ADVANCES IN AGRONOMY

DONALD L. SPARKS

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VOLUME ONE HUNDRED AND FORTY EIGHT

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PREFACE

Volume 148 contains six reviews on topics of current interest to crop and soil scientists. Chapter 1 reviews the impact of biochar on rice paddies using meta-analysis. Chapter 2 covers the role of clay mineralogy in stabilizing soil organic carbon. Chapter 3 discusses ways to better establish high-yielding maize systems to ensure sustainable intensification in China. Chapter 4 deals with the effects of climate change in South Asia on soil processes and wheat cropping. Chapter 5 compares and contrasts distributed temperature sensing for soil physical measurements and the heat pulse method. Chapter 6 is a comprehensive review on the physiology, biochemistry, genetics, and management of rice in saline soils.

I thank the authors for their informative reviews.

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CHAPTER FOUR

Soil Processes and Wheat Cropping Under Emerging Climate Change Scenarios in South Asia

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Abstract

Wheat is one of the most important staple foods as it provides 55% of the carbohydrates and 20% of the food calories and protein consumed worldwide. Demand for wheat is projected to continue to grow over the coming decades, particularly in the developing world, to feed an increasing population. More than 22% of global area under wheat is located in South Asia which is home to about 25% of the world's population. The Intergovernmental Panel on Climate Change has projected that in the 21st century South Asia is going to be hit hard by climate change. Changes in mean annual temperature will exceed 2°C above the late-20th-century baseline and there can be declines in the absolute amount of precipitation during December to February, when wheat is grown in the region. Temperature, precipitation, and enhanced CO_2 level in the atmosphere, the three climate change drivers can affect wheat cropping both directly at plant level and indirectly through changes in properties and processes in the soil, shifts in nutrient cycling, insect pest occurrence, and plant diseases. Studies pertaining to the effects of climate change on soil processes and properties are now becoming available and it is becoming increasingly clear that climate change will impact soil organic matter dynamics, including soil organisms and the multiple soil properties that are tied to organic matter, soil water, and soil erosion. Warmer conditions will stimulate soil N availability through higher rates of mineralization so that fertilizer management in wheat is also going to be governed by emerging climate change scenarios. Similarly, higher temperatures and altered precipitation regimes will determine the net irrigation water requirements of wheat. Several simulation models have projected reduced wheat yields in the emerging climate change scenarios, but occurrence of an extreme heat event around senescence can lead to crop models to underestimate the effects of heat on senescence by as much as 50% for late sowing dates for 2°C rise in mean temperature. So as to project productivity of wheat in South Asia in the emerging climate change scenarios with increased certainty, integrated holistic modeling studies will be needed which also take into account effect of extreme heat events as well as the contribution of altered soil processes and properties.

1. INTRODUCTION

Owing to a 20–30 year lag in our global climate system, even with all the efforts being made through international negotiations to reduce greenhouse gas emissions, the world is bound to become warmer from 1850–1900 to 1986–2005 by 0.61°C (5%–95% confidence interval: 0.55–0.67°C) (IPCC, 2014). In South Asia too, increasing annual mean temperature trends at the country scale have been observed during the 20th century and temperatures in next century are likely to increase further (Christensen et al., 2007). The projected spatial and temporal changes in precipitation and temperature are bound to shift current agroecological zones (Kurukulasuriya and Mendelsohn, 2008) as warming will be associated with changes in rainfall patterns, gaseous composition of the atmosphere, and soil temperature patterns. Soil functions and processes will also be influenced. Major impacts are expected on the viability of both dryland subsistence (Challinor et al., 2007b) and irrigated crop production (Knox et al., 2010). As climate is a primary determinant of agricultural productivity, climate change is going to influence crop growth and yield, hydrologic balances, nutrient cycling in the soil, and other components of agricultural systems. Predicting and mitigating the impacts of climate change on agroecosystems are going to be the greatest challenges in the present century.

Productivity of agricultural crops depends upon soil health status defined by a set of measurable physical, chemical, and biological attributes as well as functional soil processes controlled by management and climate change drivers. Rising atmospheric carbon dioxide (CO_2) levels, elevated temperature, altered precipitation (rainfall), and atmospheric nitrogen (N) deposition can potentially impact soil chemical, physical, and biological functions (French et al., 2009). Although explanation of the factors which define the effect of climate change drivers on soil processes is yet not adequate (Wixon and Balser, 2009), many studies in recent years have progressed our understanding of relationships between soil properties and climate change drivers.

Wheat (*Triticum aestivum* L.) is the second major staple food crop after rice in the South Asian region. Wheat acreage in 2014 in the South Asia was more than 50.8 M ha, which was around 23.05% of the global wheat area and it produced more than 19.34% of world's wheat (http://www.fao.org/faostat/en/#data/QC, accessed June 25, 2017). Wheat spread and acreage in South Asia are shown in Fig. 1. The demand for wheat is expected to grow at 2.5% per year during next couple of decades (Rosegrant et al., 2002). But there are predictions that South Asia is going to be hit hard by climate change and there can be large yield declines for most of the crops. In substantial area yields of both irrigated and rainfed wheat will be reduced (Nelson et al., 2009; Ortiz et al., 2008). As wheat prefers relatively cool temperatures, high temperatures affect crop growth at many stages of development. Grain yield of wheat is determined by grain number, which is determined from 30 days before anthesis until shortly after anthesis, and grain size, which is determined during grain filling. If hot conditions

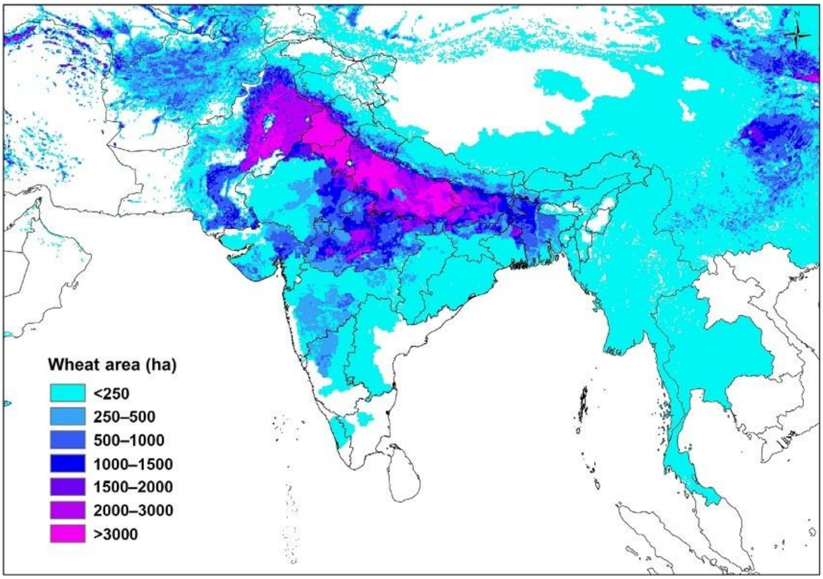

Fig. 1 Wheat spread and acreage in South Asia. The map shows wheat area in ha per 5 min by 5 min latitude–longitude grid. At equator one grid cell would be approx. 100 km^2 (10,000 ha). *Data source: Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochem. Cyc. 22, GB1003. https://doi.org/10.1029/2007GB002952; Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet. Part 2: geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cyc. 22, GB1022, https://doi.org/10.1029/2007GB002947.*

prevail toward the end of the season, the most pronounced effect is to shorten the duration of grain filling (Tashiro and Wardlaw, 1989). Warming (above 30°C) can slow grain-filling rates, also because the leaf photosynthetic apparatus may get damaged at extreme canopy temperatures, resulting in an acceleration of senescence (Zhao et al., 2007).

Wheat can grow in any type of soil but temperature and soil moisture are the key factors which define its productivity. In regions where assured irrigation is not available, amount and distribution of rainfall in timing with physiological stages can be a key factor in wheat production, even over temperature. But changes in rainfall patterns and temperature caused by climate change can also potentially influence wheat productivity by influencing different soil properties and processes (Brevik, 2012). Nutrient availability and interactions in the soil can also be altered by climate change effects because not just total nutrient but availability can become a limiting factor for optimum crop performance. Understanding these effects, and what possibly can be done to adapt to them, require an understanding of how climate and soils interact and how changes in climate will lead to corresponding changes in soil (Brevik, 2013). We have attempted to review the information available on how climate change may alter soil properties and processes such as C and N cycles, and how soil–climate change interactions are going to influence productivity of wheat in South Asia, the most densely populated geographical region in the world. South Asia comprises of eight countries, i.e., Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka, but wheat is not grown in Sri Lanka and Maldives and area under wheat in Bhutan is negligible.

2. CLIMATE CHANGE TRENDS IN SOUTH ASIA

Climate change has been defined by the Intergovernmental Panel on Climate Change (IPCC) as the change in the state of the climate due to natural variability or as a result of human activity but identified using statistical tests by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (Solomon et al., 2007). Temperature and precipitation constitute the two climate change parameters that can influence soils and crop production.

As per the Fifth Assessment Report of the IPCC (IPCC-AR5) (Hijioka et al., 2014a), over the period 1901–2009, the warming trend in Asia was particularly strong in the cold season between November and March, with an increase of 2.4°C in the mid-latitude semiarid area of Asia. Increasing annual mean temperature trends at the country scale in South Asia have been observed during the 20th century (Table 1) (Hijioka et al., 2014b). Seasonal mean rainfall in South Asia showed interdecadal variability, noticeably a declining trend with more frequent deficit monsoons under regional inhomogeneities (Table 1). The number of rainy days and total annual amount of precipitation has decreased. The frequency of heavy precipitation events is increasing, while light rain events are decreasing. The increase in the number of monsoon break days and the decline in the number of monsoon depressions in India are consistent with the overall decrease in seasonal mean rainfall. But an increase in extreme rainfall events occurred at the expense of weaker rainfall events over the central Indian region and in many other areas.

Since 1960, the temperature in Afghanistan has risen by 0.6°C at an average rate of 0.13°C per decade (Table 1), but the country has also observed exceptionally hot days and warm nights in recent years (Savage et al., 2009). Mean rainfall in Afghanistan has decreased by 6.6% per decade since 1960

Table 1 Summary of Key Observed Past and Present Annual Mean Temperature and Precipitation Trends in South Asian Countries in Which Wheat Is Grown

	Change in Temperature		Change in Precipitation		
Country	Change	Period	Change	Period	Reference
Afghanistan	+0.6°C	1960–2008	—0.5 mm month^{-1}	1960–2008	Savage et al. (2009)
	+0.13°C decade^{-1}		—2% decade^{-1}		
Bangladesh	+0.097°C decade^{-1}	1958–2007	+5.53 mm year^{-1}	1958–2007	Shahid (2010)
India	+0.56°C	1901–2009	No significant time trend	1901–2009	Attri and Tyagi (2010)
	+0.68°C century^{-1}	1880–2000			Lal (2003)
	+0.0056°C year^{-1}	1948–2008			Ganguly (2011)
Nepal	+0.06°C year^{-1}	1977–1994			Shrestha et al. (1999)
Pakistan	+0.57°C	1901–2000	+61 mm	1901–2007	Chaudhry et al. (2009)
	+0.47 T 0.21°C	1960–2007	—156 mm	1901–54	
	+0.099°C decade^{-1}	1960–2007	+35 mm	1955–2007	

Source: Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D., Lindgren, E., Surjan, A., 2014b. Asia—supplementary material. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. www.ipcc-wg2.gov/AR5 and www.ipcc.ch.

