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The 17th Dr. R.S. Murthy Memorial Lecture

Does Improved Plant Nutrition Provide a Credible Entry Point for Climate and Weather Adaptive Crop Production?

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I feel privileged and honoured to deliver the 17th Dr. R.S. Murthy Memorial lecture. I am grateful to the Indian Society of Soil Science (ISSS) for giving me an opportunity to deliver the memorial lecture which organized by Varanasi Chapter of ISSS at Banaras Hindu University, Varanasi. Growing enough food for the expanding global population is clearly the top sustainability challenge we face in the 21st century and beyond. About 1.2 to 1.5 billion hectares under agricultural crops and another 3.5 billion hectares that are grazed support the food, nutrition and livelihood security of the human family. Agriculture in its different forms and locations remains highly sensitive to long-term climate change and short-term weather variabilities. A large number of globally distributed studies identified climate change as the dominant source of the overall interannual variability of production in many regions, and a continuing source of disruption to ecosystem services (Howden *et al.* 2007). The shift in agro-ecological conditions due to climate change impose a direct adverse impact on food production, but indirectly affect incomes and access to agricultural produce (Schmidhuber and Tubiello 2007). Furthermore, the projected changes in temperature and precipitation associated with climate change are expected to change land suitability and the potential yields of crops and cultivars available today, thereby disrupting agricultural production at an unprecedented level. These effects are likely to be more intense in the lower latitudes. Lobell *et al.* (2008) identified South Asia and Southern Africa as two regions that, in the absence of adaptation, would suffer the most negative impacts on several important crops. In Sub-Saharan Africa alone, land for double cropping would decline by between 10 million and 20 million ha. Land suitable for triple copping would decline by 5 million to 10 million ha (Fischer *et al.* 2002). Additionally, droughts can dramatically reduce crop yields and livestock production in semi-arid areas, again exposing Sub-Saharan Africa and parts of South Asia to a high degree of instability in food production (Bruinsma 2003). How strongly these impacts will be felt depends on whether such fluctuations can be countered by adequate adaptive measures. The reason behind repeated mention of South Asia and Sub-Saharan Africa as two most vulnerable regions are due to their low agricultural productivity and limited capacity to cope with such adverse conditions (Godfray *et al.* 2010).

Notwithstanding these challenges, the historical increase in agricultural production needs to be maintained to meet projected growth in food demand. For example, within existing land constraints, India must increase the current food grain production of 285 million tonnes (Mt) to around 320 Mt in 2025, and 405 Mt in 2050 to feed the projected population of about 1.7 billion (Patra *et al.* 2020). This suggests that we need to maintain or improve the current trajectory of crop production by increasing the adaptive capacity of production systems (resilience) to climate change, while reducing the imprint of agriculture on climate change.

Climate Smart Agriculture (CSA) practices have been proposed to transform and reorient production systems to sustainably increase agricultural productivity and incomes by adapting and building resilience to climate change and reducing and/or removing greenhouse gas (GHG) emissions. Additionally, Garnett *et al.* (2013) defined the Sustainable Intensification (SI) approach as a radical rethinking of food systems not only to reduce environmental impacts but also to enhance animal welfare and human nutrition and support rural economies and sustainable development. Campbell *et al.* (2014) underlined the

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overarching complementarity between the SI and CSA to help continue producing affordable food and other crops of the required quantity and quality as climate impacts aggravate.

Since the Green Revolution began, plant nutrients have made a major contribution to intensifying crop production across the globe, helping feed the increasing population. Reducing the existing yield gaps as climate change impacts intensify will require greater use of plant nutrients, but far more responsibly than what we have seen previously. As far as climate change is concerned, plant nutrients are part of the problem as well as part of the solution. Inappropriate use of nitrogen (N) is strongly associated with GHG emissions, while its inadequate use is a top constraint for achieving attainable yield in South Asia and elsewhere (Gibbon *et al.* 2007; Waddington *et al.* 2010). The critical role of potassium (K) in strengthening the adaptive capacity of plants to face abiotic stresses (such as high ambient temperature, drought, and salinity, that are also the major climate change indicators) is well recognized (Hasanuzzaman *et al.* 2018). Similarly, recent research also clarifies the potential role of plant nutrition to reduce GHG concentration in the atmosphere either through carbon sequestration or through reducing emissions of gases like nitrous oxide from the soil (Waqas *et al.* 2020; Kakraliya *et al.* 2018). The following sections review the existing evidence of how plant nutrition is affected by climate and weather disruptions, and the potential role of plant nutrient management in mitigating and adapting to climate disruptions to make agricultural production systems more resilient.

Climate Change Indicators

There is little doubt that climate change is already affecting living systems (Permesan and Yohe 2003). Global temperatures are now at their highest since records began, and 17 of the 18 warmest years on record have all taken place since 2001. According to a report of the National Oceanic and Atmospheric Administration (NOAA), more areas in the world are warming than cooling (Lindsay and Dahlman 2020). The NOAA 2019 Global Climate Summary (2020) suggests that the combined land and ocean temperature has increased at an average rate of 0.07 °C per decade since 1880, while the average rate of increase since 1981 is 0.18 °C, more than twice as the entire previous time range. The global surface temperature for 1880 to 2017 (by decades) compared to trends for 1988 to 2017 shows rapid warming in the past 30 years (Fig. 1). Temperature data shows that the 10

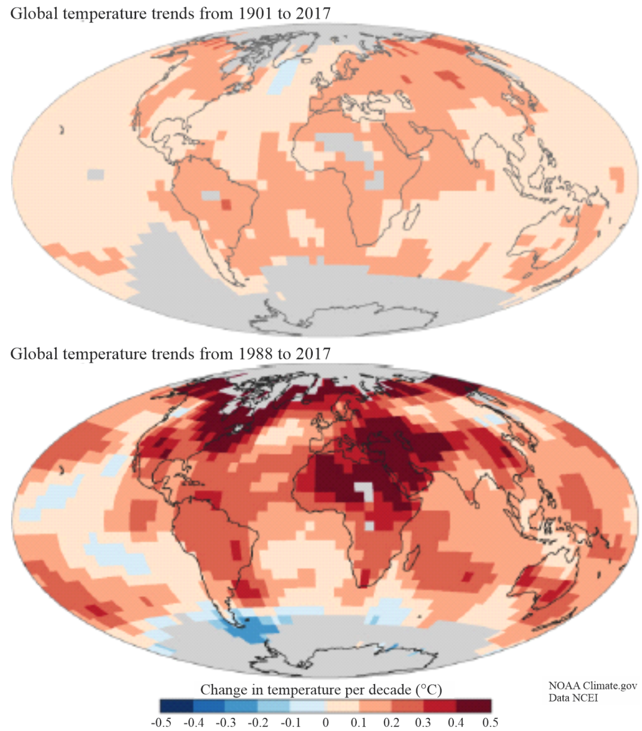

Fig. 1. Trends in global surface temperature by decade for 1880–2017 (top map) compared to trends for 1988–2017 (bottom map), showing the rapid warming of the past 30 years
Source: Maps by NOAA Climate.gov, based on data from NOAA NCEI

warmest years on record have all occurred since 1998, and 9 of the 10 have occurred since 2005. Temperature-predicting models inform that by 2020 the global surface temperature will be more than 0.5 °C warmer than the 1986-2005 average, regardless of which carbon dioxide (CO_2) emissions pathway the world follows. The overarching role of CO_2, the most important anthropogenic GHG that causes an increase in global surface temperature, is well understood and closely monitored (Lindsey 2020).

