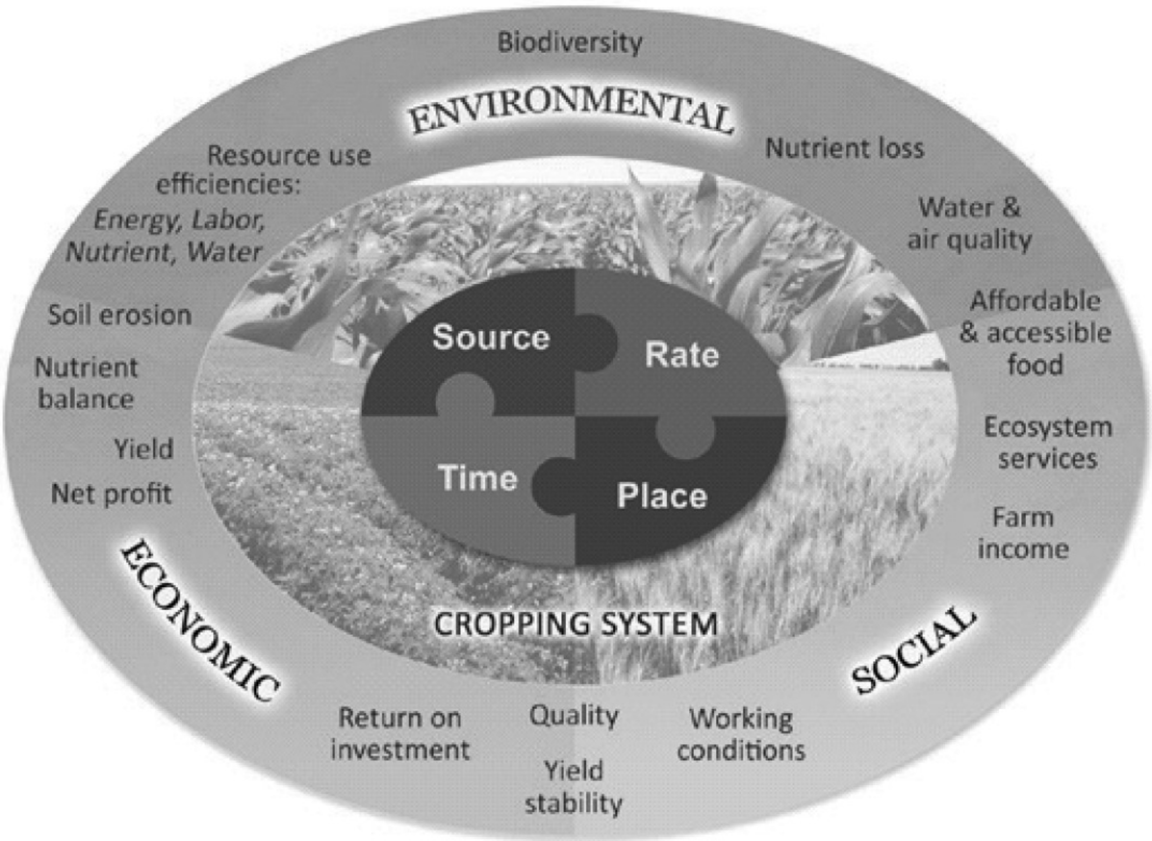

Figure 2. Performance indicators reflect the social, economic and environmental aspects of the performance of the plant-soil-climate system. Their selection and priority depend on stakeholder values.

Stewart, 1988). It was developed with input from the worldwide fertilizer industry, in both developed and developing countries, and applies to both. In addition to the International Plant Nutrition Institute (IPNI), organizations including the International Fertilizer Industry Association (IFA), The Fertilizer Institute (TFI) and the Canadian Fertilizer Institute (CFI) have contributed to the development of the 4R Nutrient Stewardship framework and continue to support its implementation (CFI, 2005; Fixen, 2007; Roberts, 2009; IFA, 2009; TFI, 2010).

3.2. Site specific nutrient management (SSNM)

Site specific nutrient management (SSNM) is an approach for supplying plant nutrients to optimally match their inherent spatial and temporal needs for supplemental nutrients (Buresh and Witt, 2007). This approach aims to enable farmers to adjust their fertilizer decision to optimally fill the deficit between the nutrient needs of the crop and supply from indigenous sources such as soil, crop residue, organic inputs and irrigation water. The SSNM approach does not necessarily aim to either reduce or increase fertilizer use, rather aims to recommend nutrients at optimal rate and time to achieve high profit for farmers with higher nutrient use efficiency and therefore protects the environment (Sapkota *et al.,* 2014). The steps followed in SSNM includes: i) Establishing yield target, ii) Estimation of indigenous supply of nutrients, iii) Estimation of crop response, and finally, iv) Estimation of nutrient rates based on crop response and agronomic efficiencies. The SSNM concept uses nutrient balance approach, in which fertilizer P and K are recommended in amounts sufficient to close the gap between the indigenous supply and plant needs to achieve the yield target in such a way that mining of nutrients can be minimized (Majumdar *et al.,* 2015). In the case of N, in-season nutrient estimation is used to determine the amount of N to be applied at different crop growth stages (Buresh and Witt, 2007). Overall, SSNM provides situation specific nutrient recommendations and therefore, if combined, could be a very successful component of CA system.