(UNDP, 2008). Along with a trend of increasing temperature and precipitation (Table 1), Bangladesh is experiencing increased frequency of natural calamities over the past several years. Cyclones have increased from 5 per decade in 1901 to 48 per decade in 2000. Flooding incidences increased from 0.6 per year in 1960 to 2.9 per year in 1990 (Khadka, 2011). In India, increasing trend in surface temperature during the last century has been reported by several workers (Hingane et al., 1985; Pant and Rupa Kumar, 1997; Rupa Kumar et al., 1994; Singh and Sontakke, 2002; Srivastava et al., 1992). Pant and Rupa Kumar (1997) found a warming trend of 0.57°C century^{-1}and conclude that warming across South Asia was mainly contributed by the postmonsoon winter season when wheat is grown. Based on mean surface air temperature for 1901–2000 all over India, Rupa Kumar et al. (2002) could show a higher rate of temperature increase during winter (0.04°C decade^{-1}) and postmonsoon seasons (0.05°C decade^{-1}) compared with the premonsoon (0.02°C decade^{-1}) and monsoon seasons (0.01°C decade^{-1}). The night time temperature is increasing at twice the rate of the day time maximum temperature (Sen Roy and Balling, 2005).

No overall significant trends in precipitation have been recorded for South Asia (Pant and Rupa Kumar, 1997; Stephenson et al., 2001; Thapliyal and Kulshrestha, 1991). Nevertheless, decreasing or increasing trends in rainfall on regional basis have been reported by Rupa Kumar et al. (1992), Kripalani et al. (1996, 2003), and Singh and Sontakke (2002). Using data from 1140 meteorological stations in India, Rao (2007) observed a negative trend in precipitation in the southern states of India, southern peninsular areas, central India, and parts of the north and northeastern regions. Positive trends in rainfall were observed for Gujarat, Maharashtra, coastal Andhra Pradesh, and Odisha. Large parts of northwestern India did not show any changes. In arid and hyperarid mountains and arid coastal areas of Pakistan, surface temperature has risen by 0.6–1°C. In the coastal belt and hyperarid plains, there has been a 10%–15% decline in both winter and summer rainfall but 18%–32% increase in the monsoon rainfall in subhumid and humid areas (Farooqi et al., 2005).

The assessment of the Fourth Assessment Report of the IPCC (IPCC-AR4) that warming is very likely in the 21st century (Christensen et al., 2007) still holds for all land areas of Asia. Changes in mean annual temperature will exceed 2°C above the late-20th-century baseline over most land areas in the mid-21st century, and range from more than 3°C to more than 6°C in the high latitudes in South and Southeast Asia in the late-21st century

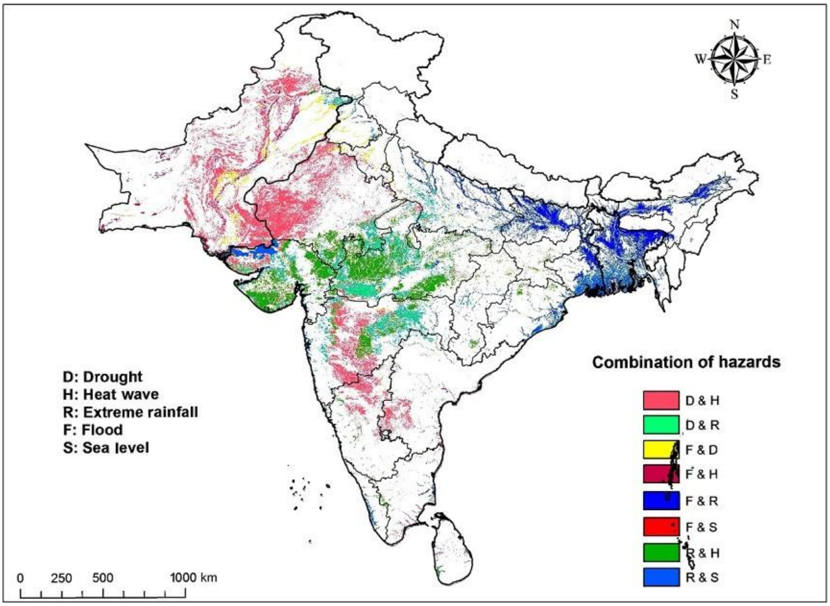

Fig. 2 Multiple weather risks in South Asia. *Adapted from Amarnath, G., Alahacoon, N., Smakhtin, V., Aggarwal, P., 2017. Mapping Multiple Climate-Related Hazards in South Asia. International Water Management Institute (IWMI), Colombo, Sri Lanka. IWMI Research Report 170, p. 41.* https://doi.org/10.5337/2017.207.

(Hijioka et al., 2014a). Projections of future annual precipitation change in Asia as outlined in IPCC-AR5 are qualitatively similar to those assessed in the IPCC-AR4. Precipitation increases are very likely at higher latitudes by the mid-21st century and in East and South Asia by the late-21st century (Hijioka et al., 2014a).

Multiple weather risks associated with possible climate change scenarios in the South Asia are depicted in Fig. 2. Climatic models show that Bangladesh will experience a median warming of 1.1, 1.6, and 2.6°C in 2030s, 2050s, and 2080s, respectively. The intensity of flooding will increase by 10% in coming decades (Khadka, 2011). In Pakistan, temperatures will rise during the first half of the 21st century, but rainfall patterns are not expected to be uniform throughout the country. While the northern regions are expected to have increased precipitation, the southern coastal regions and western Balochistan should expect decreased precipitation during coming decades (Farooqi et al., 2005). Climate change prediction models indicate general warming over India toward second half of the 21st century (Rupa Kumar et al., 2002). There is some disagreement among the models on rainfall changes. Rupa Kumar et al. (2006) could predict marked increase in both rainfall and temperature into the 21st century, particularly becoming conspicuous after the 2040s. In regions south of 25°N, the maximum temperature will increase by 2–4°C during 2050s. In the northern regions, the increase in maximum temperature may exceed 4°C. An overall decrease in the number of rainy days over a major part of India is predicted. This decrease should be more in western and central parts (by more than 15 days) while near the foothills of Himalayas and in northeast India the number of rainy days may increase by 5–10 days. According to Prabhakar and Shaw (2008), by the end of the 21st century, precipitation may decrease by 5%–25% across India, with more reductions in winter than summer rainfall. Future climatic patterns of Afghanistan show that the country will experience increased temperatures in the range of 2.0–6.2°C by 2090s (UNDP, 2008). The country will experience dry seasons, as rainfall is expected to reduce over the coming years (Savage et al., 2009) and there may occur severe droughts.

Future greenhouse gas emissions will be the product of very complex dynamic systems, determined by driving forces such as demographic development, socioeconomic development, and technological change. The IPCC Special Report on Emission Scenarios (IPCC-SRES) (IPCC, 2000) has proposed a set of four scenarios namely A1, A2, B1, and B2, which cover a wide range of the main demographic, technological, and economic driving forces of future emissions. As defined in Table 2, these scenarios describe a different world evolving through the 21st century and each may lead to different climate change trajectories. Lal et al. (2001) performed a transient experiment with a coupled atmosphere–ocean general circulation model following the four SRES emission scenarios to study climatological features associated with intraseasonal and interannual variability in monsoon circulation over the Indian subcontinent. Model projected temperature and precipitation scenarios in winter and monsoon seasons are described in Table 2. The area-averaged annual mean surface warming by 2080s is projected to be the least in B1 scenario and the maximum in A2 scenario and will range between 3.5 and 5.5°C. During winter season when wheat is grown in the Indian subcontinent, warming is projected to be at least 4°C; during monsoon season in the summer, temperature rise may range between 2.9 and 4.6°C (Table 2). The projected warming will be more pronounced during wheat season in winter than during monsoon season. Based on all the four IPCC-SRES emission scenarios, an increase of 7%–10% in area-averaged annual mean precipitation

Table 2 Annual and Winter Season Climate Change Projections for Indian Subcontinent Under the Four IPCC-SRES Emission Scenarios

		Temperature Change (°C)				Precipitation Change (%)			
Year	Season	A1[a]	A2	B1	B2	A1	A2	B1	B2
2050s	Annual	2.87	2.63	2.23	2.73	9.34	5.36	6.86	7.18
	Winter	3.18	2.83	2.54	3.00	3.22	—9.22	3.82	3.29
	Monsoon	2.37	2.23	1.81	2.25	10.52	7.18	7.20	8.03
2080s	Annual	5.09	5.55	3.53	4.16	9.90	9.07	7.48	7.62
	Winter	5.88	6.31	4.14	4.78	—19.97	—24.83	—4.50	—10.36
	Monsoon	4.23	4.62	2.91	3.47	14.96	15.18	11.12	10.10

[a] Special Report on Emission Scenarios (SRES) as developed by IPCC (2000) constitute an appropriate tool to analyze how driving forces such as demographic development, socioeconomic development, and technological change may influence future emission outcomes and to assess the associated uncertainties. The A1 scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. The B1 scenario describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines.

Source: Lal, M., Nozama, T., Emori, S., Harasawa, H., Takahashi, K., Kimoto, M., Abe-Ouchi, A., Nakajima, T., Takemura, T., Numaguti, A., 2001. Future climate change: implications for Indian summer monsoon and its variability. Curr. Sci. 81, 1196–1207.

is projected over the Indian subcontinent by 2080s. However, a decline of 5%–25% is projected in the area-averaged winter precipitation. Thus, in general, wheat growing season in South Asia is projected to experience rise in surface temperature coupled with reduced precipitation in the decades to come.

3. EFFECT OF CLIMATE CHANGE ON SOIL PROPERTIES

Temperature, precipitation, and enhanced CO_2 level in the atmosphere are the three climate change drivers, which influence different properties and processes in soils being used as medium for plant growth. The atmospheric CO_2 concentration has already reached 400 ppm and is further going to increase in years to come (Datta et al., 2015). There is a close relationship between air temperature and soil temperature; an increase in air temperature will generally lead to an increase in soil temperature. The temperature regime of the soil is also governed by gains and losses of radiation at the surface, the process of evaporation, heat conduction through the soil profile, and convective transfer via the movement of gas and water. Warmer soil temperatures accelerate soil processes leading to increase in the rate of decomposition of organic matter, increased microbiological activity, rapid release of nutrients, increased rates of nitrification, and quicker chemical weathering of minerals. Climate change can directly influence soil moisture levels through changes in precipitation, evapotranspiration controlled by temperature and climate-induced changes in vegetation, plant growth rates, rates of soil water extraction, and the effect of enhanced CO_2 levels on plant transpiration. Changes in precipitation rapidly affect soil water regimes since the timescale for response to rainfall in the soil is usually within a few hours. Changes in soil water fluxes dictate a host of microbiological soil processes, availability of nutrients in the soil, uptake of nutrients by plants, and losses of nutrients from the soil. Changes in soil moisture status may also influence the climate itself and contribute to drought conditions through reduction in available moisture, altering circulation patterns, and increasing air temperatures. As predicted for South Asia, warmer temperatures and less rainfall during winter will lead to less soil moisture with potentially large implications for crops like wheat. With many different interacting influences on soil moisture status, it is not an easy task to predict the effect of climate change on soil water at regional or local level. This difficulty is accentuated because soil water contents are highly variable in space and general climate change models are not yet capable of predicting the climate changes likely at regional and particularly local level.