The NOAA's Mauna Loa Atmospheric Baseline Observatory, a premier atmospheric research facility that has been continuously monitoring and collecting data related to atmospheric change since the 1950s, reported the atmospheric CO_2 increased from 320 ppm in 1960s to 420 ppm in 2020s (Fig. 2). Atmospheric CO_2 concentration continued a rapid rise in 2019, with the average for the month of May peaking at 414.7 ppm at the same observatory. This is the highest seasonal peak recorded in 61 years of observations on top of Hawaii's largest volcano, and the seventh consecutive year of steep global increases in CO_2. The 2019 peak concentration was 3.5 ppm higher than the 411.2 ppm peak reached in May, 2018 (Fig. 3). This

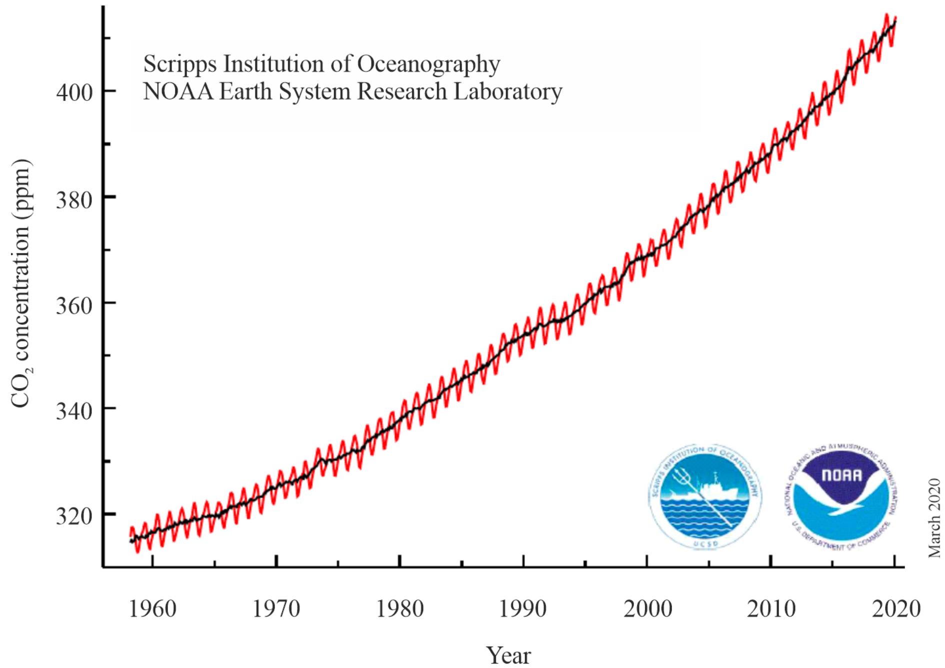

Fig. 2. Atmospheric CO_2 concentration at Mauna Loa Observatory.

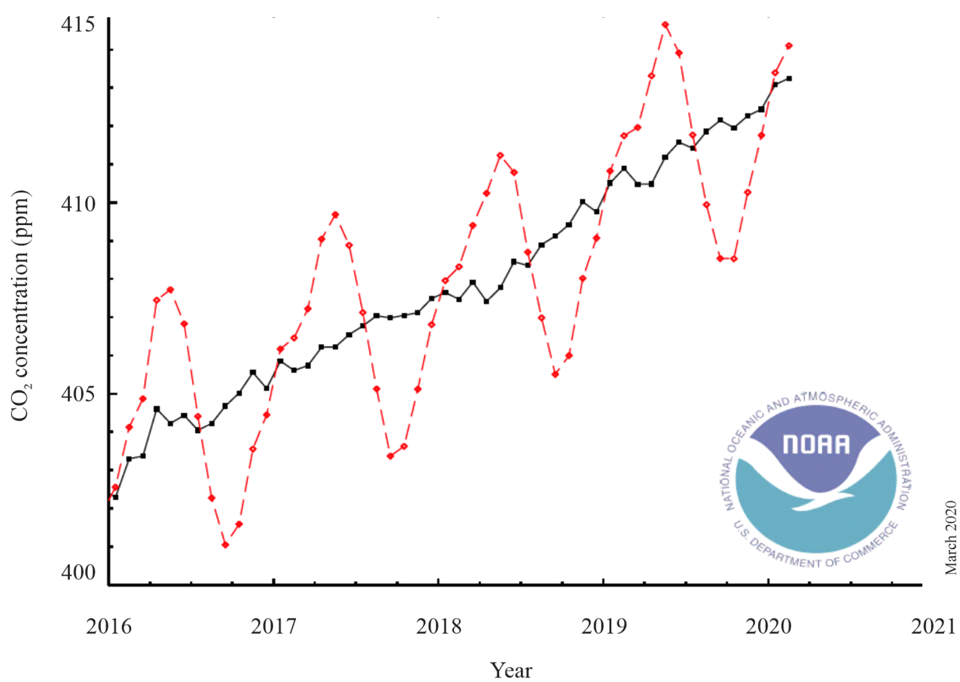

Fig. 3. Recent monthly mean CO_2 concentration for the last 60 months at Mauna Loa Observatory

represents the second-highest annual jump on record. In fact, the last time the atmospheric CO_2 concentration was this high was more than 3 million years ago, when temperature was 2 to 3 °C higher than during the pre-industrial era, and sea level was 15 to 25 m higher than today (Lindsey 2020). Meanwhile, it is predicted that there will be 3.5 °C temperature increase at CO_2 concentration of 500 ppm and the impact on global flora and fauna will be significant. Hansen *et al.* (2008) pointed out that paleoclimate evidence and ongoing climate change suggest that atmospheric CO_2 level needs to be under 350 ppm or even less to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon.

Agriculture Impact on Climate Change

The combustion of fossil fuels and other human activities are the primary sources of increased CO_2 concentration and other GHGs causing global climate change. Among the anthropogenic activities, agriculture is a significant contributor to GHG emissions. These emissions comprise non-CO_2 GHG (methane and nitrous oxide) that are emitted directly from crop and livestock activities within the farm gate, as well as CO_2 emissions from associated land use, land use change and land degradation in connection with deforestation, or from drainage of carbon-rich organic soils (Tubiello 2019). The "2014 Fifth Assessment Report", developed by the Intergovernmental Panel on Climate Change (IPCC), estimated that current emissions from agriculture, forestry and other land use are responsible for around a quarter of anthropogenic GHG emissions (Smith *et al.* 2014).