3.3. Residue management

The conservation agriculture practice advocates crop residue retention, whichideally should be accounted for while developing nutrient management strategies. When residues are kept at surface versus incorporated, nutrient availability differs. Since organic matter is a key factor in soil quality and nutrient dynamics, the management of previous crop residues has profound effect on soil nutrient dynamics. The quantity of residues left in the field, the composition of the residues and its placement (retained or incorporated) influence the decomposition rates in thesoil.

As mentioned before, whether N is mineralized or immobilized depends on the C:N ratio of the organic matter being decomposed by soil microorganisms. The progress of N mineralization and immobilization following residue addition is illustrated in Figure 1. There is rapid increase in the number of heterotrophic organisms during the initial stages of fresh organic matter decomposition as indicated by elevated CO_2 evolution. If the C:N ratio of the residue is > 20:1, net immobilization will occur as shown in the hatched area under the top curve (Fig. 1). The insufficient nitrogen in the substrate will induce the organisms to draw on the mineral nitrogen in the soil leading to immobilization of N. The residue C:N ratio will, however, decrease as the decay proceeds because of decreasing C (respiration as CO_2) and increasing N (N immobilized from soil solution) and a new equilibrium will be reached, accompanied by mineralization of N (Figure3). A combination of high C:N ratio plant residues and low soil N is expected to reduce N availability to plants at least at the initial phases of crop growth. Retention of cereal straws, most commonly practiced in South Asia, with reported range of C:N ratios between 60:1 to 100:1(Havlin *et al.,* 2005) and generally low available N in soils of the region is expected to prolong the stage of N immobilization. Crops planted immediately after cereal residue incorporation in such soils may become deficient in N and will require sufficient external N application to satisfy the need of the microorganisms and the growing crop.

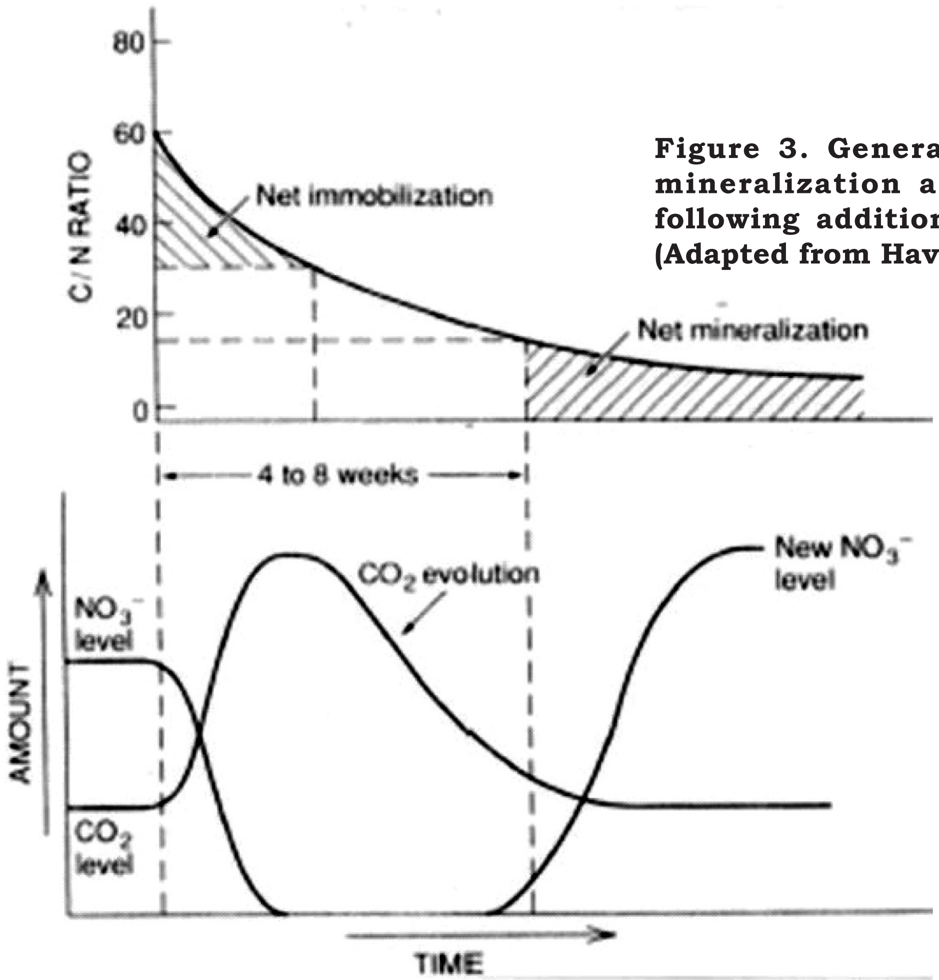

Figure 3. General description of N mineralization and immobilization following addition of residue to soil (Adapted from Havlin *et al.,* 2005)

Table 2. Average annual grain yield (kg/ha) over 10 year continuous corn production on a Maury soil.