Not many studies are available which provide an understanding of relationships between soil properties and the climate change drivers. One reason could be that changes in many soil properties under the influence of climate change take place over a long time. Different soil properties respond to climate change according to varying timescales (Varallyay, 1990). Parameters such as bulk density, porosity, infiltration rate, permeability, nitrate content, and composition of soil air can change on a daily basis, depending on the weather. At the other end of the timescale, weathering of minerals as part of soil formation and changes in soil texture are more likely to be on millennial timescales (Table 3). The effect of climate change on soil properties and associated soil processes can have a range of implications depending upon how soil is managed. Major soil physical, chemical, and biological

Table 3 Time Scale for Change in Soil Properties Under the Influence of Climate Change

Time Scale Categories	Soil Parameter	Properties and Characteristics
$<10^{-1}$ year	Temperature; moisture content; bulk density; total porosity; infiltration rate; permeability; composition of soil air and solution	Compaction; drainage; workability
10^{-1}–10^{0} year	Total water capacity; field capacity; hydraulic conductivity; pH; nutrient status; composition of soil solution	Microbial activity; plant nutrient regimes; erosion
10^{0}–10^{1} year	Wilting percentage; soil acidity; cation exchange capacity; exchangeable cations	Moisture; soil fertility; salinity–alkalinity; desertification; permafrost
10^{1}–10^{2} year	Specific surface; clay mineral association; organic matter content	Soil biota; salic; calcareous; sodic; vertic properties
10^{2}–10^{3} year	Primary mineral composition; chemical composition of minerals	Color; iron concretions; soil depth; cracking
$>10^{3}$ year	Texture; particle-size distribution; particle density	Parent material; depth; abrupt textural change

Modified from Varallyay, G.Y., 1990. Influence of climatic change on soil moisture regime, texture, structure and erosion. In: Scharpenseel, H.W., Schomaker, M., Ayoub, A. (Eds.) Soils on a Warmer Earth. Elsevier, Amsterdam. p. 46.

properties which define status of soil health in relation to climate change impacts are listed in Table 4.

Soil Physical Properties

Soil physical properties define movement of air and water/dissolved chemicals through soil, as well as conditions affecting germination, root growth, and erosion processes. Soil physical properties form the foundation of several chemical and biological processes, which may be further governed by climate, landscape position, and land use. Thus, a range of soil physical properties when altered by climate change can trigger a chain reaction that leads to soil environment, which may greatly influence growth and production of crops including wheat. Some key soil physical indicators in relation to climate change include soil structure, water infiltration rate, bulk density, rooting depth, and soil surface cover.

The structure of the soil dictates organic C accumulation, infiltration capacity, movement and storage of gases, water and nutrients, emergence

Table 4 Impact of Climate Change on Some Soil Properties Associated With Different Soil Processes

Soil Property	Soil Processes	Climate Change Impact
Soil structure	Aggregation, organic matter turnover, retention, and transportation of water and chemicals	Medium
Porosity	Plant available water capacity, soil crusting, aeration, water entry	High
Infiltration	Soil water availability and movement, leaching of nutrients, erosion	High
Bulk density	Soil structural conditions, compaction	Low
Available water	Field capacity, permanent wilting point, water flow	High
pH	Soil acidification, salinization, soil structural stability, biological and chemical activity thresholds	Medium
Electrical conductivity	Plant and microbial activity thresholds, leaching of salts, soil structure decline, salinization	Medium
Plant available N, P, and K	Availability of nutrients for plant uptake, losses from the soil–plant system	Medium
Soil organic matter	Organic matter storage and quality, plant residue decomposition, metabolic activity of soil organisms, mineralization–immobilization turnover, microbial activity, nutrient supply	High
Total soil C and N	C and N mass and balance, soil structure, nutrient supply	High
Microbial biomass C and N	Microbial activity, soil processes mediated via microbes	High
Microbial diversity	Nutrient cycling and availability	High
Microbial quotients	Substrate use efficiency, substrate quality	High

Source: Adapted from Allen, D.E., Singh, B.P., Dalal, R.C., 2011. Soil health indicators under climate change: a review of current knowledge. In: Singh, B.P., Cowie A.L., Chan, K.Y. (Eds.), Soil Health and Climate Change. Springer-Verlag, Berlin, Heidelberg. Soil Biology, vol. 29, pp. 25–45.

of crops and root, and microbial community activity. It can also be used to measure soil resistance to erosion and management changes because it is a measure of aggregate stability, the resistance of soil aggregates to external energy such as high-intensity rainfall and cultivation (Blanco-Canqui and Lal, 2004; Moebius et al., 2007; Rimal and Lal, 2009). Since nature and quality of the structure of a particular soil are strongly influenced by the amount and quality of organic matter present and also by the inorganic constituents of the soil matrix and cultivation methods, a decline in soil organic matter levels as could occur under climate change may lead to a decrease in soil aggregate stability, an increase in susceptibility to compaction, lower infiltration rates, increased run-off, and hence an increased susceptibility to erosion. Soils with high clay contents, particularly those with smectitic mineralogy, have the potential to shrink when dry, resulting in formation of large cracks and fissures. When the soils rewet, the cracks close. Drier climatic conditions would be expected to increase the frequency and size of crack formation. The increased drying of the soil will lead to increased difficulties in the management of clayey agricultural soils with a high shrink–swell potential. The importance of soil structure in future management of soil and water, movement of nutrients within the soil and the landscape are important aspects to be considered in an environment under climate change.

Porosity and pore size distribution are a measure of the ability of a soil to store root zone water and air necessary for plant growth. Soil porosity and water release characteristics directly influence a range of soil physical indices including soil aeration capacity, plant available water capacity, and relative field capacity (Reynolds et al., 2009). Root development and soil enzyme activities are closely related to soil porosity and pore size distribution (Piglai and De Nobili, 1993). Future climate change scenarios consisting of elevated CO_2 and temperature, and variable and extreme rainfall events may not only alter soil porosity and pore size distribution but also root development and soil biological activities, so that soil functions are likely to be affected in unexpected directions (Allen et al., 2011). Studies on soil porosity and pore size distribution in response to climate change are limited and hence urgently required to guide development of climate change adaptive strategies.

Soil water infiltration rate is gaining increasing importance in soil water modeling (Dalal and Moloney, 2000) but it can significantly change with soil use, management, and time. The soil available water and distribution may respond rapidly to climate change, especially to variable and high-intensity rainfall or drought events, and thus management strategies such as conservation tillage and application of organic manures, which maintain or even enhance water infiltration and available water in soil may help in mitigating the impacts of severe rainfall and drought events (Lal, 1995). Bulk density is another routinely assessed soil property in agricultural systems used for characterizing the state of soil compactness, aeration, and infiltration (Dalal and Moloney, 2000; Reynolds et al., 2009). Since bulk density is, in general, negatively correlated with soil organic matter (Weil and Magdoff, 2004), loss of organic C from increased decomposition due to elevated temperatures (Davidson and Janssens, 2006) may lead to increase in bulk density and hence making soil more prone to compaction via land management activities or climate change stresses such as variable and high-intensity rainfall and drought events (Birka´s et al., 2009).

Soil Chemical Properties

Soil pH, a function of parent material, time of weathering, vegetation, and climate, affects a range of soil biological and chemical functions including acidification, salinization, crop performance, nutrient availability and cycling, and biological activity (Dalal and Moloney, 2000). Rapid changes in soil pH may not be expected due to climate change drivers such as elevated temperatures, CO_2 fertilization, variable precipitation (Brinkman and Sombroek, 1999), and atmospheric N deposition (DeVries and Breeuwsma, 1987; McCarthy et al., 2001). But it is likely that drivers of climate change will affect organic matter status, C and nutrient cycling, plant available water, and hence plant productivity, which in turn will affect soil pH (Reth et al., 2005). Significant increases in rainfall will lead to increases in leaching, loss of nutrients and increasing acidification as dictated by the buffering pools existing in soils. The extent of increased leaching or increased evaporation will depend on the degree of change in rainfall and temperature and consequent changes in land use and its management.

Soil electrical conductivity is associated with trends in salinity, crop performance, nutrient cycling (particularly nitrate), and biological activity and, along with pH, can act as a surrogate measure of soil structural decline especially in sodic soils (Dalal and Moloney, 2000). Smith et al. (2002) used elevation gradient as a surrogate for increasing temperatures and decreasing precipitation under climate change scenarios and found that electrical conductivity decreased and pH increased in a semiarid environment. A comprehensive assessment of the influence of drivers of climate change on soil electrical conductivity is not yet available. Sorption capacity and cation exchange capacity are important determinants of soil chemical quality, particularly the retention of major nutrient cations Ca, Mg, and K, and immobilization of potentially toxic cations Al and Mn. Since cation exchange capacity of coarse-textured soils and low-activity clay soils is greatly determined by soil organic matter (Weil and Magdoff, 2004), the increasing decomposition, and loss of soil organic matter due to elevated temperatures (Davidson and Janssens, 2006) may lead to the loss of cation exchange capacity of these soils. Low cation exchange capacity of soil may result in increased leaching of base cations in response to high and intense rainfall events.

Measurement of extractable nutrients provides indication of the capacity of the soil to support plant growth. Detailed investigations on the direction and exact magnitude of change in plant available nutrients in response to climate change drivers are not yet available. Cycling of plant nutrients such as N is intimately linked with soil organic C cycling (Weil and Magdoff, 2004), and hence drivers of climate change such as elevated temperatures, variable precipitation, and atmospheric N deposition are likely to impact N cycling (Bijay-Singh, 2011) and possibly the cycling of phosphorus and sulfur as well.

Soil Biological Properties

Biological properties of the soil are complex adaptive systems which integrate key soil processes. According to Kibblewhite et al. (2008), if chemistry and physics of the soil system provide the context, it is the soil biota which is adaptive to changes in environmental circumstances. Comprehensive information on biological properties of the soil in the context of climate change is limited. Soil organic matter and its constituents, and soil microbial biomass constitute the major biological indicators which can be influenced by climate change. Soil organic matter is fundamentally derived from CO_2 in the atmosphere, converted to biomass by photosynthesis in plants, and ultimately released into soils by vegetation death and decomposition. Because accumulation of soil organic matter is essentially a biological process, it is controlled by moisture, temperature, type and rate of biological activity, vegetation, and land use. Soil organic matter pools, roots, and associated rhizosphere organisms all have distinct responses to environmental and climate change drivers, although availability of C substrates will regulate all the responses (Pendall et al., 2004).

Soil organic matter is one of the most complex and heterogeneous components of soils and has often been conceptually divided into compartments or pools which decompose rapidly (active, labile, or microbial), slowly (intermediate and unprotected), or not at all (passive, recalcitrant, and protected). It drives a large number of functions including the contribution to the charge characteristics of soils, a sink for and source of C and N, and to a variable extent in regulation of P and S cycling, making complexes with multivalent ions and organic compounds, providing microbial and faunal habitat and substrates, as well as affecting aggregate stability, trafficability, water retention, and hydraulic properties (Weil and Magdoff, 2004). A decrease in soil organic matter can lead to reduced fertility and biodiversity as well as loss of soil structure resulting in reduced water holding capacity, increased risk of erosion, and increased bulk density and hence soil compaction (Weil and Magdoff, 2004). It is highly susceptible to changes in land use and management and to changes in soil temperature and moisture.

How climate change will impact on soil organic matter remains scientifically controversial and without consensus (Ågren and Wetterstedt, 2007). On the one hand, it is recognized that global warming and increasing CO_2 levels in the atmosphere can favor increased plant growth, which in turn could provide more organic matter for the soil. On the other hand, a rise in air temperature and that of the soil would be consistent with an increase in decomposition and loss of soil organic matter. According to Davidson and Janssens (2006) and Kuzyakov and Gavrichkova (2010), it is the accessibility and availability of soil organic matter to microorganisms that govern its losses rather than the rate-modifying climate factors such as temperature. Nevertheless, the balance of opinion seems that under the emerging warming climate change scenarios, losses of soil organic matter via decomposition are likely to exceed the gains from increased plant growth thereby leading to lowering of soil organic matter levels in the soil. In most experiments, elevated CO_2 stimulated net primary productivity, but the fate of this C, especially the portion allocated below ground, largely remains unknown (Leavitt et al., 2001; Tate and Ross, 1997); partly due to the difficulty in measuring a small increment of soil organic matter against a large background (Hungate et al., 1996). Also, the increase in plant growth due to CO_2 fertilization effect may not be as large as originally thought (Jarvis et al., 2010; Zaehle et al., 2010) because negative effects of increasing levels of ozone and increased temperatures on plant growth may cancel out any CO_2 fertilization effect that does take place (Jarvis et al., 2010). Thus soils may actually lose organic matter as atmospheric CO_2 levels and global temperatures increase, creating a positive feedback system that could push temperatures even higher (Brevik, 2012). But loss of too much organic matter is bound to have negative impacts on soil physical, chemical, and biological properties (Brevik, 2009; Wolf and Snyder, 2003).