Many studies have estimated GHG emissions from different types of agricultural activities (Maraseni and Qu 2016; Yue *et al.* 2017; Maraseni *et al.* 2018). Agriculture is directly responsible for 14% of total GHG emissions, and broader rural land use decisions have an even larger impact. Deforestation currently accounts for an additional 18% of emissions. In addition, if pre-and post-process emissions are included, global food systems could contribute between 19 and 29% of global GHG emissions (Vermeulen *et al.* 2012). In 2017, emissions from agriculture were 11.1 Gt CO_2 eq yr^{-1} [1 Gigatonne (Gt) = 10^{15} g], comprised of 6.1 Gt CO_2 eq yr^{-1} from crop and livestock activities within the farm gate and 5.0 Gt CO_2 eq yr^{-1} from agricultural land use, largely due to deforestation and peatland degradation (FAO 2020). Several studies reported high growth rates of emissions from agriculture (Akrofi-Atitianti *et al.* 2018; FAOSTAT 2020), in some instances overtaking emissions from the energy sector (EPA 2013). The already large environmental impact of agriculture on global energy use and GHG emissions is likely to increase as our population grows and requires more protein and calories (Beddington *et al.* 2012; Kastner *et al.* 2012). Therefore, improvements in the agricultural sector is necessary to capture the significant climate mitigation opportunities through GHG emission reductions.

Impact of Climate Change on Agricultural Production

Climate is a primary determinant of agricultural productivity, and the vulnerability of the agricultural sector to both climate change and weather variability is well established.

Concern over the potential effects of long-term climatic change on agriculture has triggered significant research efforts. This research, while outlining possible effects on crop yields and their economic consequences (Adams *et al.* 1998; Stevanovicì *et al.* 2016;), identified climate variability as one of the most crucial factors, explaining almost 60% of yield variability and thus impacting food production and farm income in recent times (Osborne and Wheeler 2013; Ray *et al.* 2015; Matiu *et al.* 2017). By 2050, climate change is expected to negatively impact at least 22% of the cultivated areas of the world's important crops, notably rice and wheat (Campbell *et al.* 2011). Lobell *et al.* (2011) estimated the climate trend impact on grain yield was a reduction of 3-7% for maize, 1-3% for rice, 5-14% for wheat and 1-7% for soybean between 1980 and 2008. Among the changes, temperature increase has the most likely negative impact on crop yields. Zhao *et al.* (2017) combined different assessment methods to show consistent negative temperature impacts on crop yields at the global scale, generally underpinned by similar impacts at country and regional scales. Without atmospheric CO_2 fertilization, effective adaptation, and genetic improvement, the authors predict an average reduction of global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1% for each degree-Celsius increase in global mean temperature.

In South Asia, it is predicted that the annual average maximum temperature may increase by 1.4 to 1.8 °C in 2030 and 2.1 to 2.6 °C in 2050, and thus, heat-stressed areas in the region could increase by 12% in 2030 and 21% in 2050 (Tesfaye *et al.* 2017). Projections claim that almost half of the Indo-Gangetic Plains (IGP), the major food basket of the South Asian region, may become unsuitable for wheat production by 2050 as a result of heat stress (Ortiz et al. 2008). Aryal *et al.* (2019) found that global warming has reduced wheat yield in India by 5.2% from 1981 to 2009, despite adaptation (Gupta *et al.* 2017). With high risks of climate change-induced extreme weather events, the crop yields in the region are predicted to decrease by 10 to 40% by 2050, with risks of total crop failure in several highly vulnerable areas

(Kakraliya *et al.* 2018). Varying exposure to weather, particularly high temperature at critical growth stages, would reduce rain-fed maize yields by an average of 3.3 to 6.4% in 2030 and 5.2 to 12.2% in 2050. Irrigated maize yields may be reduced by 3 to 8% in 2030 and 5 to 14% in 2050 if current varieties are grown in South Asia (Tesfaye *et al.* 2017). Arshad *et al.* (2017) found that despite variability in input use and crop management, there is a negative effect of both season-long and terminal heat stress on rice and wheat.

These impacts, although highly variable in space and time, could be caused by a shift in growing seasons, especially on controlling the daily temperatures (Fiwa *et al.* 2014; Zhao *et al.* 2015; Lemma *et al.* 2016) and/or the duration and magnitude of heat and water stress in agricultural production systems (Lobell *et al.* 2015; Schauberger *et al.* 2017) that can directly harm the crop physiological processes. Wang *et al.* (2018) reported that the major grain (rice, wheat, maize and soybean) production areas globally have experienced a significant increase in drought duration, impacted area, and severity. There was an average of 2.2 dry months and the dry area increased by 1.1% per decade, and the developing countries and regions are generally more susceptible to extreme droughts and suffer more losses than developed countries and regions. Increased variability in both temperature and rainfall patterns, changes in water availability, shifts in growing season, rising frequency of extreme events such as terminal heat, floods, storms, droughts, sea level rise, salinization and perturbations in ecosystems have already affected the livelihood of millions of people in South Asia (Kakraliya *et al.* 2018). Increased temperatures and evapotranspiration and lower precipitation across some regions will stress already overexploited aquifers for irrigation water, causing ripple effects of climate impacts. A relatively modest warming of 1.5 to 2 °C in South Asia has the potential to impact the availability and stability of water resources due to increased monsoon variability and glacial meltwater, leading to challenges for future agricultural success (Vinke *et al.* 2017).

The dynamics of climate change along with increasing population will also exacerbate desertification, deforestation, erosion, degradation of water quality, and depletion of water resources in the near future that will further complicate the challenge of food and nutritional security. A multi-country analysis revealed that 71% of households worldwide experienced food insecurity and climate shocks in the last five years. The periods of food insecurity ranged from less than one month per year in India, to more than six months in Ethiopia (Niles and Solerno 2018; Pataczek *et al.* 2018). Global economic losses in production of three major crops (wheat, maize, and barley) attributed to climate change in the recent past are estimated at approximately US$5 billion per year (Lobell and Field 2007).

Not all effects of climate change may be adverse to crop and food production (Lal 2013). Kukal and Irmak (2018), assessed yield trends in the US Great Plains between 1968 to 2013, and observed that the temperature trend was beneficial for maize yields, but detrimental for sorghum and soybean yields, whereas the observed precipitation trend was beneficial for all three crops.

Favorable effects of climate change have been reported for some regions because of northwards shift of maize cultivation in the U.S. (Hatfield *et al.* 2011), rice in China (Hijmans 2007) and wheat in Russia (Ivanov and Kiryushin 2009). Yang *et al.* (2015) found that northern limits of multiple cropping systems have been shifted northward, expanding the projected area of cultivated land for triple-cropping systems in China. The northern shifts resulted in a 2.2% (~8,000,000 t) increase in national production of three major crops (maize, wheat, and rice) from 1981 to 2010, and may cause a positive impact on the crop production in China if concomitant changes adapted in multiple cropping systems take place.