N-Rate (kg/ha)	No-till	Conventional tillage
0	4767	5958
84	7715	8028
168	8028	7840
336	8342	8216

Source : Adapted from Blevins et al., 1980

3.4. Precision Agriculture

Precision nutrient management tools use layers of GIS information including reliable weather data and soil databases, remote sensing information, digital terrain data and other information with erosion and hydrological models to conduct site-specific simulations across field and natural ecosystem (Berry *et al.,* 2003). Precision conservation agriculture could be the key component of utilizing all these advanced tools of nutrient management together or as and when required for developing sustainable nutrient management protocols. Jenrich (2011) described how precision conservation agriculture can be used to increase conservation effectiveness and yields for selected smallholder farmers in Sub-Saharan Africa. The author mentioned that precision agriculture can increase operational precision without capital investments and improve outputs significantly.The report mentioned different types of precision agricultural practices, including precise land preparation (e.g., using conservation agriculture, hand-dug planting holes),and improved land and crop management, in combination with some precisely applied fertilizer. The application of precision conservation agriculture helps optimizing available resources through best site-specific land and field practices, contributing to rapid yield increases. A combination of 4R nutrient stewardship, along with timely field operations and weeding, plant spacing, and populations could make significant yield improvement without any investment, simply by improving synchronization of management with the crop uptake demands of an even plant population. Additionally, precision conservation agriculture has also been successful in adding of other agrochemicals and lime. As with the fertilizer, the lime is precisely applied around the root zone of each plant to improve the environment around the plant root zone and use the minimal resources more effectively.For example, optimizing the date of planting of maize (*Zea mays* L.) in Zimbabwe is the key to maximize productivity. The traditional farming systems in Zimbabwe do not capitalize the synchronization of planting with better growing conditions for maize. In general, due to tillage constraints, many farmers plant late in Zimbabwe, reducing their yield potential. The adoption of precision conservation agriculture could help farmers improve synchrony of planting with the environmental conditions of the growing season to help increase average maize yields. This can be achieved without large investments, enabling many more farmers to be food secure and to sell surplus product.

3.5 Crop rotation

Rotation of crops and introduction of legume in the cropping system is a critical part of conservation agriculture and needs special attention in terms of nutrient management. In Sub-Saharan Africa, studies have reported that crop rotation is an important component of CA system and there are several examples of crop rotation helping yield improvement under CA practices. In Sub-Saharan Africa, Sahelian regions play an important role in the livelihood of large number of farming communities. The geographical area of Sahelian countries include Burkina Faso, Mali, Niger and Senegal, and success stories of conserving agriculture in the region may help in understanding and draw lessons for other areas. Intercropping and crop rotation appears as an important CA practice that is being followed here (Table 3). It is obvious that inclusion of legume in the cropping system changes the dynamics and release pattern of the nutrients. However, information is scant on how nutrient management can be combined with crop rotation forhigher productivity and profitability with lesser environmental footprint, and needs further research for those countries.

4. Application of advanced nutrient management strategies under conservation agriculture practices

As mentioned above, the successful implementation of conservation agriculture needs special nutrient management strategies. The concept is now global and there are quite a few examples of successful amalgamation of these two pillars under different growing conditions.

All the advanced nutrient management protocols such as 4R nutrient stewardship, SSNM principles, and precision agriculture, are followed in different regions. However, a ready to use nutrient management tool following those principles is a real need. In this regard Nutrient Expert® (NE) nutrient decision support system has given evidence of successful use. NE uses the principles of site-specific nutrient management (SSNM) applied through 4R Nutrient stewardship strategies in its algorithm and recommendation process (Mandal *et al.*, 2016). The tool enables farm advisors to develop fertilizer recommendations tailored to a specific field or growing environment for cereals (Chuan *et al.,* 2013, Pampolino *et al.,* 2012; Sapkota *et al.,* 2014.). In the recommendation process, NE considers the most important factors affecting nutrient management recommendations in a particular location, and provides recommendation guidelines that are suitable to that particular farming condition. The tool uses a systematic approach of capturing the site-specific information that is important for developing recommendation (Xu *et al.,* 2014).