Low-density fraction and macroorganic components of soil organic matter, which consist mainly of mineral-free particulate plant and animal residues and serve as readily decomposable substrate for soil microorganisms as well as a labile nutrient reservoir (Gregorich et al., 1994; Post and Kwon, 2000; Wagai et al., 2009), are responsive to management practices and may act as early indicators of response to climate change. The amount of organic matter that can be mineralized in the soil is an indicator of organic matter quality and acts as the interface between autotrophic and heterotrophic organisms during the nutrient cycling process (Gregorich et al., 1994). It can serve as a useful indicator to assess soil health under climate change as it affects nutrient dynamics within single growing seasons.

Microbial biomass is the living component of soil organic matter and it is considered to be the most labile C pool in soils. As most of the biogeochemical processes in soil are microbially mediated, microbial biomass is a sensitive indicator of changes in soil processes, with links to soil nutrient and energy dynamics, including mediating the transfer between soil organic C fractions (Haynes, 2008; Post and Kwon, 2000; Weil and Magdoff, 2004). Although soil microbial biomass is responsive to short-term environmental changes (Haynes, 2008), recent studies have revealed significant decline in the soil microbial biomass during long-term simulated climatic warming experiments (Rinnan et al., 2007). Microbial biomass generally responds positively to increased temperature but responses to elevated CO_2 are highly idiosyncratic (Pendall et al., 2004). Possibly, responses to the interaction of CO_2 and temperature would be dominated by the more ubiquitous temperature effect, or the effects may offset one another. Castro et al. (2010) found that fungal abundance increased in warmed treatments whereas bacterial abundance increased in warmed plots with elevated atmospheric CO_2 levels but decreased in warmed plots under ambient atmospheric CO_2 level. Changes in precipitation altered the relative abundance of *Proteobacteria* and *Acidobacteria*. In relatively moist soil environments, *Acidobacteria* decreased with a concomitant increase in the *Proteobacteria*.

Like microbial biomass, soil enzyme activities are also closely linked to the several soil processes, soil biology, and cycling of nutrients. These are easily measured and integrate information on both the microbial status and the physicochemical soil conditions. Although enzyme activities show rapid response to changes in soil management (Aon et al., 2001; Garc´ıa-Ruiz et al., 2009), it is not very clear as to how these will respond to the drivers of climate change.

4. INFLUENCE OF CLIMATE CHANGE ON SOIL PROCESSES

Soils are intricately linked to the atmospheric climate system through the C, N, and hydrologic cycles. The global soil C cycle has been greatly perturbed by human activity, both directly through farming and indirectly through anthropogenic climate change (Amundson et al., 2015). Soils contain more organic C than the combined C in global vegetation and the atmosphere (Lehmann and Kleber, 2015). Therefore, any change in climate is going to have an effect on soil processes and properties. Research on the effects of climate change on soil processes is still in the early stages, but from the results of the studies that have been carried out so far, it is possible to provide some insight into the expected effects of climate change on soil processes. Global warming significantly affects soil C dynamics (Bradford et al., 2016). As changing climates will influence the C and N cycles, soil processes linked with soil organic matter dynamics and N transformations and ultimately with soil fertility are going to be strongly affected (Davidson and Janssens, 2006; Hungate et al., 2003; Wan et al., 2011). The exact direction and magnitude of these impacts will be dependent on the amount of change in atmospheric gases, temperature, and precipitation amounts and patterns (Brevik, 2012). Acidity, salinity, and erosion will also be influenced by the drivers of climate change.

Soil Organic Matter Decomposition/Soil Respiration

Soil organic matter is made up of accumulated, decaying debris of biota living on or in the soil. It is extremely heterogeneous, encompassing everything from root exudates in the last hour to persistent millennia old humidified material (Amundson, 2001). Soil organic C status across South Asia is shown in Fig. 3. The benefits of organic matter arise not from its accumulation, but from its decay (Janzen, 2006). Soil organic matter decay is considered as a measure of soil performance and soil respiration is used as an indicator of soil health. According to Janzen (2006), the more the decay, the better the soil; the more active the soil biota, the richer the biological reward. The extent to which climate change will alter the rates of organic

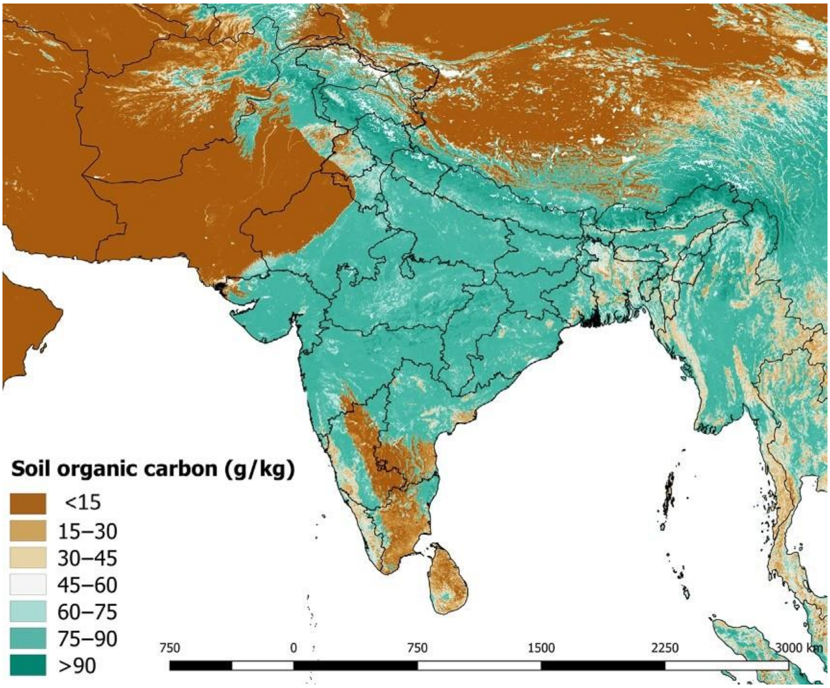

Fig. 3 Soil organic carbon (SOC) status (0–15 cm depth) across South Asia. *Data source: Hengl, T., de Jesus, J.M., Heuvelink, G.B., Gonzalez, M.R., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., Guevara, M.A., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12(2), e0169748.*

matter decomposition depends, in part, upon the physiological response of soil microorganisms to altered temperature and precipitation regimes. Increased temperature accelerates the rates of microbial decomposition leading to loss of soil organic matter. But this increase in respiration may not persist as temperatures continue to rise. In a 10-year soil warming experiment, Melillo et al. (2002) observed a 28% increase in CO_2 flux in the first 6 years of warming when compared to the control soils, followed by considerable decreases in CO_2 released in subsequent years, and no significant response to warming in the final year of the experiment. Possibly increased temperatures cause microbes to undergo physiological changes that result in reduced C use efficiency (Allison et al., 2010). Soil microbes may also adapt to higher soil temperatures and eventually return to normal decomposition rates. While warmer global temperatures will enhance microbial activity and rates of organic matter decomposition (Kirschbaum, 1995; Schimel et al., 1994), such a response gets dampened if warmer temperatures were accompanied by drier soil conditions.

Soil matric potential influences microbial activity by modifying substrate availability. Rates of microbial processes are generally most rapid near field capacity (—0.01 MPa), and they linearly decline as soil matric potential becomes more negative (Linn and Doran, 1984). Therefore, it is likely that declines in soil matric potential below field capacity (—0.01 MPa) will modify the temperature-dependent increase in substrate pools for microbial respiration (MacDonald et al., 1995; Zogg et al., 1997). According to Pendall et al. (2004), soil organic matter is potentially very sensitive to direct and indirect effects of elevated CO_2 and temperature. Soil organic matter pools, roots, and associated rhizosphere organisms all have distinct responses to environmental change drivers. Elevated CO_2 increases C supply below ground, whereas warming is likely to increase respiration and decomposition rates; possibly these effects will moderate one another. However, indirect effects on soil moisture availability and nutrient supply may alter processes in unexpected directions. For example, elevated atmospheric CO_2 and precipitation changes might increase soil moisture in an ecosystem, but this increase may be counteracted by warming (Dermody et al., 2007). Similarly, warming may increase microbial activity in an ecosystem, but this increase may be eliminated if changes in precipitation lead to a drier soil condition or reduced litter quantity, quality, and turnover (Castro et al., 2010).

Warmer temperatures and altered plant allocation below ground due to elevated atmospheric CO_2 concentrations (Luo et al., 2006) constitute the two important drivers for soil organic matter decomposition under the upcoming climate change scenarios. Nevertheless, resultant effects are less certain because warming may increase microbial activity and therefore accelerate soil organic C turnover (Conant et al., 2011; Davidson and Janssens, 2006), while more plant allocation below ground may increase stocks due to additional inputs or decrease stocks through priming effects (Cheng et al., 2014; Kuzyakov, 2010). According to Kirkham (2016), when plant tissues grown under elevated atmospheric CO_2 decompose, increased levels of CO_2 are emitted. Carney et al. (2007) observed soil organic C levels declining under increased atmospheric CO_2 levels due to increased microbial activity.

Temperature affects the chemical processes of soil organic matter adsorption and desorption onto mineral surfaces, but little is known about the activation energies of these processes. As both adsorption and desorption processes might increase with increasing temperatures, the net effect would be minimal over the next few decades (Davidson and Janssens, 2006). Soil water film thickness, through which the diffusion of soluble organic C substrates and extracellular enzymes occurs, is also determined by the climate-driven hydrologic balance among drainage, precipitation, and evapotranspiration. Likewise leaf litter hydrophobicity associated with drought-prone ecosystems is affected by climate. These processes are significant contributors to variability of soil C stocks and soil fertility, but the extent to which they will participate in positive or negative feedbacks to climate change is not clear (Davidson and Janssens, 2006; von Lützow and Kögel-Knabner, 2009).

Nitrogen Mineralization

To supply N to crop plants, mineralization is an essential step (Mullen, 2011; Pierzynski et al., 2009). Therefore, plant productivity would be negatively affected if N mineralization in the soil is reduced. When CO_2 enrichment increases the soil C/N ratio, decomposing organisms in the soil need more N, which can reduce N mineralization (Gill et al., 2002; Hungate et al., 2003; Reich et al., 2006a). In fact, N limitation of CO_2 fertilized plants has been reported by Holland (2011) and Hungate et al. (2003). Although increased temperatures stimulate N availability in the soil, but still the net result is reduction in decomposition of soil organic carbon (Holland, 2011). Increasing temperatures increase N mineralization (Joshi et al., 2006; Norby and Luo, 2004; Reich et al., 2006b), which could have a positive effect on plant growth. However, An et al. (2005) observed that N mineralization increased due to warming in the first year but was reduced afterward.

Nitrification and Denitrification

Nitrification and denitrification are controlled by complex, interacting environmental and biological factors that are likely to be modified by climate change (elevated CO_2 and warming). Diffusivity of oxygen within the soil environment strongly influences the balance between nitrification and denitrification with the latter favored under anaerobic conditions when the water-filled pore space is greater than 50% (Ussiri and Lal, 2013). The precise mechanisms and controls involved are still the subject of much debate (Butterbach-Bahl et al., 2013). Nitrification is favored by increasing the availability of NH_4^+ at moderate pH and in well-aerated soils, but declines as soils become very dry. The temperature response of nitrification is approximately bell shaped with an optimum between 20 and 35°C (Avrahami et al., 2003; Parton et al., 2001). Denitrification is generally favored by high availability of labile C as a source of energy and of NO_3^- as an electron acceptor. It is favored in poorly aerated soils and exhibits a response to temperature similar to that of nitrification, but can have a higher temperature maximum (Šimek and Cooper, 2002; Strong and Fillery, 2002). Soil moisture deficit commonly associated with different global warming scenarios, reduced the activity of nitrifying bacteria by slowing diffusion of substrate supply and through cytoplasmic dehydration (Stark and Firestone, 1995).