The positive growth response is partly attributed to the CO_2 fertilization effect (Erda *et al*. 2005). Free Air Carbon Enrichment (FACE) experiments indicate productivity increases in the range of 15 to 25% for C3 crops (like wheat, rice and soybeans) and 5 to 10% for C4 crops (like maize, sorghum and sugar cane) (Lotze-Campen and Schellnhuber 2009). Quantitative reviews of different studies demonstrated that elevated CO_2 concentration stimulated the yields of C3 legumes and C4 plants by 11 to 31% and 14 to 54%, respectively (Kimball 1983; Tubiello *et al.* 2007).

However, atmospheric enrichment of CO_2 will be associated with higher global temperatures and altered precipitation patterns, and these factors may lessen or negate any production increases or even depress production below current levels (Brouder and Volenec 2008). The aggregate impacts of climate change on global-scale agricultural productivity are often variable and difficult to quantify (Gornall *et al.* 2010) and the trade-offs may turn out more negative than positive. Van Groenigen *et al.* (2013), using meta-analysis, showed that increased atmospheric CO_2

(ranging from 550 to 743 ppmV) and warming (ranging from + 0.6 to + 0.8°C) increase the GHG intensity of rice cultivation. Increased atmospheric CO_2 increased GHG intensity by 31.4%, because CH_4 emissions are stimulated more than rice yields. Warming temperatures increased GHG intensity by 11.8% per 1 °C, largely owing to a decrease in yield. This analysis suggests that rising CO_2 and warming will approximately double the GHG intensity of rice production by the end of the 21st century, stressing the need for management practices that optimize rice production, while reducing its GHG intensity as the climate continues to change.

Plant Nutrition and Climate Change

Plant Nutrition Instigating Climate Change

Nitrogen (N) fertilizer use is often cited as a causal factor of climate change. Nitrogen is the most limiting nutrient in major production systems, particularly in the tropics (Dutta *et al.* 2018). Necessity of adequate N application for improving and sustaining crop productivity for the existence of the human family is well established (Smil 2002; Erisman *et al.* 2008). However, significant fractions of the anthropogenically mobilized N are lost through emissions of ammonia (NH_3), nitrous oxide (N_2O), and nitric oxide (NO), of which N_2O is a potent greenhouse gas (Bouwman *et al.* 2013). The issue of N transfers within the agro-food system has been of major interest because of the dichotomy in its role as the most limiting agricultural production factor and its significant negative impact on the environment when lost to the hydrosphere and atmosphere at the successive steps of the agro-food chain (Billen *et al.* 2015). A spatially explicit global inventory of livestock and crop production systems shows that a balanced or low surplus N budget in the beginning of the 20th century changed to a global surplus of 138 Tg yr^{-1} (1 Tegagram = 10^{12} g) of N between 1950 and 2000, most of which was lost to the environment (Bouwman *et al.* 2013).

Of the global anthropogenic N_2O emissions in 2005, agriculture accounted for about 60%. Agricultural N_2O emissions have increased by nearly 17% from 1990 to 2005 (Smith *et al.* 2007). Inefficient use of N fertilizer, manure and other N sources is common, and the surplus N is susceptible to loss as N_2O emission (McSwiney and Robertson 2005; Bhatia *et al.* 2010). Camargo *et al.* (2013), using a cradle-to-farm-gate analysis, found that N had the largest impact on energy use and GHG emissions for a wide range of crops, resulting from the large amount of energy required to produce N fertilizer through the Haber–Bosch process (54.8 MJ kg^{-1}) and from the large global warming potential (GWP) associated with N_2O emissions (298 kg CO_2e kg^{-1} N_2O). Nitrous oxide emissions from agricultural soils represent about 5% of the total global anthropogenic GHG emissions, which are predominantly linked to inorganic and organic N fertilizer applications to arable upland systems (Weller *et al.* 2016). Total direct N_2O emissions from Chinese croplands were estimated to be 313 Gg (1 Gigagram = 10^{9} g) N_2O–N in 2007, and the contribution to N_2O emissions from croplands by synthetic N fertilizers was 79.4% (Gao *et al.* 2011). Chai *et al* (2019) estimated that total national emissions related to synthetic N manufacture and fertilization during 2015 to 2017 were 52.1 and 80.4 Mt CO_2-eq yr^{-1} for wheat and maize in China, respectively.

Sharma *et al.* (2008) provided a comprehensive review of N_2O emission from agricultural soils in India, where field measurements suggested average N_2O-N emission of 0.0025 and 0.0055 kg kg^{-1} N applied from rice and wheat fields, respectively. The authors summarized several studies that estimate N_2O-N emission from Indian agricultural soils at a range of 79.94 to 279 Gg N_2O-N yr^{-1}, the variability arising most likely from estimation methods, area covered and use of different coefficients. The direct emission of N_2O from soils due to the use of N fertilizer contributed about 146 Gg for the year 1994, which is about 81% of the total N_2O in terms of CO_2-eq.

Climate Change Impact on Plant Nutrition

The soil properties and functions that are mostly affected by climate change are soil structure, organic matter content, nutrient dynamics, soil organisms, soil pH and cation exchange capacity (FAO 2013). These all have a close bearing on plant nutrition. Plant nutrition, in general, can be impacted by climate change at multiple scales. High ambient temperature and change in water regimes due to changes in rainfall patterns will significantly impact prevailing root zone temperature and moisture regimes and may fundamentally impact how nutrients are accessed and used by crops. The interactive effects of soil moisture and nutrient availability are two key edaphic factors that determine crop yield (Ziska and Bunce 2007). Increasing soil moisture deficit due to drought may slow down water-dependent diffusion and mass flow of nutrients to the roots. Impaired root growth due to moisture stress decreases the capture of less mobile nutrients such as phosphorus (P) (He and Dijkstra 2014).

Under conditions of reduced transpiration (low water influx in roots), some have theorized that acquisition of nutrients that travel from bulk soil to the root surface primarily by mass flow will be negatively affected, resulting in nutrient deficiency (Lynch and St Clair 2004). Mackay and Barber (1985) examined the effect of drought on P uptake and availability and found reduced nutrient uptake, root surface area and ion diffusivity with moisture stress for both high and low fertility experimental treatments. Increased frequency of high-intensity rainfall events can cause erosion, leading to loss of nutrient-rich top soil and surface-broadcast fertilizer, as well as leaching of nitrates and K from soil, thereby leading to nutrient depletion. A 1% increase in precipitation is expected to lead to a 1.5 to 2% increase in soil erosion rates (Nearing *et al.* 2004). Increased frequency of drought further intensifies erosive losses as plant biomass and its positive and protective effects on soils are reduced (Nearing *et al.* 2004; Niklaus 2007).