Table 3. Crop rotation as measure of conservation agriculture

Country	Crop	Management Practices	Yield	Reference
Burkina Faso	Sorghum is one of the major crops of the country having 1.40 M ha harvested area with a total production value of $229.06M.	The intervention of CA practice was change in cropping system to sorghum-cowpea intercropping from existing sorghum monoculture.	The grain yield of both sorghum as well as cowpea was double compared to sorghum or cowpea monocultures.	Zougmoré *et al.* 2000; 2004.
		The CA practice included half -moon cultivation combined with organic or mineral fertilisers.	Improved sorghum grain yield from 900 kg/ha in existing conventional tillage to 1600 kg/ha under CA system.	Zougmoré *et al.* 2003
		Rotation of Cowpea – Sorghum and Groundnut – Sorghum.	The rotations increased succeeding sorghum yields by 290% and 310%, respectively.	Bado*et al.* 2006.
Burkina Faso	Rice is another major crop of the country with a harvested area of 0.49 M ha.	In the case of rice, the improved fallow (Mucuna) is considered as one of the major CA practices.	Upland rice yield was significantly higher in improved fallows than in the natural fallows.	Segda*et al.* 1998.
Mali	Sorghum is a major crop in the country.	The major CA practice followed here is inclusion of green manure (Cassia tora L.) at various rates along with urea and rock phosphate as normal fertilizer application practice.	After three cropping seasons regardless of the quantity of biomass of green manure applied, Cassia tora L. associated with urea and RPT increased both the grain and dry matter yields of sorghum compared with farmers' practices.	Mbaikoubou, 2005.
Mali	Other widely harvested crops in Mali are Pearl Millet and Cowpea.	CA practice included rotation of pearl millet-cowpea. Urea and roc k phosphates are used as common fertilizers.	Study reported that the rotation increased pearl millet grain yield by 17% to 31% each year between 1991 and 1995 When nitrogen was applied up to 40 kg ha^{-1}.	Bagayoko*et al.* 1996; Goita and Sidibé 2009.
Niger	Millet is a major crop in this country.	Following CA practices are generally followed in the country - Minimum tillage, Zaï, and Mulching. In a specific study the following four treatments were followed: i) Zaï : 200 g cattle manure was added per Zaï hole (2.8 t/ha) ii) Mulching: millet straw (2.0 t/ha) was spread in the mulching iii) Zaï+ Mulching iv) Control: The control treatment did not receive cattle manure or millet straw.	Observed millet grain Yield (ave. of two years 2012-13) across treatments : Zaï+ Mulching: 291 kg/ha Zaï : 193kg/ha Mulching : 93 Control : 35 kg/ha	Boubacar M. Moussa, *et al.* 2016.

South Asia

Mitra *et al.* (2019) reported that nutrient management practice based on Nutrient Expert®- Wheat in combination with zero tillage as a promising option for wheat cultivation in North Eastern hill plains for yield improvement and farm profitability, while maintaining the soil health through better nutrient use efficiencies. They mentioned that nutrient dose of Nutrient Expert® with application of N, $P_2O_5$and K_2O at 140, 32.9 and 65 kg/ha respectively in combination with zero tillage produced high yield, good economics and nutrient use efficiency over conventional agricultural practices. In another study, Kumar *et al.* (2012) reported that nutrient management with NE along with CA system provided significantly higher yield compared to conventional tillage system (Table 4).

Table 4. Effects of nutrient management and tillage practices on wheat grain yield (average of two years (2010-11 & 2011-12), n = 29)

Nutrient Management	Yield (kg/ha) at different Tillage Management systems	
	No-till (CA)	Conventional (CT)
Nutrient Expert (33:33:33 splitting of total N)	5521 a[1] A[2]	5239 a B
State Recommendation	5093 b A	4969 b A
Farmer's Practice	4766 c A	4532 c A

[1]Within column, means followed by the same small letter are not significantly different at p = 0.05 using Tukey's HSD test; [2]Within rows, means followed by the same capital letter are not significantly different at p = 0.05 using Tukey's HSD test.

In another study, Spakota *et al.* (2014) reported that CA practices along with improved nutrient management not only improves the yield but also helps reducing the greenhouse gas (GHG)emission significantly. The study highlighted that NE-Wheat based fertilizer recommendation in combination with CA reduced the GHG emission from conventional tillage system from 1800 to less than 200 kg CO_2eq ha^{-1}.

A study, comparing the combined effect of nutrient management options and tillage practices in 84 sites in Southern India (Satyanarayana et al., 2012) across kharif (rainy) and Rabi (winter) seasons showed that NE-Maize based recommendation recorded higher grain yield in CA (9.3 t/ha) in comparison to CT (8.4 t/ha) and the magnitude of yield increase over CT (Figure 4) was higher in Kharif (20%) than in the Rabi (3%) season.