Nitrification and denitrification both result in the release of nitrous oxide (N_2O), a powerful greenhouse gas with a global warming potential of nearly 300 times that of CO_2 over a 100-year time period (Solomon et al., 2007). While fertilizer N rate is the strongest predictor of N_2O emissions from soils (Albanito et al., 2017), environmental factors such as soil moisture, temperature, partial pressure of oxygen, available organic carbon, and soil C/N ratio are strong influencers of emission rates (Stehfest and Bouwman, 2006). Given the temperature sensitivity of processes such as denitrification, climate change-induced soil warming is likely to have a strong positive effect on N_2O emissions (Butterbach-Bahl et al., 2013). In well-drained soils, the higher the soil organic matter content, generally the higher the potential emissions of N_2O with rates found to be an order of magnitude greater in cultivated organic compared to mineral soils (Velthof and Oenema, 1995). Thus, any climate-induced change in soil organic C and C:N ratio will significantly influence soil N_2O and other greenhouse gas emissions.

Szukics et al. (2010) found that increasing soil temperature from 5 to 25°C stimulated N cycling by inducing the activity of microorganisms responsible for nitrification and denitrification. The nitrification rate and NO_3^- concentration increased most rapidly at the 55% water content. In the 70% water content soils, the NO_3^- pool was increasingly depleted as soil temperature increased and was almost completely depleted at 25°C. The depletion in hot, wet soils was attributed to complete denitrification and the release of nitrogen gases into the atmosphere. Although, uncertainty still remain regarding the dynamics of N_2O and extent of its emission from the soil as function of temperatures under field conditions (Butterbach-Bahl et al., 2013), increasing temperatures are going to increase soil emission of N_2O—a positive feedback to global warming (Butterbach-Bahl and Dannenmann, 2011; Veraart et al., 2011). It seems that denitrification is extremely sensitive to increasing temperatures.

Ammonia Volatilization

Globally, the percentage of N loss as NH_3 ranged from 0.9% to 64% (a mean of 17.6%) of the applied N but the percentage was the highest in South Asia (30.7%). The amount of NH_3-N volatilized per cropping season in South Asia averaged 37.5 kg Nha^{-1}; global average was 19.1 kg Nha^{-1} (Pan et al., 2016). Most NH_3 emissions result from agricultural production and are expected to be extremely climate sensitive. Temperature and moisture play a key role in determining the concentration of NH_3 in equilibrium with surface pools and hence in defining net NH_3 fluxes on diurnal to annual scales. According to solubility and dissociation thermodynamics, NH_3 volatilization potential follows a Q_{10} (the relative increase over a range of 10°C) of 3–4 so that it nearly doubles every 5°C (Sutton et al., 2013). However, due to the interaction between temperature and moisture and other factors (e.g., stomatal opening, growth dilution of NH_x pools, soil infiltration, and decomposition rates), the temperature dependence of NH_3 emission may not always follow the thermodynamic response. Therefore, Sutton et al. (2013) have proposed that a reduced Q_{10} of 2 (1.5–3) may be applied for terrestrial volatilization sources. Riddick et al. (2016) incorporated climate dependency in a global model to enable it simulate N pathways from manure and fertilizer added to the surface of the land under changing climatic conditions and found that the pathways of N added to the land are highly spatially and temporally heterogeneous. The model predicted that spatial and temporal variability in the amount of NH_3 volatilized from agricultural fertilizers and manures ranged from 14% in industrialized countries to 22% in developing countries. As a result of temperature dependency, NH_3 volatilization was observed to be the highest in the tropics with the largest emissions in India and China where application of fertilizer and manure is high.

The Interaction Between the C Cycle and the N Cycle

Soils are integral parts of several nutrient cycles. The two that are the most important from the perspective of soils and climate change interactions are the C and N cycles because both these elements are important components of soil organic matter. In the context of climate change, the interactions between the N cycle, the C cycle, and climate are expected to become an increasingly important determinant of the earth system (Gruber and Galloway, 2008). However, adequate emphasis has not been given to these interactions. For example, the C cycle–climate change models generally assumed a strong CO_2 fertilization effect and did not consider N limitation of the terrestrial biosphere. Thus, these models may have overestimated the ability of the terrestrial biosphere to act as a CO_2 sink in the future (Thornton et al., 2009). Using free-air concentration enrichment technology that allows investigation of the effects of rising CO_2 and on field crops under fully open-air conditions at an agronomic scale, Long et al. (2005) could show smaller increases in yields of rice, wheat, maize, and soybean than anticipated from studies in chambers. These findings suggest that projections of global food security are overoptimistic because the fertilization effect of CO_2 is less than that used in many models. Furthermore, N limitation may become more pronounced in some ecosystems as atmospheric CO_2 concentration increases (Luo et al., 2004; Reich et al., 2006a). On the other hand, future increase in temperature may enhance soil N mineralization, thereby counteracting any adverse effects of elevated CO_2 on N availability (Hovenden et al., 2008). Interactions between C:N ratios in plants and soils, increased soil fertility, and microbial activity are also not very well understood and may need to be addressed in climate models.

Nutrient Acquisition

Soil moisture deficit as projected in many global warming scenarios not only impacts crop productivity but also reduces yields through its influence on the availability and transport of soil nutrients. Nutrient diffusion over short distances and the mass flow of water-soluble nutrients over longer distances are adversely affected by soil moisture deficit. Drought alters the composition and activity of soil microbial communities, which determine the C and N transformations that govern soil fertility and nutrient cycling (Schimel et al., 2007). Frequent and/or intense rainfall events associated with some climate change scenarios adversely influence nutrient acquisition by crop plants in agricultural areas with poorly drained soils which may become hypoxic (St. Clair and Lynch, 2010). Hypoxia can result in nutrient deficiency since the active transport of ions into root cells is driven by ATP synthesized through the oxygen-dependent mitochondrial electron transport chain (Atwell and Steer, 1990; Drew, 1988). Under hypoxic conditions, significant losses of N can also occur through denitrification thereby leading to reduced N acquisition by crop plants (Marchner, 1995).

According to Bassirirad (2000), temperature increases in the rhizosphere can also stimulate nutrient acquisition by increasing nutrient uptake via rapid ion diffusion rates and increased root metabolism. But positive effects of warmer temperature on nutrient capture also depend on adequate soil moisture. For example, if under dry conditions higher temperatures result in extreme vapor pressure deficits which triggers stomatal closure (Abbate et al., 2004), nutrient acquisition driven by mass flow will decrease (Cramer et al., 2009). Under soil moisture deficit caused by warmer temperatures nutrient acquisition is slowed down because diffusion pathway to roots becomes longer as ions travel around expanding soil air pockets (Brouder and Volenec, 2008).

Soil Erosion

Every year, 75 billion tons of top soil are lost worldwide to erosion by wind and water, and through agriculture; this costs about US$ 400 billion a year (Montanarella, 2015). In India, water erosion is the major cause of topsoil loss (in 132 million ha) and terrain deformation (in 16.4 million ha) (Misra and Dave, 2013). Climate change is likely to affect soil erosion by water through its effect on rainfall intensity, soil erodability, vegetative cover, and patterns of land use. Pruski and Nearing (2002) found that a change in precipitation amount and intensity had a greater effect on soil erosion and runoff generation than a change in storm frequency. Specifically, a 1% change in precipitation resulted in, on average, a 2.4% change in soil loss, and 2.5% change in runoff if a change in precipitation amount and intensity accounted for all of the change, and resulted in a 0.9% change in soil erosion and 1.3% change in runoff if a change in frequency accounted for all of the change. Although general circulation models still have difficulty simulating the regional distribution of monsoon rainfall, processes driving the monsoon, its seasonal cycle and modes of variability are becoming increasingly clear (Turner and Annamalai, 2012). In South Asia, most monsoon depressions, which represent almost all extreme events (rainfall $>100\,\mathrm{mm\,d^{-1}}$), form over the warm waters of the northern Bay of Bengal and move west–northwest along the monsoon trough. Analyzing daily gridded rainfall observations reveal a decrease in moderate rainfall events (of 5–100 $\mathrm{mm\,d^{-1}}$) (Rajeevan et al., 2006), but an increase in extreme events over central India since the 1950s (Gautam et al., 2009). These extreme rainfall events should lead to increased erosion of soil.

García-Fayos and Bochet (2009) found strong correlations between climate change and soil erosion and negative impacts on aggregate stability, bulk density, water-holding capacity, pH, organic matter content, total N, and soluble P in the soil. Work of Zhang et al. (2004b) shows that adoption of conservation tillage and no-till systems can help to combat to a large extent soil loss under different expected climate change scenarios. Adoption of conservation agricultural practices results an increase in organic concentration at surface soil and led to reduction in soil erosion (Lal, 2015).

Soil Acidity and Salinity

Acidification is a natural process that usually occurs as a consequence of leaching of basic cations as well as nitrate in high-rainfall areas. Substantial increase in rainfall may lead to increased leaching and cause acidification, whereas decline in rainfall should reduce intensity and extent of acidification. Soils in subhumid, arid, and subarid climate zones can potentially be influenced in terms of acidification by climate change from leaching conditions to evaporative conditions. In general, warm temperatures and reduction in total rainfall due to anticipated climate change scenarios in wheat growing regions in South Asia should not pose a serious soil acidification threat. However, excessive use of urea to supply N to rice and wheat and that too not in a balanced proportion with P and K can lead to soil acidification.

Increasing salinization of soil is associated with changes in the hydrology of catchments as a consequence of changes in land use and climate. The changes in hydrology of the landscape have led to rises in water tables and the increasing mobilization of salts stored in the landscape (Charman and Wooldridge, 2007). Localized changes in rainfall, plant growth, deep drainage, and seepage flows as caused by climate change have the potential to change the hydrology of catchments. However, the degree to which the hydrology of catchments is transformed by changes in rainfall, evapotranspiration, runoff, and deep drainage will vary depending on the characteristics of individual catchments. Although accurate prediction of the impacts of climate change on local salinity requires some local hydrological modeling of individual catchments, some general trends can probably be suggested. Reduced rainfall and increased evapotranspiration may lead to insufficient water flows to keep the catchment flushed, and evaporation and drying of some wetter areas may result in some outbreaks of salinity.

In semiarid regions in South Asia, wheat is mostly grown under irrigation conditions. In irrigated agriculture, salts come to the fields with the irrigation water and, when not leached out, accumulate in the soil profile through evaporative water loss, a process that removes the soil water but concentrates salts in the topsoil (secondary salinization). Thus, regions, which mostly depend on irrigation for crop production, are already vulnerable to soil salinity (Brady and Weil, 2008) and will be even more affected when temperatures will rise under climate change. Content of water-soluble Na^+ ions in soil layers rises rapidly with increase in temperature, but is not so closely related to air humidity. A rise in soil temperature significantly enhances accumulation of salinity in the soil, especially in the 10–15 cm soil layer (Guo et al., 2011). Rainstorms clearly create an effect of desalinization (Zhang et al., 2004a).

According to FAO (2002), about 1%–2% of the irrigated areas in dryland regions become unsuitable for crop production for some fraction of the year due to salinity. Appropriate soil and water management practices can help mitigate soil salinity. Recently, it has been demonstrated that conservation agriculture practices consisting of reduced tillage, residue retention, and appropriate rotation, can influence the location and accumulation of salts by reducing evaporation and upward salt transport in the soil (Brady and Weil, 2008).