Nutrient conservation is affected as higher temperatures are likely to increase the decomposition of organic matter because of a stimulation of microbial activity, and likely lead to increased concentration of solution-phase N (Pendall *et al.* 2004). If N mineralization rates exceed plant uptake, nutrient leaching may be the consequence. Nitrogen losses primarily occur in the situation when plant demand is low and rising soil temperature increases mineralization rates. This potential N loss is exacerbated by increased precipitation and loss of snow cover as predicted for many temperate regions (Niklaus 2007).

Increasing atmospheric CO_2 concentration may also progressively decrease the mineral N available for plant uptake, termed as progressive nitrogen limitation (PNL), in the long-term. When an ecosystem is exposed to elevated CO_2, photosynthesis is stimulated because of the enhanced efficiency of C-fixing enzymes. The additional C that flows into the ecosystem at elevated CO_2 is used for production of plant biomass, stored in soil organic matter (SOM), and returned to the atmosphere through autotrophic and heterotrophic respiration. The additional growth of long-lived plant biomass (*e.g.* wood in forests) and the increased C storage in soil cause N to be sequestered in organic matter (van Groenigen and van Kessel 2002), progressively decreasing the mineral N available for plant uptake in the long-term. The reduced N availability in turn constrains the further CO_2 fertilization effect on plant growth over longer timescales.

There are, however, conflicting views of the impact of PNL on crop growth. Liang *et al.* (2016) used meta-analysis to indicate that elevated CO_2 stimulates N influx via biological N fixation, but reduces N loss via leaching, leading to an increased N supply for plant growth. The additional N supply via the enhanced biological N fixation and the reduced leaching may partially meet the increased N demand under elevated CO_2, potentially alleviating PNL. However, the increased N_2O emissions may partially offset the mitigation of climate change by stimulated plant CO_2 assimilation. Moreover, changes in soil microenvironments, ecosystem communities and above and below ground interactions induced by the different responses of NH_4^+ and NO_3^- to CO_2 enrichment may have long-term effects on the terrestrial biogeochemical cycles and climate change.

Numerous effects of elevated atmospheric CO_2 on plants have been documented, including changes in plant elemental composition. Brouder and Volenec (2008) provided an excellent overview of existing knowledge on interactive influences of atmospheric CO_2, temperature, and soil moisture on plant growth, development, yield and other physiological processes. As ambient CO_2 increases, plants typically show increased concentrations of C in their tissues, with correspondingly reduced concentrations of other elements, including N (Cotrufo *et al.* 1998), P (Gifford *et al.* 2000) and several trace elements (Loladze 2002). The C3 crops (other than legumes) have lower concentrations of protein in the presence of elevated CO_2, whereas C4 crops seem to be less affected. Taub *et al.* (2008) used meta-analysis to examine the effect of elevated atmospheric CO_2 on the protein concentrations of major food crops, incorporating 228 experimental observations on barley, rice, wheat, soybean and potato grown at elevated (540 to 958 µmoL moL^{-1}) compared with ambient (315 to 400 µmoL moL^{-1}) CO_2. For wheat, barley and rice, the reduction in grain protein concentration was 10 to 15% of the value at ambient CO_2. For potato, the reduction in tuber protein concentration was 14%. For soybean, there was a much smaller, although statistically significant reduction of protein concentration of 1.4%. This study suggests that increasing CO_2 concentrations of the 21st century are likely to decrease the protein concentration of many human plant foods.

Myers *et al.* (2014) reported that C3 grains and legumes have lower concentrations of zinc and iron when grown under field conditions at the elevated atmospheric CO_2 predicted for the middle of this century. Elevated CO_2 was associated with significant decreases in the concentrations of zinc (Zn) and iron (Fe) in all C3 grasses and legumes. Wheat grains grown at elevated CO_2 had 9.3% lower Zn and 5.1% lower Fe than those grown at ambient CO_2. Elevated CO_2 was associated with lower protein content in C3 grasses, with a 6.3% decrease in wheat grains, and a 7.8% decrease in rice grains. Elevated CO_2 was associated with a small decrease in protein in field peas, and there was no significant effect in soybeans or C4 crops. Dietary deficiencies of Zn and Fe are a substantial global public health problem. An estimated two billion people suffer from deficiencies of these trace elements, causing a loss of 63 million life annually. Most of these people depend on C3 grains and legumes as their primary dietary source of Zn and Fe.

Lloyd *et al.* (2011) used the projected changes in undernourishment from Nelson *et al.* (2009) to predict the impact of climate change on human nutrition. They estimated a relative increase in moderate stunting of 1 to 29% in 2050, compared with a future without climate change. Severe stunting was projected to increase by 23% (central Africa) to 62% (South Asia). Under elevated CO_2, 18 countries may lose >5% of their dietary protein, including India (5.3%) (Medek *et al.* 2017). By 2050, assuming today's diets and levels of income inequality, an additional 1.6% or 148.4 million of the world's population may be placed at risk of protein deficiency. In India, an additional 53 million people may become at risk (Medek *et al.* 2017). Another recent report suggested that 175 million more people will be Zn deficient and 122 million more people will be protein deficient by 2050, because of elevated CO_2, mostly in Asia and Africa (Steiner *et al.* 2020).

Soil organic matter is a key indicator of agricultural productivity and overall soil health, and the mean annual temperature (MAT) and precipitation (MAP) are major climatic drivers of SOM levels and dynamics in the soil (Morrow *et al.* 2017). The SOM decomposition rates are often accelerated by increasing temperatures, and SOM and MAT are usually inversely correlated (Wynn *et al.* 2006). Elevated ambient temperature, precipitation and associated erosion is expected to reduce carbon capture in soils, decreasing nutrient-holding capacity and other soil health parameters, and adversely affecting the productive capacity of soils. Morrow *et al.* (2017) found that soil organic C and total N, as well as the hydrolyzable and non-hydrolyzable fractions, were negatively correlated with the current ratio of MAT to MAP, called the climate ratio. Based on the future climate projections (2030 and 2070) of increased climate ratio, the authors predicted a decline in surface SOM and associated soil health across the Inland Pacific Northwest United States. In the alpine grasslands of the Tibetan Plateu, the SOM turnover rate at the 5 to 10 cm depth was positively associated with the bacteria/fungi biomass ratio and the relative abundance of *Acidobacteria*, both of which are related to precipitation. Partial correlation analysis suggested that increased precipitation could accelerate the SOM turnover rate in topsoil by structuring soil microbial communities (Han *et al.* 2017)