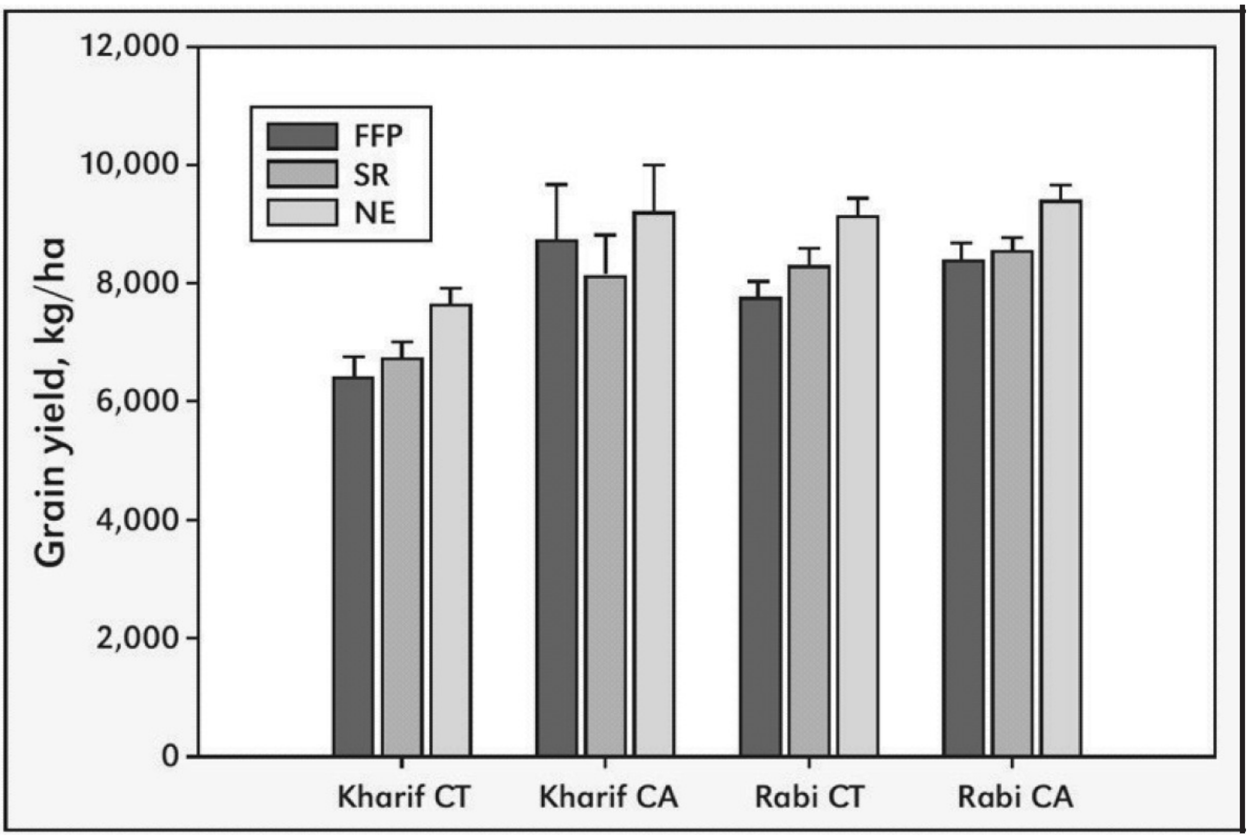

Figure 4. Effect of nutrient management options under varied seasons and crop establishments on grain yield of maize. FFP: Farmers' Fertilizer Practice; SR: State Recommendation; NE: Nutrient Expert-Maize based fertilizer recommendation

Considering the challenges associated with the depletion of water resources in north western Indo-Gangetic Plain, Parihar *et al.* (2017) suggested a new cropping system – maize – wheat – mung bean (MWMb) instead of traditional rice - wheat system to mitigate the challenges associated with the water. The objective of the study was to determine the productivity, water-use efûciency (WUE) and incident radiation conversation efficiency (IRCE) of MWMb cropping system at different tillage practices and nutrient management strategies. The study highlighted thatcombinations of zero tillage and NE-based fertilizer recommendation resulted in higher system WUE and IRCE, grain and biomass yield compared to conventional tillage and + unfertilized/ farmers' fertilizer practices. Combining site specific nutrient application and reduced tillage has complementarity to attain higher system productivity, WUE and IRCE compared to the use of these crop management practices in isolation.

In Nepal the adoptions of CA technologies are in the primary stage and concerted efforts of all the stakeholders in the partnership and participatory approaches are required for their expansion. Labor scarcity, increasing production costs and declining or static productivity are the major challenges of agriculture in Nepal. CA practices help reverse degradation processes, improve resource quality, reduce production costs and help achieve sustained high productivity. Therefore, CA based crop management practices across the various agro-ecologies need to be identified and promoted in Nepal (Shrestha *et al.* 2014). A study conducted by Tripathi (2010) at wheat growing field of Nepal suggested that incorporation of residue along with no-till increased the wheat yield to 2.83 t/ha from 2.05 t/ha achieved with conventional tillage practices. They also observed an increase of a profit from Nepalese Rupees (NR) 10,000 to more than NR 27,000/- due to shift in CA system.

In country like Pakistan, Sharif et al. (2017) reported that the conservation agriculture (CA) has potential to improve soil structural stability by enhancing organic matter contents, provide equal yield and economical benefit by reducing input cost. Latif *et al.* (2013) reported that adopting no tillage over conventional tillage increased wheat yield from 3.97 to 4.61 kg/ ha.