5. POSSIBLE EFFECTS OF CLIMATE CHANGE-DRIVEN SOIL PROCESSES ON WHEAT CULTIVATION IN SOUTH ASIA

In the decades to come, although wheat growing season in South Asia is projected to experience warmer temperatures coupled with reduced precipitation, there are a number of reasons why climate change may influence wheat yields both positively and negatively. An increase in temperature will shorten the phenological phases which in turn will reduce the time available for resource capture and hence potential yield. A simultaneous anticipated decrease in rainfall will reduce water availability, particularly if wheat is grown in rainfed areas, thereby leading to reduced wheat grain yield. Mitchell et al. (1993) observed significant increases in wheat yields from a CO_2 doubling at optimum temperature but high CO_2 did not make up for yield losses when plants were grown at high temperatures that caused stress and a shortening of the grain-filling period. Additional available C under an elevated CO_2 climate will create an initial yield increase, because of increased efficiency of use of light, water, N, and P (Barrett and Gifford, 1999; Drake et al., 1997; Gifford et al., 2000) in dry environments reduced water use and water-use efficiency because of lower soil water availability and the shortened growth periods due to accelerated phenology will reduce yields. In dry environments with nutrient limitations, the C-fertilization effect on rainfed wheat has been considered small (Amthor, 2001).

Although, irrigated wheat, which occupies most of the area in South Asia, is not likely to exhibit effects of reduced water, it is not an easy task to distinguish the role of climate change-driven soil processes from the warming-induced effects, such as shortening of the phenological phases, on the performance of wheat crop. Factors limiting crop responses to climate may include plant adaptation to CO_2, source–sink relationships, nutrient acquisition, pest–crop interactions, and site-specific characteristics as well as changes in soil processes such as C and N mineralization, and nitrification–denitrification.

Elevated CO_2 levels decrease stomatal opening and transpirational loss resulting in an increase in water-use efficiency in many plants. Doubling atmospheric CO_2 has been shown to reduce seasonal evapotranspiration by 8% in wheat grown under day/night temperatures of 28/18°C (Hatfield, 2011). Evapotranspiration rates are temperature dependent, which means the water benefits of increased atmospheric CO_2 could be reduced or lost in areas where temperatures also rise (Brevik, 2012). Scale is an important consideration, as the larger the scale, the greater the complexity of interacting variables such that the benefits of elevated CO_2 on water use at the leaf level may be offset by an increase in leaf area index at the canopy and landscape levels (Field et al., 1995).

Soil moisture and temperature are primary determinants of nutrient availability and root growth and development so that carbon allocation to roots governs nutrient acquisition. Thus it is reasonable to expect that process outcomes will be reflective of the changed climate (Brouder and Volenec, 2008). Several crop modeling studies suggest that climate change impacts on nutrient use efficiency will be primarily affected through direct impacts on root surface area. Presence of nutrients in soil solution is controlled by adsorption/desorption, mineralization/immobilization, fertilizer application, temperature, pH, soil moisture, and solution ionic strength. Increased temperature may increase process rates; increased CO_2 may enhance root exudates that alter buffering power, enhance fine root growth and turnover; changes in solution ionic strength caused by changes in rainfall patterns may enhance or depress different soil processes. Increased temperature may enhance volatilization of surface-applied N fertilizers like urea whereas changes in rainfall patterns may enhance or depress volatilization and leaching (Brouder and Volenec, 2008). According to Pendall et al. (2004), increased CO_2 may not exert a significant direct effect on N mineralization per se but associated warming can cause increased N mineralization, leading to increased solution-phase N.

Nutrient movement in soil is governed by mass flow and diffusion. With adequate soil moisture levels as found under irrigated wheat, soil warming will increase rates of ion diffusion and transpiration-driven mass flow of nutrients. But in rainfed wheat, heat-driven evapotranspiration that results in soil moisture deficits will slow ion diffusion. High temperatures that result in extreme vapor pressure deficits may reduce mass flow of nutrients by triggering stomatal closure. Nutrient uptake as governed by root morphology and architecture is controlled by length, diameter, surface area, branching and spatial distribution, distance between roots, root hairs, and specialized structures (Brouder and Volenec, 2008).

Climate change may strongly influence solution concentrations of N as it is controlled by a number of microbiological processes. Pendall et al. (2004) reviewed the available information and concluded that increased CO_2 may not exert a significant direct effect on N mineralization per se but associated warming can cause increased N mineralization, leading to increased solution-phase N. It has been speculated that soil C pool size will not change because increased soil respiration and decomposition caused by soil warming will be moderated by the increased C supply below ground (Kirschbaum, 2000). But interactive and indirect effects of water and soil nutrient availability may lead to unexpected outcomes as there exist uncertainties in understanding of key feedback processes (Pendall et al., 2004).

The ability of soils to support and sustain agriculture under climate change conditions is highly variable. Jaramillo-Velastegu´ı (2011) confirmed significant interactions between the properties of 10 soil orders and atmospheric CO_2 level in the physiology and growth of the C3 grass *Festuca arundinacea*. Only a few fertile soils were able to increase plant productivity with elevated CO_2. Most other soils belonging to different orders presented mineral deficiencies and imbalances that restricted plant growth. These reductions occurred together with dilution or accumulation of minerals and carbohydrates in the leaf under elevated CO_2. In order to mitigate the effects on wheat cropping in South Asia, which may arise from climate change, it will become necessary for farmers to pay closer attention to soil structure. With longer periods of hotter and drier weather and spells with greater rainfall, the ability of the soil to buffer these events may be critical for soil and yield preservation. With studies on global climate change soil processes mediated effects on wheat in South Asia remaining relatively sparse, still only generalized contributions of these effects can be made to the expected overall effects.

6. EFFECT OF CLIMATE CHANGE ON IRRIGATION WATER REQUIREMENT OF WHEAT IN SOUTH ASIA

In South Asia, large but poorly documented area under wheat is irrigated; in India, the largest wheat producing country in the region, only 13% of the total wheat area is rainfed (Aggarwal et al., 2008). Since irrigation prevents effects of warming on water stress and greater transpiration rates help to cool canopies and prevent losses related to direct temperature damage, irrigated systems are generally less harmed than rainfed systems by increasing warming (Lobell and Gourdji, 2012). Besides direct impacts of climate change on crop production, there is concern about future agricultural water requirements vis-à-vis water availability under the combined effects of climate change, growing population demands, and competition from other economic sectors. Studies carried out to determine levels of regional and global water availability over the 21st century (Arnell, 2004; Vorosmarty et al., 2000) indicate that climate change is likely to increase water scarcity around the globe, particularly in regions already facing it. Agricultural irrigation demand in arid and semiarid regions of Asia is estimated to increase by at least 10% for an increase in temperature of 1°C (Fischer et al., 2002; Liu, 2002). According to Sivakumar and Stefanski (2011), efforts to offset declining surface water availability due to increasing variability in rainfall patterns is going to be hampered by the fact that groundwater recharge will decrease considerably in some already water-stressed regions, where vulnerability is often exacerbated by the rapid increase in population and water demand.

Very few studies have specifically addressed future changes in irrigation water for agriculture. Döll (2002) used a global irrigation model developed by Döll and Siebert (2001) by integrating simplified agroecological and hydrological approaches to investigate impacts of climate change and variability on agricultural water irrigation demand by comparing the impacts of current and future climate on irrigated cropland. It was found that changes in precipitation, combined with increases in evaporative demands will increase the need for irrigation worldwide by 5%–8% by 2070; larger impacts, about +15%, were projected for Southeast Asia and the Indian subcontinent.

As many interactive processes determine the dynamics of crop production beyond agroclimatic conditions (Fischer et al., 2005), Fischer et al. (2007) carried out a detailed study to improve, within a coherent agroecological zone framework, estimates of irrigation water requirements under current and future decades brought about by changes in both climate and socioeconomic conditions. Analysis of the impacts of climate change on net irrigation water requirements, gross agricultural water withdrawals for irrigation, and renewable water resources revealed that higher temperatures and altered precipitation regimes determined the net irrigation water requirements in two distinct ways. First, by affecting crop evapotranspiration rates, and thus crop water demand; and second, by modifying the duration over which a crop could be grown and irrigated at a given location. In 2080, net irrigation requirements from climate change increase, in relative terms, will be significantly more in developed than in developing regions. The time evolution of net water requirements indicated a smooth transition patterns with gradual increases in each decade. Exceptions will be the Indian subcontinent for which a small decrease in net irrigation water requirements up to 2040 was projected. Low levels of warming earlier in the century, combined with increased precipitation signals, may improve crop water balances before 2050. After 2050, temperature increases are likely to be strong enough to increase water deficits—and thus irrigation requirements of crops—regardless of changes in precipitation patterns. Also, before 2050 CO_2 concentrations may contribute to lower crop water demands over and above increases caused by warmer temperatures; after 2050, the temperature signal would overcome these positive CO_2 effects (Fischer et al., 2007).

7. NUTRIENT MANAGEMENT IN WHEAT IN EMERGING CLIMATE CHANGE SCENARIOS

With any potential changes in agricultural productivity come a potential for associated changes in crop nutrient use. Current nutrient management recommendations for wheat are based on an understanding of crop-specific needs for achieving expected yields and soil-specific nutrient supply characteristics. What needs to be known is to what extent does our existing knowledge remain useful under a changed climate? This question can be best addressed though an assessment of the potential for climate change factors to influence the physiological efficiency of nutrient use within the plant and to alter the availability of nutrients in soil and their transport through soil and across root membranes (Brouder and Volenec, 2008).

Increased N use efficiency has been observed in response to increased CO_2 level in the atmosphere (Drake et al., 1997). Fangmeier et al. (1999) could also record high nutrient retrieval and nutrient utilization in elevated CO_2 concentration in the atmosphere in field-grown wheat. But with increased N use efficiency under elevated CO_2, N yield in cereals does not automatically increase (Kimball et al., 2002) because of the decrease in plant N concentration which is caused by the effect of dilution due to the more rapid growth under elevated CO_2 or due to changes occurring at the level of the photosynthetic apparatus (Fuhrer, 2003). In contrast to elevated CO_2, warming tends to reduce plant N use efficiency due to increased sink limitation with increasing temperature, especially in plants with reproductive sinks (Reddy et al., 1991). In a recent study, Lam et al. (2012) observed that irrespective of CO_2 level in the atmosphere, fertilizer N recovery in wheat was higher under supplementary irrigation than rainfed conditions. Thus fertilizer N needs of wheat under future CO_2 environments will be high provided it is irrigated or grown in high rainfall zones rather than in hot and dry climates. And fertilizer N application rate in a semiarid wheat cropping systems will need to be increased in proportion to the yield gains expected under future CO_2 environments to avoid a progressive decline in soil N.

Depending upon whether wheat plants will be bigger, smaller, or similar in size when compared with today's specimens, their nutrient content and physiological efficiency will be scaled according to size. To date, no conclusive evidence has been obtained that physiological efficiency in wheat is altered in high CO_2 environments (Long et al., 2006). Nutrient stress has the potential to reduce growth stimulation by elevated CO_2 (Campbell and Sage, 2006; Lynch and St Clair, 2004). Based on an understanding of the physiological efficiency that is specific to the crop and of the utilization efficiency that is specific to the unique combination of crop and soil, nutrient recommendations for wheat under changed climate will operate on the same premise as current recommendations. Simple, empirical models will continue to be used to translate this information from theory into practice. Thus information pertaining to current soil fertility/plant nutrition recommendations will remain viable irrespective of climate change (Brouder and Volenec, 2008).