Managing Plant Nutrition for Climate Resilience

The pressure of increasing food production in the face of climate change has strongly put the focus on sustainable intensification. The SI approach provides the opportunity to increase food production from existing farmland with a lower environmental impact and without undermining the capacity to continue producing food in the future (Pretty and Bharucha 2014). Plant nutrient management is a major component of the SI strategy, and the cause and effect relation of plant nutrition, being part of the problem and the solution of climate change, makes its role in CSA quite evident. Campbell *et al*. (2014) underlined the strong complementarity between SI and CSA, and suggested SI as an essential means of adapting to climate change, while CSA provides the foundations for incentivizing and enabling intensification. Burney *et al.* (2010) found that investment in yield improvements compares favorably with other commonly proposed mitigation strategies. Although emissions from factors such as fertilizer production and application have increased, the net effect of higher yields has avoided emissions of up to 161 Gt of carbon (590 $GtCO_2e$) since 1961, indicating yield improvements should be prominent among efforts to reduce future GHG emissions. Post Green Revolution, production intensification has been strongly driven by fertilizer use due to increased nutrient demand from higher yields (Pretty and Bharucha, 2014), and the global yield variability is now strongly influenced by fertilizer use (Mueller *et al.* 2012). Mueller *et al.* (2012) estimated that 73% of global croplands not currently achieving attainable yields could close these yield gaps by solely focusing on nutrient inputs (with 18, 16 and 35% increases in N, P_2O_5 and K_2O application relative to baseline global consumption, respectively). Jointly increasing irrigated area and nutrient application could close yield gaps on all underachieving areas (with 30, 27 and 54% increases in N, P_2O_5 and K_2O application, respectively, and a 25% increase in irrigated hectares. To minimize the environmental impacts of intensification, increased nutrient application to close crop yield gaps must be complemented by efforts to decrease overuse of crop inputs wherever possible. Addressing imbalances and inefficiencies of nutrients could globally reduce N and P fertilizer application on maize, wheat and rice by 11 Mt of N (28%) and 5 Mt of P (38%) without impacting current yields (Mueller *et al.* 2012).

Plant nutrients play critical roles in imparting adaptive capacity to plants, providing the necessary foundation for sustainable crop yields in marginal or stressed environment. Kato *et al*. (2003) showed that plants grown under high-intensity light with a high N supply had greater tolerance to photo-oxidative damage and higher photosynthesis capacity than those grown under similar high light with a low N supply. Potassium is clearly a frontrunner in helping plants adapt to abiotic stresses such as high/low temperature, drought, salinity etc. which are hallmark of climate impacts. The role of K in addressing such abiotic stresses are well documented (Zorb *et al.* 2014; Hasanuzzaman *et al.* 2018). In the past decades, moderate to severe water scarcity due to climate change has become a worldwide concern, especially in semiarid and arid regions. Recent publications (Qu *et al.* 2020; Bhattacharyya *et al.* 2018) underline the role of adequate K fertilization when water scarcity challenges crop growth and production. Many studies have elucidated the role of adequate K in triggering drought resistance mechanisms within plants (Hosseini *et al.* 2016; Jákli *et al.* 2017). There is increasing evidence that drought-affected plants have a larger internal requirement for K (Anschütz *et al.* 2014). Water scarcity is generally associated with high temperature, an indicator associated with maximum damage to crop production. Both chronic and abrupt heat stress are expected to increase as a consequence of anthropogenically driven global warming (Giri *et al.* 2017). High temperature stress may cause severe damage to the proteins, disturb their synthesis, affect cell division, inactivate major enzymes and damage membranes (Fahad *et al*. 2017). Short-term heat stress, if severe, can decrease total protein concentration, nutrient uptake, and assimilation of proteins in roots (Giri *et al.* 2017). Exogenous application of macro and micronutrients ameliorated the high temperature impact on cotton. These nutrients up-regulated the antioxidant enzymes (SOD, POX, CAT, AsA, phenolics and MDA), improved chlorophyll contents, net photosynthetic rate, water relations and seed cotton yield (Sarwar *et al.* 2019). Aktar and Islam (2017) while reviewing heat stress management in wheat identified clear roles of exogeneous application of K (Dias and Lidon 2010), Ca (Waraich *et al.* 2011), Mg and Zn (Mengutay *et al.* 2013) for improving the yield and quality of wheat under high temperature stress.

Similarly, salinity affects hundreds of millions of hectares of agricultural land worldwide (Rengasamy 2010). Climate change is expected to exacerbate soil salinity in many ways. Recent research suggests that sea level may rise by one meter or more in the 21st century, and increased salinity from saltwater intrusion would increase the vulnerable population to about one billion by 2050 (Dasgupta *et al.* 2015). Dasgupta *et al.* (2015) suggested that climate change poses major risk in 69 coastal sub-districts of Bangladesh, and may increase soil salinity by 39 to 51% by 2050. The plant's ability to increase K^+ fluxes and reduce Na^+ fluxes in presence of salinity to attain a higher K^+/Na^+ selectivity ratio is essential for salt tolerance. Potassium plays essential roles related to osmotic adjustment, maintaining turgor and regulating the membrane potential, cytoplasmic homeostasis, protein synthesis, and enzyme activation that help plants cope with salt stress (Hasanuzzaman *et al.* 2018).

Along with managing nutrients to provide adaptive capacity to plants, another major objective of sustainable plant nutrition is to reduce GHG emission associated with fertilizer N application. Properly managing the source, rate, time and method of N fertilizer application provides significant opportunities to reduce GHG emission. Snyder *et al*. (2009) reviewed different N management options for reducing its impact on climate change. Bouwman *et al.* (2002a, 2002b) found that N_2O emissions were lower with the use of NO_3-based fertilizers, compared to NH_4 -based fertilizers, or organic or synthetic-organic sources. Higher N_2O emissions with NH_4-based fertilizers may be related to potential NO_2 accumulation or N_2O production during nitrification (Venterea and Stenanas 2008). Intuitively, one might expect a higher N_2O loss with an abundance of NO_3-N in soil systems from NO_3^- based fertilizers compared to other N fertilizers, since NO_3^- and NO_2^- are essential for denitrification. However, higher N_2O emissions with anhydrous NH_3 were found in several studies when compared with other N sources (Breitenbeck and Bremner 1986a; Venterea *et al.* 2005). These conflicting reports and the summary by Snyder *et al.* (2009) raise questions about the importance of N source in addressing N_2O emissions, and illustrate the need for continued research.