Sub-Saharan Africa

CA studies in smallholder farming systems of sub-Saharan Africa (SSA) have shown that a minimum of 3 tons of biomass is required to attain the required minimal surface coverage (Guto *et al.*, 2012). Crop production levels in a majority of smallholder farms in sub-Saharan Africa (SSA) are, however, often insufficient to produce enough biomass to meet this threshold (Giller *et al.,* 2009). For example, mean yields of maize, the key staple crop in SSA, are often less than 2 t ha^{-1} under typical smallholder farming practices (GYGA, 2020), with the associated biomass insufficient to provide enough residue for successful implementation of CA (Vanlauwe *et al.,* 2014).

On-farm studies in eastern (Vanlauwe *et al.,* 2006; Njoroge *et al.,* 2017), southern (Kurwakumire *et al.*, 2014), and western Africa (Kihara *et al.,* 2016) have however demonstrated that balanced fertilizer applications can substantially increase maize grain yields across diverse agro-ecological and farm conditions. Such yield increases not only result in improvements in crop productivity, but alsoincreases potentially available biomass for retention in the field.. Appropriate fertilizer use has subsequently been identified as a key for enhancing crop productivity, and the production of sufficient crop residues to ensure soil cover under smallholder CA systems in SSA(Vanlauwe *et al.,* 2014). Indeed, a call has been made to include the appropriate use of fertilizer as an essential fourth principle for enhancing the success of CA within smallholder farming systems of sub-Saharan Africa (SSA) (Vanlauwe *et al.,* 2014).

Findings from eastern Africa have shown that modest applications of 30 kg N ha^{-1} to CA treatments under no-till and with available residues retained can increase maize yields by about40% over CA treatments with no N applied (Kihara *et al.,* 2012). Even in instances whereavailable crop residues are supplemented with animal manure applications, addition of modest amounts of fertilizer N have been shown to enhance crop yields and biomass production gain (Kihara *et al.,* 2011). Recent findings by Sithole and Magwaza (2019) showed that maize yields under no-tillage (NT) were higher than those under conventional tillage (CT) only at high fertilizer N application rates but not at medium or low rates, emphasizing the need to apply the correct proportion of fertilizer for enhanced yields under CA systems.

The study by Thierfelder *et al.* (2013) assessed key entry points for the integration of conservation agriculture in smallholder farming systems of southern Africa, by evaluating the effect of tillage, residue retention, fertilizer application and weed control on maize yields within on-farm and on-station locations in Malawi, Mozambique, Zimbabwe, and Zambia.

To assess the effect of CA components on crop yields, the study considered (1) a farmers' practice with conventional tillage and no fertilizer (CT); (2) conventional tillage and mineral fertilizer (CT+F); (3) a no-tillage system with no fertilizer and no residue retention (NT); (4) no-tillage with no fertilizer but with residue retention (NT+R); (5) no-tillage with no residue retention but with fertilizer applied (NT+F); (6) no-tillage with fertilizer and residue retention (NT+F+R); and (7) no-tillage with fertilizer, residue retention and herbicide (NT+F+R+H).

While mean treatment maize yields varied across sites (Figure 3), the largest yields were observed in treatments including fertilizer irrespective of tillage practice (Figure 3). This illustrates the strong effects of fertilizer application on crop productivity in smallholder farming systems of SSA. Such strong effects are attributable to the low fertility of majority of soils in the SSA due to continuous cultivation with minimal or no external nutrient inputs, and the presence of inherently low fertility soils. The observed strong response to fertilizer application irrespective of tillage system therefore demonstrates that the appropriate use of fertilizer needs to be a key component of any framework designed to enhance crop productivity in smallholder farming systems of SSA.

With fertilizer application included as a key component of CA system, independent evaluation of individual CA components allowed for a more pronounced assessment of the effect of each component on crop productivity (Figure 5). In the absence of residue application, conventional tillage generally resulted in relatively more grain yield compared with no-tillage (Figure6a). While there was a positive yield response to no-tillage with residues instead of without (Figure 6b), fertilizer application was the most important factor in enhancing maize yields as indicated by the doubling of mean maize grain yield in some sites (Figure 6c).