Many existing recommendations for sustainable management of relatively immobile nutrients like P and K in wheat are based on the tenet of nutrient replacement. In case wheat plants produced under climate change are simply bigger, but otherwise the same in their gross nutrient content per unit biomass, then the current nutrient balance calculations for fertilizer recommendations will remain applicable. In crop species like wheat and rice that have been extensively improved for agriculture, nutrient concentrations, especially in grain, can be relatively constant when yields are not limited by other factors. For example, Dobermann et al. (1996) observed that K concentration in grains of modern varieties of irrigated rice grown in the Philippines, Indonesia, Vietnam, China, and India were fairly constant across environments.

High-input systems with adequate fertilizer use should be more sensitive to weather changes due to lack of other limiting factors (Schlenker and Lobell, 2010). Also, high-input systems will be better able to take advantage of CO_2 fertilization in C3 crops while maintaining nutritional quality (Ainsworth and Long, 2005). For low-fertility systems with minimal fertilizers, atmospheric CO_2 should help to maintain biomass production under drought conditions, but higher CO_2 is more likely to decrease protein levels without additional N inputs into the system (Taub et al., 2008). As large area under wheat in South Asia can be classified as high-input systems to which substantial amount of fertilizers are applied, it can be expected that these systems will be hard hit by emerging climate change scenarios.

At the system level, warmer conditions stimulate soil N availability through higher rates of mineralization. It may lead to increased productivity (Parton et al., 1995), but also to higher N losses from the system, particularly if N demand by the plant is not synchronized with N supply (Fuhrer, 2003). Therefore, ideal solution for management of fertilizer N in wheat in South Asia seems to be the need-based and site-specific nutrient management. Shifting nutrient management in wheat from blanket recommendations which are developed for large tracts to site-specific nutrient management, is also important because agricultural fields in the South Asian countries are typically small with high spatial variability in management practices, inherent soil fertility, crop residue management, historical fertilizer use, input of organic materials, fertilizer application method and schedule, and resources available to a farmer. Jat et al. (2014) have described the recently introduced site-specific nutrient management strategies for wheat in South Asia that take into account field-to-field variability and can help increase fertilizer use efficiency more than that achieved by following blanket fertilizer recommendations. Site-specific and need-based nitrogen management strategies based on gadgets like optical sensors, chlorophyll meters, and leaf color charts as being developed for wheat in South Asia (Bijay-Singh, 2014; Bijay-Singh et al., 2011, 2013, 2017; Jat et al., 2014; Varinderpal-Singh et al., 2010, 2012, 2014, 2017) should help formulate fertilizer management practices under changing climates in the decades to come.

8. CLIMATE CHANGE ADAPTATION OF WHEAT GROWN FOLLOWING CONSERVATION AGRICULTURE PRACTICES

In South Asia, the adoption of no-till practices by farmers has occurred mainly in the wheat crop. In the wheat–rice cropping system extensively followed in the Indo-Gangetic plains across India, Pakistan, Nepal, and Bangladesh, on more than 5 million ha is under adoption of no-till wheat, but only marginal adoption of permanent no-till systems and full conservation agriculture principles (Hobbs et al., 2008). This is because all rice are grown under some form of tillage system. Conservation agriculture practices help farmer to sow wheat in time because tillage takes too much time resulting in delayed seeding and yield loss of the wheat crop after rice (Hobbs et al., 2008; Hobbs and Gupta, 2003). The uptake of no-till wheat has been rapid in the north-western India and Pakistan which are relatively better endowed with respect to irrigation and mechanization and where the size of holdings is relatively large compared to the eastern Indo-Gangetic plain (Derpsch and Friedrich, 2009). Crop residue management has long been relatively neglected in South Asia but has recently received increased attention in the quest for sustainable agriculture and improved soil health (Bijay-Singh et al., 2008; Dawe et al., 2003; Mohanty et al., 2007; Yadvinder-Singh et al., 2005). There are reports on overall soil health improvement under conservation tillage. Gathala et al. (2011) observed gradual improvement in soil physical properties under zero tillage resulting in high wheat yield in a 7 years rice–wheat rotation in north-western India. Under zero tillage direct seeding, almost double least-limiting water range was observed than under conventional system. Jat et al. (2015) also found higher wheat yield in no-till flat system with simultaneous improvement in soil biological properties in north-western India than in permanent bed system under maize–wheat cropping system. In permanent raised bed maize–wheat system, residue retention was an integral part to maintain productivity in scanty rainfall years as well as mulch with *Sesbania*, *Jatropha*, and *Brassica* proved to be beneficial in producing higher yield than in the no mulch system. Improvement of soil organic C, soil physical, and biological properties under maize–wheat–mungbean system in inceptisols of north-western India was also reported by Parihar et al. (2016). Surface soils (0–15 cm) under permanent bed maize–wheat–mung bean system recorded the highest organic C content compared to conventional maize–mustard–mung bean system. Powlson et al. (2016) conducted a meta-analysis of soil organic C stock changes under conservation agriculture practices in sub-Saharan Africa and Indo-Gangetic plain and found that the annual increase in soil organic C stock was between 0.28–0.96 and 0.16–0.49 Mg $Cha^{-1}year^{-1}$ as compared to conventional practices, respectively. Depending on the agroecological region and management practices, conservation agriculture can increase C sequestration in soil at a rate ranging from about 0.2 to 1.0 tha^{-1} $year^{-1}$ (Jat et al., 2016). After 7 years of continuous conservation agriculture-based practices in the eastern Indo-Gangetic plain, crop rotation consisting of zero-till direct-seeded rice and zero-till wheat with residue retention increased soil organic C by 4.7 tha^{-1} at 0–60 cm soil depth as compared to conventional rice–wheat system, which resulted in a decrease in soil organic C by 0.9 tha^{-1} (Sapkota et al., 2017). Jat et al. (2009) evaluated the effect of precision land leveling and zero tillage on water use, productivity, and soil physical quality in rice–wheat rotation and recorded higher wheat yield under zero tillage than under conventional system. Improvements in soil physical properties and water use were also observed under precision land leveling and double zero tillage situations under rice–wheat rotation. Effect of different tillage systems on crop production, water-use efficiency, economic profitability, and soil physical quality in maize–wheat cropping was studied by Jat et al. (2013). Significantly higher wheat yield was observed under permanent raised bed system than under conventional tilled system. Soil physical properties and water-use efficiency were improved under conservation agriculture-based systems. Paustian et al. (2016) reported that a variety of management practices and technologies including conservation agriculture are known to reduce emissions and promote C sequestration in soil, most of which also provide environmental cobenefits. Recently, with significant developments in machinery, which allow combining the stubble mulching and seed drilling functions (Sidhu et al., 2007), an increasing trend is being observed in the wheat–rice system toward retaining rice crop residues in wheat sown with minimum tillage thereby moving these wheat-based systems toward more complete models of conservation agriculture.

Lesser extremes of soil temperatures, better retention of soil moisture, reduced vulnerability to effects of drought and lesser erosion as compared to the conventional tillage systems represent a managed adaptation of wheat cropping in conservation agricultural systems to climate change effects. The conservation agricultural systems have a higher adaptability to climate change because of the higher effective rainfall due to higher infiltration and therefore minimum flooding and soil erosion as well as greater soil moisture-holding capacity than the conventional systems even in irrigated wheat crop (Kassam et al., 2009). Soil moisture conditions in rooting zones during growing seasons under conservation agriculture are better than under both minimum and conventional tillage. Thus, conservation agriculture has advantage over tillage agriculture in terms of the greater soil moisture-holding capacity and duration of plant available soil moisture. In South Asia, wheat grown following conservation agriculture practices can continue toward maturity for longer than those under conventional tillage. Also, the period in which available nutrients can be taken up by plants is extended, increasing the efficiency of use. Availability of soil moisture in greater volume and for longer duration to plants (between the field capacity and wilting point of soil) is bound to have significant positive outcomes both for farming stability and profitability. The range of pore sizes which achieves this also implies the presence of larger pores which contribute to through flow of incident rainwater or applied irrigation water down to the groundwater (Shaxson et al., 2008). Landers (2007) measured a six-fold difference between infiltration rates under conservation agriculture systems and traditional tillage. Improved growing season moisture regime and soil storage of water and nutrients helps crops under conservation agriculture require less fertilizer. The adoption of zero tillage and retaining rice straw on the soil surface under wheat–rice system as it is practiced in Indo-Gangetic plains of South Asia alters the N demand of the wheat crop due to changes in soil temperature and soil moisture under rice straw mulch, which in turn affect microbial transformations of N. Residue retention also leads to increase in soil organic matter which can induce changes in nutrient transformations in the soil as well as improvement in soil physical properties (Verma and Bhagat, 1992). Also, in soils of good porosity, anoxic zones hardly have time to form in the root zone, thus avoiding problems of the reduction of nitrate to nitrite ions in the soil solution (Flaig et al., 1977).

Good mulch cover under conservation agriculture buffers temperatures at the soil surface which otherwise are capable of harming plant tissue at the soil/atmosphere interface, thus minimizing a potential cause of limitation of yields. Mulch also protects the soil surface from direct impact by high-energy raindrops and thus prevents surface sealing and maintains infiltration capacity of the soil. At the same time the mulch minimizes soil evaporation (Kassam et al., 2009). It thus seems that under climate changing scenarios emerging under South Asian conditions, wheat cropping following conservation agriculture principles will outperform the crops grown under conventional tillage. A recent study by Aryal et al. (2016) in north-western

India showed that wheat sown under conservation agriculture can cope better with extreme climates particularly untimely excess rainfall than conventional wheat. Conservation agriculture-based wheat produced higher average yield than conventional wheat during both bad and normal years (Fig. 4); the difference was two-fold greater during the bad year (16% vs 8%).

One of the major long-term productivity benefits of conservation agriculture practices would be to reverse the widespread, chronic soil degradation (Lal, 2004) that threatens yields in intensive wheat-cropping systems like those of the Indo-Gangetic Plains in South Asia. That no-till increases soil organic C is because it inhibits microbial activity which slows decomposition (Lupwayi et al., 1999, 2004). Increasing organic matter levels also increase nutrient release and biological activity. For example, Wright and Hons (2005) concluded that no tillage and increased cropping intensity improved soil fertility by increasing soil organic matter and potential nutrient supply to crops. Using IPCC methodology, Grace et al. (2012) assessed the impact of a change to no-till made for wheat-based production systems in the Indo-Gangetic Plain, but observed that calculated annual rates of soil

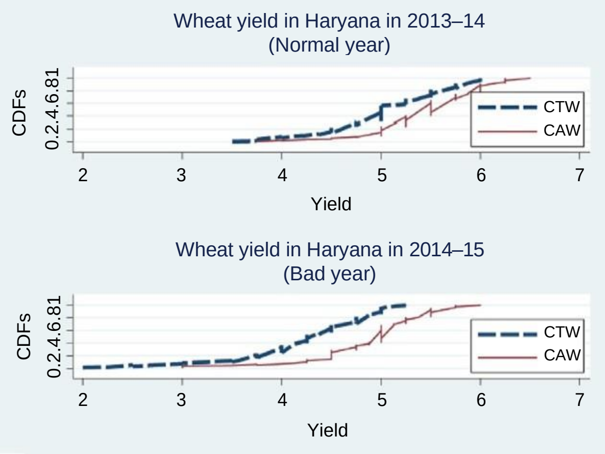

Fig. 4 Stochastic dominance analysis of the wheat yield difference between conventional wheat (CTW) and conservation agriculture-based wheat (CAW) in a normal and bad year in the Haryana state in north-western India. Stochastic dominance analysis allowed comparison of the cumulative distribution functions (CDFs) of wheat yield between CAW and CTW for the normal and bad year separately. *Source: Aryal, J.P., Sapkota, T.B., Stirling, C.M., Jat, M.L., Jat, H.S., Rai, M., Mittal, S., Sutaliya, J.M., 2016. Conservation agriculture-based wheat production better copes with extreme climate events than conventional tillage-based systems: a case of untimely excess rainfall in Haryana, India. Agri. Ecosyst. Environ. 233, 325–335.*

organic C accumulation under no-till were not large. These were in the range 0.2–0t Cha^{-1} and were broadly consistent with annual rates measured in other regions of the world (Stockmann et al., 2013; Virto et al., 2012). However, several studies suggest that the effects of zero-till on C sequestration have been over estimated (e.g., Powlson et al., 2014), not least due to methodological errors. Apparent changes in soil C sequestration under zero tillage result from an altered depth distribution with a greater amount of C near the soil surface where sampling has been concentrated. Nevertheless, the high concentration of organic C near the surface in no-till is generally beneficial for soil properties that often translate into improved crop growth. Powlson et al. (2014) concluded that while no-till is beneficial for soil quality and adaptation of agriculture to climate change, its role in mitigation of global warming has been overstated.