Enhanced-efficiency of N fertilizers (slow and controlled-release fertilizers and stabilized N-fertiliz-

Table 1. Summary of N_2O emissions induced by common fertilizer N sources, based on Bouwman *et al.* (2002a, 2002b) and Stehfest and Bouwman (2006)

N source	Mean fertilizer induced emission[1]		Balanced median emission[2]	
	n	N_2O as % of applied N	n	kg N_2O-N ha^{-1}
Calcium ammonium nitrate	61	0.7	73	1.56a[3]
Ammonium nitrate	59	0.8	131	1.12a
Anhydrous ammonia	38	0.9	38	1.04a
Nitrate-based fertilizers[4]	53	0.9	53	0.80b
Urea ammonium nitrate (solutions)	37	1.0	40	0.78b
Urea	98	1.1	131	0.96b
Ammonium-based fertilizers[5]	59	1.2	74	0.82b
IPCC default		1		

[1]Bouwman *et al.* 2002a, 2002b; [2]Stehfest and Bouwman 2006; [3]Values followed by a common letter are not significantly different, based on two-tailed statistical tests (Stehfest and Bouwman 2006); [4]Includes potassium nitrate, calcium nitrate, sodium nitrate (Bouwman *et al.* 2002a, 2002b); [5]Includes ammonium bicarbonate, ammonium chloride, ammonium sulfate (Bouwman *et al.* 2002a, 2002b)

ers) are sources that can minimize the potential of nutrient losses to the environment, as compared to "reference soluble" fertilizers. Controlled-release technologies, by affecting the timing of N release from fertilizer (Shaviv 2000), have potential to reduce leaching losses of NO_3^-, volatile losses of N as NH_3, and N_2O emissions (Chien *et al.* 2009). Reductions in these losses may improve recovery efficiency of N and provide greater stability in fertilizer N performance. Halvorson *et al.* (2009) found that N source had little impact on irrigated maize grain yield, but did impact N_2O emissions. Controlled release and stabilized N sources reduced N_2O emissions by 29 to 50% compared to UAN and urea, under a no-till continuous maize system. Better understanding of the potential impacts of inefficient fertilizer N management has renewed the interest in use of slow or controlled-release fertilizers and the use of urease and nitrification inhibitors.

The N_2O emission rates increased linearly with increasing N rates in irrigated cropping system research in Colorado (Halvorson *et al.* 2008). Snyder *et al.* (2009) summarized several examples showing when an agronomic N threshold level is exceeded, N_2O emissions can increase dramatically. For example, Malhi *et al.* (2006) observed that N_2O emissions increased when N rates exceeded 80 kg ha^{-1} in a specific cropping study. Similarly, N_2O emissions in an irrigated maize study began to increase significantly compared to unfertilized treatments with N rates above 100 kg ha^{-1} (Kachanoski *et al.* 2003; Grant *et al.* 2006). However, results are not always consistent, and Sehy *et al.* (2003) found no significant increase in N_2O emissions with increasing fertilizer N rates (ranging up to 175 kg N ha^{-1} yr^{-1}) in high-yielding areas, on a site where maize yields were not responsive to increased N rate. McSwiney and Robertson (2005) indicated that agricultural N_2O fluxes could be reduced with no or little yield penalty by reducing N fertilizer inputs to levels that just satisfy crop needs. The emission factors attributed to fertilizer use generally rise when applications exceed ecosystem N uptake capacity over time. This capacity could be estimated from pre-planting measurements of residual soil N, and from annual estimates of gains or losses in soil organic N and of removals in harvest N (Grant *et al.* 2006). Snyder *et al.* (2009) suggested choosing appropriate N rates based on crop requirement, N supply from different sources, and following best practices for selecting the right source, timing and method of N fertilizer application to optimize crop yield and minimize residual NO_3-N.

Shortening the time in which NH_4-based fertilizers can undergo nitrification or NO_3-based fertilizers can be denitrified before plant N uptake, is likely to decrease N_2O emissions (Bouwman *et al.* 2002a). Hultgreen and Leduc (2003) showed that the N_2O emission potentials could be lowered by timing the application of soluble N fertilizer such as urea with the time of crop N uptake. Timing N applications to provide just what the plant needs and just when it needs it would be the ideal scenario. However, practical labor, economic, and logistical challenges often prevent such perfect N timing management in farmer fields. Complexities of weather uncertainty (IPNI 2007) and unpredictable soil N release necessitate some compromise in N management. In the past, many farmers have preferred to apply N fertilizer earlier than the plant needed it to avoid N deficiencies (Randall and Goss 2001). Buresh and Witt (2008) estimated that more than 50% of the applied urea volatilized within 7 to 10 days after N application in 3-week old transplanted rice. Such NH_3 loss during panicle initiation was much less and ranged from 10 to 15% of the applied urea N. Different tools such as the leaf color charts, chlorophyll meter, and optical sensors are used now to monitor crop N status and to adjust N fertilization on-the-go to better synchronize N supply with crop N demand in cereal crops. Bijay-Singh *et al.* (2020) extensively reviewed the evolution and development of field-specific strategies based on these tools that significantly improved N use efficiencies and reduced environmental footprint. Meta-analyses of multiple field studies find that optimizing fertilizer N rate, timing, and source can reduce N_2O emissions in maize systems by up to 50% (Eagle *et al.* 2017).

The placement of fertilizer affects GHG emission from agricultural fields, but results are not conclusive. In some cases, emissions were higher when fertilizer N was placed deeper as compared to shallow application (Breitenbeck and Bremner 1986b; Drury *et al.* 2006). On the contrary, recovery by Chinese cabbage was 22% higher when urea was deep banded as compared to shallow incorporation of urea (Hou *et al.* 2010). A study of broadcast or deep-placed urea in no-till rice fields in China also showed that compared to broadcasting, deep placed urea reduced soil CH_4 emissions by 36 to 39% and N_2O emissions by 29 to 31%. The mitigation of soil CH_4 and N_2O emissions under deep placement was significant, reducing the total GHG emissions by 34% and carbon footprint by 46% (Liu *et al.* 2020). Snyder *et al.* (2009) concluded that any subsurface placement of N sources should be just deep enough to ensure good soil closure and N retention, while urea and urea-containing N sources should be incorporated.

The 4R Nutrient Stewardship (4RNS) concept of applying the right source of nutrient, at the right rate, at the right time, and at the right place (Bruulsema *et al.* 2016) synthesized such knowledge in a cropping system and landscape perspective that supports the environmental, economic, and social dimensions of sustainability. Environmental concerns related to fertilizer use was a strong driver of its development (Fixen 2020) and adoption (Amiro *et al.* 2017). The concept was incorporated in a fertilizer decision support tool, the Nutrient Expert (NE) (Pampolino *et al.* 2012), that successfully addressed the economic and environmental priorities of crop production, a necessary part of the climate smart action. Several recent studies using the NE tool improved or maintained yield and reduced environment footprint such as the GHG intensity, or increased the carbon capture. Sapkota *et al.* (2014) showed the net return and the total carbon footprint in wheat production under no-till system in northwestern India were lower when nutrient management was guided by the NE as compared to existing strategies. A similar study in summer maize in North-Central China (Zhang *et al.* 2017) showed that the fertilizer recommendation from the NE tool reduced the calculated total N_2O emission, total GHG emission, and GHG emission intensity by 35.1 and 17.5%, 35.2 and 18.4%, and 37.3 and 17.4% when compared with the farmers' practice (FP) and soil test-based fertilizer (ST) recommendation, respectively. Several other authors reported similar benefits, as well as increased carbon sequestration while using site-specific balanced fertilizer application recommended by the NE tool. Kakraliya *et al.* (2018) used NE-based fertilizer recommendations along with a suite of climate smart practices that increased rice-wheat system productivity by 8%, improved profitability, total water productivity and energy productivity by 23, 31 and 53% respectively, and reduced global warming potential (GWP) by 40%. Over the 3 year average, this suite of practices reduced GWP and GHG intensity by 40 and 44% respectively, compared to existing farmers' practices.