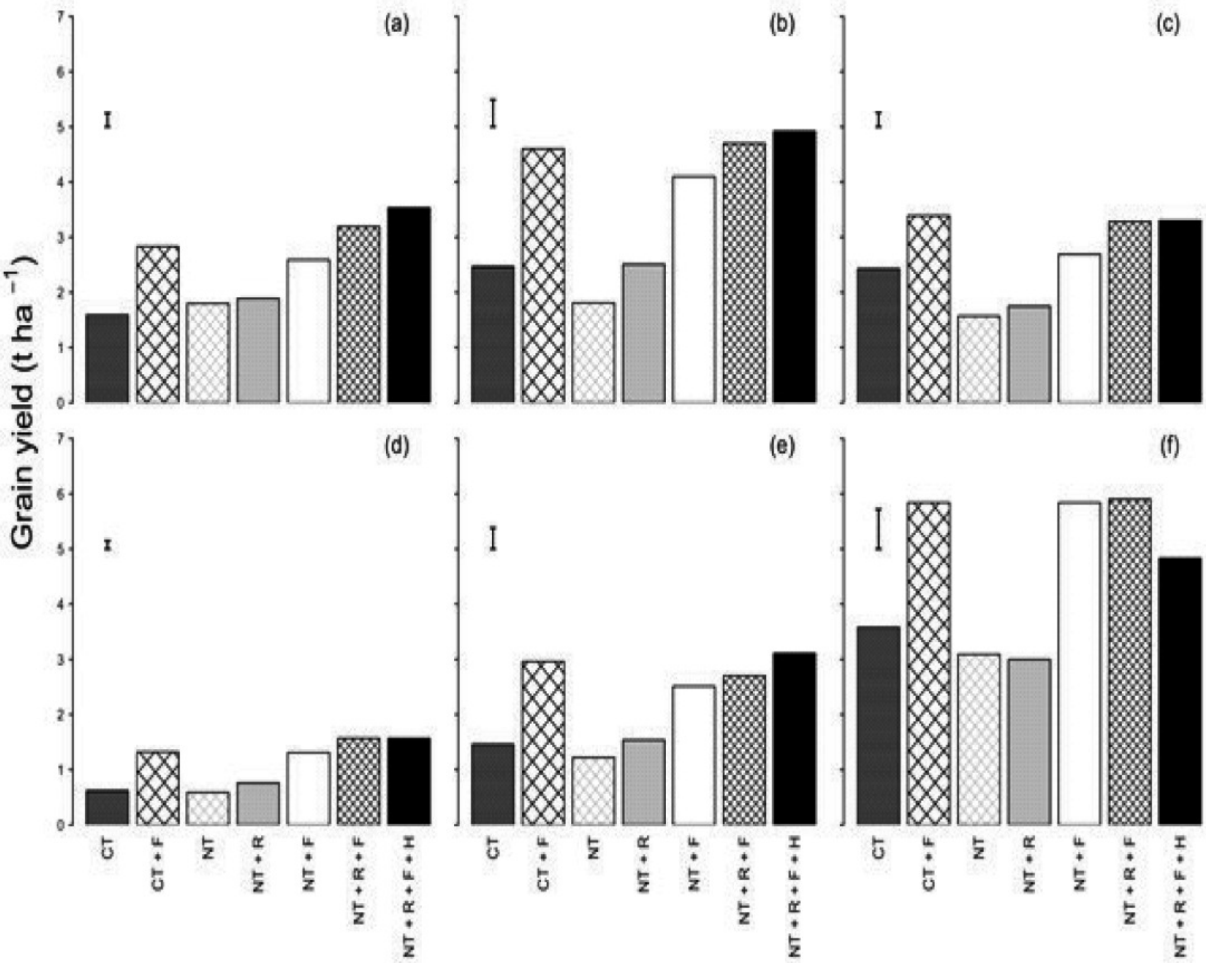

Figure 5. Maize yield as affected by tillage, mulch, fertilizer and weed control in: (a) Balaka, Malawi; (b) Chitedze, Malawi; (c) Barue, Mozambique; (d) Hwedza, (Zimbabwe; (e) Murehwa, Zimbabwe; and (f) Monze, Zambia. Error bars show the standard error of differences (SED) between mean yields in a particular site

North Africa

It is noteworthy to mention that CA system has gained a lot of attention in Northern Africa, especially for the small-holder farming system along with Sub-Saharan Africa. For example, Mrabet *et al.* (2012) has summarized the beneficial effect of CA system and no tillage (NT) in the smallholder farming system of Morocco. The NT systems have resulted in reduced soil erosion, greater soil water conservation, improved soil quality,stable and higher crop yields, and higher soil organic matter. These effects beneûted both farmers and society in terms of higher returns and efûciencies. The summary of studies concluded that efforts have been carried out over the past three decades to