Increasing the agronomic nutrient use efficiency from either mineral or organic fertilizers (defined as the kg additional yield per kg nutrient applied) is central to climate change mitigation, as it means fewer nutrient losses and thus less N_2O emission (Powlson *et al.* 2018). Compared with FP and ST recommendation, the NE-based fertilizer recommendation in winter wheat in China (Zhang *et al.* 2018) increased agronomic efficiency of N (AEN) by 70.0 and 13.3%, recovery efficiency of N (REN) by 73.8 and 13.3%, and partial factor productivity of N (PFPN) by 58.5 and 22.2%, respectively. Compared with the FP and ST treatments, the NE-based fertilizer recommendation reduced total N_2O emissions by 54.8 and 26.3%, total GHG emissions by 44.8 and 22.9%, and GHG emission intensity by 45.8 and 22.0%, respectively. On-farm datasets from 2001 to 2012 with 1,971 field experiments for maize from four maize agro-ecological regions of China (Xu *et al.* 2015) showed that NE-based site-specific nutrient management increased N use efficiency by 12%, reducing potential loss of N to the environment.

This narrative will be incomplete without highlighting the role of balanced fertilization on C sequestration in soil, a major mitigating strategy in climate smart agriculture. Agricultural soil is a potential sink for atmospheric C as soil organic carbon (SOC). Fertilizer use contributes to soil C sequestration in agriculture by increasing biomass production and by improving C:N ratios of residues returned to the field. The use of mineral fertilizer can also support the maintenance of C stocks in non-agricultural land if improved fertility on agricultural land reduces demand for land conversion (Hijbeek *et al.* 2019). Brar *et al.* (2013) showed that the rice–wheat cropping system in the Indo-Gangetic Plains of India contributed toward C sequestration (1.94 Mg C ha^{-1}), with SOC pools and C sequestration rate of 7.84 Mg C ha^{-1} and 0.22 Mg C ha^{-1} yr^{-1}, respectively even without any fertilization. The soil organic C pools, C sequestration and rate of C sequestration increased to 9.19 C ha^{-1}, 3.30 Mg C ha^{-1} and 0.37 Mg C ha^{-1} yr^{-1} respectively by balanced fertilization, and were significantly amplified (9.99 Mg C ha^{-1}, 4.10 Mg C ha^{-1} and 0.46 Mg C ha^{-1} yr^{-1}, respectively) when farmyard manure was applied in conjunction with chemical fertilizer. Site-specific nutrient management using the NE tool in combination with conservation practices (Parihar *et al.* 2020) in a maize-wheat-mungbean rotation significantly increased the annual C sequestration in Northwestern India. Hijbek *et al.* (2019) summarized two recent meta-analyses based on 64 and 114 field experiments across the world (Ladha *et al.* 2011; Geisseler and Scow 2014) to indicate that SOC content was on average 8.5% and 8% higher in the topsoil of fields with mineral fertilizer application compared to unfertilized plots. The authors, however, cautioned that one needs to be careful about the tradeoffs between GHG emission and C sequestration as some studies show that soil carbon sequestration may not fully compensate for GHG emissions associated with fertilizer application (Bos *et al.* 2017; Gao *et al.* 2018).

Conclusions

The article highlighted the reciprocal relation between climate change and plant nutrition. Plant nutrition is part of the problem as well as the solution in this conundrum. Overall, balanced and site-specific nutrient management provides significant mitigation and adaptation potential as part of the CSA practices portfolio. Several of the essential plant nutrients have established roles addressing one or more of the climate impacts on production systems. While a balanced and adequate supply of all limiting nutrients strengthen the crops capacity to cope with the overall impact of climate change or weather instabilities. In the mitigation front, site and context-specific plant nutrient management provides opportunities to minimize total GHG emission or reduce emission intensity by producing more yield per unit of GHG, and/or sequester more C in the soil or plant biomass.

However, one must acknowledge that plant nutrition management practices are adapted in a site-specific manner to a specific growing environment where multiple factors co-operate. A clear example is the 4R strategy in nutrient stewardship. From a purely bio-physical point of view, the benefits from 4R stacks up when the plant nutrient source suits the soil properties; the application rate is based on the target yield of the crop, and how much of the nutrient is already available to the plant from other sources; the application time matches the uptake pattern of the crop as best as possible to increase uptake and reduce loss; and finally the nutrient is applied in such a way that roots can easily take it up. These basic principles need to be considered and combined in the context of the specific crop, the growing environment, and the socio-economic setting to create the right solution that fits the particular situation and transforms science to economic advantage. A specific 4R strategy which is appropriate for a particular context may not work at all in another context and may lead to severe economic loss to the practitioner. Moreover, the climate resilience opportunity offered by improved nutrient management magnifies as other climate smart crop management options and support mechanisms become accessible to the growers. For example, benefits multiply when improved crop nutrition is combined with resilient germplasm and conservation agriculture. Further layering of modern Information and Communication Technology (ICT) tools and supportive policy, along with rigorous gender and socio-economic assessment, with crop management would then provide CSA options that have truly transformative potential. This calls for more interdisciplinarity in research as the predicted change in climate is unprecedented, and new ways of doing research and supporting farmers with information will be required to keep the crop production trajectory upward in the face of climate change.

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An Introduction to the Dr. R.S. Murthy Memorial Lecture Series

Dr. R.S. Murthy Memorial Lecture was instituted in the year 2002 at the request of the Nagpur Chapter of the Indian Society of Soil Science, which donated Rs. 1,00,000 to ISSS for this purpose. This lecture is organized annually through one of the Chapters of ISSS. An obituary of Dr. R.S. Murthy was printed earlier in the Journal of the Indian Society of Soil Science, Vol. 31, pp. 171-172 in 1983. The first lecture, started in the 67th Annual Convention of ISSS held at Jabalpur, was delivered by Dr. Ram K. Gupta. The subsequent lectures in this series were delivered by Dr. R.K. Saxena (2003), Dr. B.V. Venkata Rao (2004), Dr. B. Mishra (2005), Dr. S.K. Chandra (2006), Dr. V.K. Suri (2007), Dr. J.C. Tarafdar (2008), Dr. K.P.R. Vittal (2009), Dr. G. Behera (2010), Dr. Anand Prakash Singh (2011), Dr. P.S. Minhas (2012), Dr. R.A. Sharma (2013), Dr. S.K. Chaudhari (2014), Dr. Buddheswar Maji (2015), Dr. M. Velayutham (2016), Dr. C. Devakumar (2017) and Dr. Kaushik Majumdar (2018).