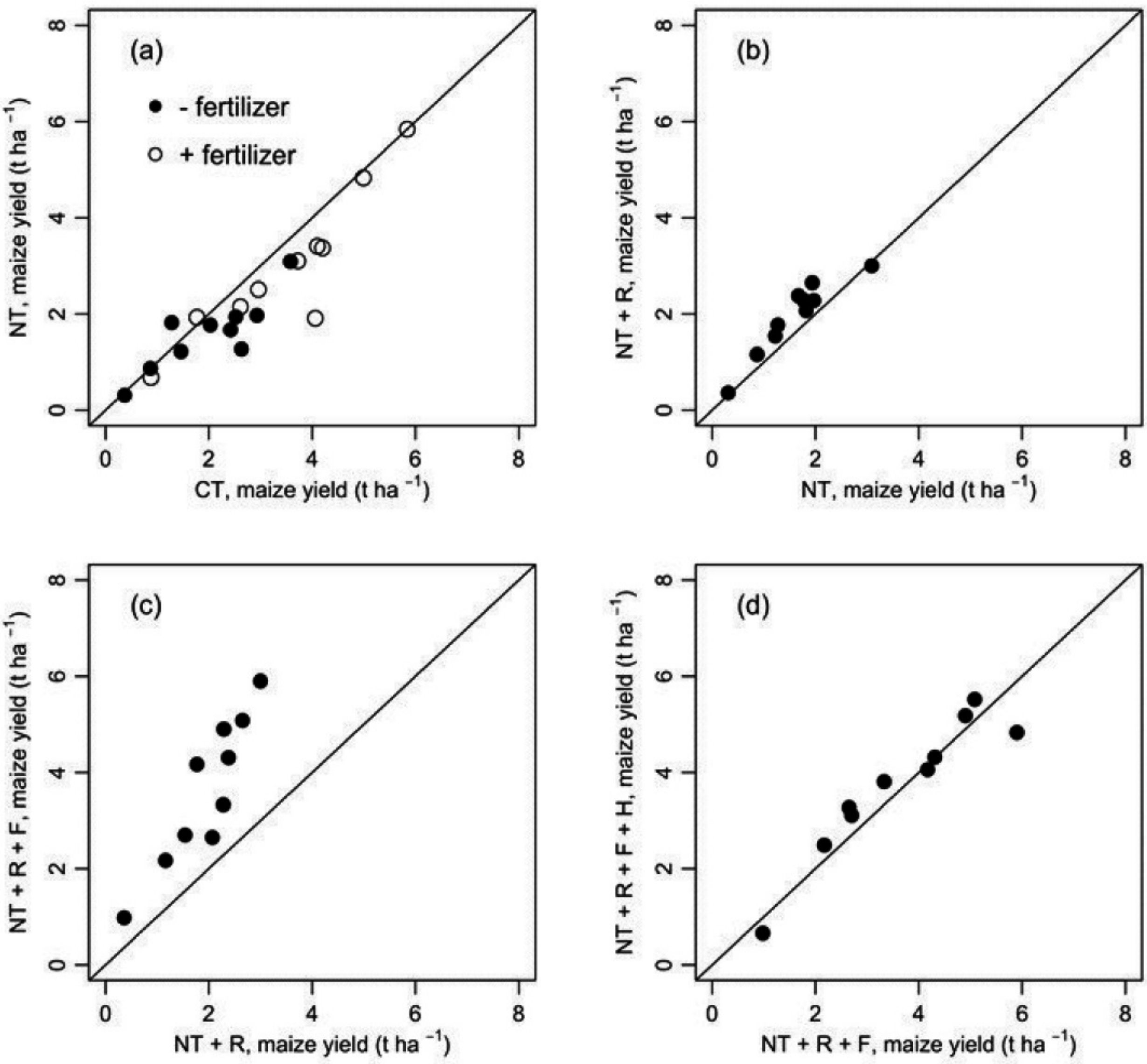

Figure 6. Effect of key components of conservation agriculture including: (a) tillage; (b) residue application; (c) fertilizer application; and (d) herbicide application, on maize yield response in on-farm locations in southern Africa. The y axis represents yield with the component under consideration. Diagonal lines represent the 1:1 line

Table 5. Regional assessment of wheat yield (Mg ha^{-1}) under no-tillage (NT) and conventional tillage system (CT)

Region and average rainfall	Soil type	Rotation	NT	CT	Years of experiment
Abda (270 mm)	Vertisol	Wheat - Fallow	3.10	2.40	19
	Vertisol	Continuous Wheat	1.60	1.60	19
Chaouia (358 mm)	Mollisol	Continuous Wheat	2.47	2.36	4
	Vertisol	Wheat - Fallow	3.70	2.60	10
	Vertisol	Continuous Wheat	1.90	1.40	10
	Mollisol	Different rotations	2.21	1.90	9
	Vertisol	Wheat - Chickpea	1.87	0.76	3
	Rendzina	Wheat - Chickpea	2.53	1.47	9
Zaers (410 mm)	Vertisol	Wheat - Lentils	1.97	1.41	4
	Entisol	Wheat - Lentils	2.99	2.72	4
	Alfisol	Wheat - Lentils	2.71	2.49	4
Sais (438 mm)	Vertisol	Different rotations	2.55	2.49	4
	Alfisol	Different rotations	2.72	2.74	4
Gharb (570 mm)	Vertisol	Continuous Wheat	2.80	2.26	3

Adopted from Mrabet *et al.* (2012)

Conclusions

Conservation agriculture (CA) is considered a promising solution for the smallholder farming system of South Asia, Sub-Saharan Africa and beyond. However, it is noteworthy to mention that the farmers are not impressed if the economic benefits are not superior to those of the conventional systems. Component technologies such as nutrient management, particularly balanced nutrient application, plays a crucial role in coming up with better profitability in the CA system. Studies highlighted that advanced nutrient management strategies, such as 4R Nutrient Stewardship, SSNM, and Precision Agriculture have helped smallholder farmers of South Asia, Sub-Saharan Africa and other regions improving productivity and profitability as well as environmental stewardship. The present article providesevidence to the frontline extension professionals and agronomist that combining site specific nutrient management strategies with CA practices are critical for large-scale adoption of conservation agriculture.

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