Wheat cropping following conservation tillage may lead to reduced soil losses via erosion. No studies have been conducted in South Asia to support this, possibly because fields are leveled in the Indo-Gangetic plain. Nevertheless, Zhang et al. (2004b) reported that under the assumed climate change at Oklahoma in United States, predicted average soil loss under conventional tillage was about 2.6 times that under conservation tillage and 29 times that under no-till. From the same region, Zhang and Nearing (2005) predicted that the average annual soil loss in the tillage systems other than no-till in 2077–2099, compared with historical climate (1950–1999) increased by 18%–30% for A2a and remained similar for B2a SRES emission scenarios.

9. WHEAT PRODUCTIVITY IN A CHANGING CLIMATE IN SOUTH ASIA

Changes in productivity of wheat in South Asia will be the result of direct effects of changes in atmospheric CO_2, temperature, and precipitation at the plant level, or indirect effects at the system level, for instance, through shifts in nutrient cycling, soil physical environment, crop–weed interactions, insect pest occurrence, and plant diseases. To determine the impacts of climate change in agriculture coupling crop simulation models to predicted future climate scenarios is the commonly used approach. Ortiz et al. (2008) used the megaenvironment (ME) zonation to classify wheat growing regions into relatively homogenous environments. Two main wheat environments have been recognized in the Indo-Gangetic plain in South Asia which account for more than 15% of the global production.

Megaenvironment 1(ME-1) is a favorable, irrigated, low rainfall environment with high yield potential and it covers wheat growing areas in north and north-western India, Pakistan, and Afghanistan. Wheat grown in eastern and central India and Bangladesh has been classified as megaenvironment 5 (ME-5), which is a heat stressed environment (early and late season heat stress) with available irrigation. These two major wheat megaenvironments in South Asia have been differentiated on the basis of the coolest quarter minimum temperature ranges (3–11°C for ME-1 and 11–16°C for ME-5). The future scenario worked on the basis of a doubling of CO_2 using a CCM3 model (Govindasamy et al., 2003) and downscaled to a 30-arc-second resolution as part of the Worldclim dataset (Hijmans et al., 2004) revealed a 51% decrease of the most favorable and high yielding ME-1 area due to heat stress, thereby leading to likely yield losses of the wheat grain harvest. According to Joshi et al. (2007), a significant part of wheat in South Asia is considered to be under heat stress out of which the majority is present in India. The most heat stressed locations of are eastern Gangetic plains, central and peninsular India, and Bangladesh, whereas it is moderate in north western parts of Indo-Gangetic plain (Chatrath et al., 2007). Gangadhar Rao and Sinha (1994) and Saini and Nanda (1986) observed that wheat yields in India decreased due to the adverse effects of temperature during grain filling and maturity stages of the growth.

Simulations carried out by Aggarwal and Kalra (1994) revealed that at CO_2 level of 425 ppm and 1°C rise in mean temperature during wheat season in India will lead to small increase in yield of irrigated wheat where current yields are higher than 3.5 tha^{-1}. An increase of 2°C in temperature reduced potential yields in most places. The magnitude was, however, less at places with low potential productivity. In subtropical (above 23°N) environments there was a small decrease in potential yields (1.5%–5.8%) but in tropical locations the decrease was 17%–18% (Table 5). Irrigated wheat yields increased slightly for latitudes greater than 27°N but were reduced in all other places. At several locations above 27°N, where rainfed wheat yields were greater than 2 $t\,ha^{-1}$, an increase in yields with climate change was seen. Between 25 and 27°N, although rainfed yields were high, there was a significant decrease due to climate change. These results were closely related to the effects of changed climate on crop duration. Depending upon the magnitude of temperature increase, crop duration, particularly the period up to anthesis was reduced. Revelations similar to those by Aggarwal and Kalra (1994) were made by Aggarwal and Sinha (1993). Wheat production in Pakistan would decline under the emerging climate

Table 5 Percent Change in Grain Yield of Wheat in Different Regions of India in Response to Climate Change Scenarios in Terms of Increase in Mean Temperature by 2 C and CO_2 Concentration in the Air to 425 ppm

	Potential Yields (tha^{21})		Irrigated Yields (tha^{21})		Rainfed Yields (tha^{21})	
	Current	% Change	Current	% Change	Current	% Change
>27°N	6.66	—3.9	4.89	3.7	2.95	28.6
25–27°N	5.84	—1.5	4.78	—4.4	3.34	—7.2
23–25°N	5.86	—5.6	4.18	—10.8	1.17	—19.6
20–23°N	4.18	—18.4	2.29	—18.3	0.51	—11.8
<20°N	3.69	—17.3	2.43	—21.4	0.97	—23.9

Source: Aggarwal, P.K., Kalra, N., 1994. Simulating the Effect of Climatic Factors, Genotype and Management on Productivity of Wheat in India. Indian Agricultural Research Institute, New Delhi, India, p. 156.

change scenarios (Hussain et al., 2005). The decline in the yield of irrigated wheat in the semiarid areas of Pakistan is expected to be in the range of 9%–30% for temperature increases of 1–4°C (Malik et al., 2005). In the mountainous Swat and Chitral districts of Pakistan (average altitudes 960 and 1500 m above sea level, respectively), for projected temperature increases of 1.5 and 3°C wheat yield may decline by 7% and 24%, respectively, in Swat district but may increases by 14% and 23%, respectively, in Chitral district (Hussain and Mudasser, 2007).

Hundal and Kaur (1996) examined the climate change impact on productivity of wheat in north-western India using CERES–wheat (Godwin et al., 1989) crop simulation model and concluded that, if all other climate variables were to remain constant, temperature increase of 1, 2, and 3°C will reduce the grain yield of wheat by 8.1%, 18.7%, and 25.7%, respectively. Lal et al. (1998) also used CERES–wheat and showed an increase in wheat yields due to doubling the CO_2 levels was canceled by a 3°C rise in temperature. Similar conclusions were made by Attri and Rathore (2003). Using CropSyst model, Jalota et al. (2014) projected that in the Indian Punjab, yields of wheat would decrease due to shortening of crop duration after 2020. Evapotranspiration, transpiration, drainage, and irrigation requirement would decrease and soil water evaporation would increase. Aggarwal (2003) developed two scenarios based on IPCC (Houghton et al., 2001) as optimistic (low increase in temperature; high increase in CO_2) and pessimistic (high increase in temperature; low increase in CO_2) scenarios for different years. The results from simulation experiments showed that irrigated wheat yields in north India will not be significantly affected due to direct effect until 2050. It is only in 2070 when the temperature increases are very large, that the crops show large reduction in yield.

Easterling et al. (2007) carried out a meta-analysis of response of yield of wheat grown in tropical regions to climate change using local mean temperature as metric of change. As a part of the IPCC-AR4, this exercise revealed that up to 1.5°C of warming could result in increases in wheat yields. Subsequently yield will decline with increased warming. As several studies of wheat yield projections have been published after IPCC-AR4 including some meta-analyses and summary studies for South Asia (Knox et al., 2012), Challinor et al. (2014) carried out a meta-analysis of impacts based on an update of the IPCC-AR4 climate dataset. Based on 45 datasets for wheat in tropical regions, mean response of wheat was yield reduction to warming beyond 1.5°C. The boots trapped fits to studies indicate robust yield reductions for wheat in tropical regions over most of the temperature range, especially beyond 2°C of local warming. Although there is a general conclusion that the benefits of CO_2 at the global scale will eventually be outweighed by the harm from climate change induced by CO_2 and other greenhouse gases, there is considerable debate about exactly when net impacts will become negative (Lobell and Gourdji, 2012). Based on climate trends for 1980–2008, Lobell et al. (2011) obtained evidence that net global impacts were negative, but the study focused on actual warming rather than just the amount of warming due to greenhouse gases. According to Lobell and Gourdji (2012), a likely scenario in the near term is that warming will slow yield growth by about 1.5% per decade while CO_2 increases will raise yields by roughly the same amount. After 2050, it is likely that benefits due to high CO_2 levels will diminish and climate effects will be larger (Easterling et al., 2007).

An important source of uncertainty in predicting the effects of climate change on wheat is the limited understanding of crop responses to extremely high temperatures (Asseng et al., 2011). Sustained temperature increases over the season will change the duration of the crop development but short episodes of high temperature at critical stages of crop development can impact yield independently of any substantial changes in mean temperature (Wheeler et al., 2000). As crop growth, development, and yield responses to climatic variability are a mixture of linear and nonlinear functions, changes in the mean, variability, and rate of occurrence of extremes in temperature all affect crop processes but not necessarily the same processes (Porter and

Semenov, 2005). Short periods of high temperatures can do disproportionate damage when coinciding with flowering or pollination. Using regional climate model PRECIS and the GLAM crop model under present (1961–90) and future (2071–2100) climate conditions in India, Challinor et al. (2007a) showed that the seasonal mean and short episodes of high temperature at critical stages of crop development are not the main deciding factors for crop yield because the majority of wheat in South Asia is irrigated for extended growing periods. Instead it is the extreme temperatures during critical growth stages, such as on set of senescence, which results in drastic negative effects on the crop yield. Possibly, extreme temperatures during anthesis can induce premature senescence and result in yield loss. Lobell et al. (2012) used 9 years of satellite measurements of wheat growth in northern India to monitor rates of wheat senescence following exposure to temperatures greater than 34°C. A statistically significant acceleration of senescence from extreme heat, above and beyond the effects of increased average temperatures was detected. It was found that crop models underestimate the effects of heat on senescence by as much as 50% for some sowing dates for 2°C rise in mean temperature. This is because onset of senescence is an important limit to grain filling, and therefore grain yields. Thus warming presents an even greater challenge to wheat in South Asia than implied by previous modeling studies. Effectiveness of adaptations will also depend on how well these reduce crop sensitivity to very hot days (Lobell et al., 2012).

An increase in mean temperature can be expected fairly confidently, but the impacts on productivity may depend more on the magnitude and timing of extreme temperatures. Similarly, fresh water availability is critical, but predictability of precipitation is highly uncertain. Also, indirect effects of climate change through pests and diseases have been studied locally but a global or regional assessment is not yet available (Gornall et al., 2010). In case, terminal heat effect in wheat cropping in South Asia is the major cause for yield reduction due to global warming, adverse effects on the crop via climate change-mediated changes in soil processes should not be very important. However, the simulation experiments discussed in this section reveal that when the mean temperature increase will be 2°C or more, wheat crop is going to be adversely affected both by direct effects on plant processes as well as modification of soil processes. Of course, occurrence of extreme temperatures during onset of senescence in wheat will do additional damage.

10. CONCLUSIONS AND RESEARCH NEEDS

South Asia covering 3.3% of the world's land surface area is home to about 25% of the world's population, which continues to grow rapidly, creating an ever greater demand for food grains. Wheat is the second major staple food crop after rice in the region. The task of producing additional quantities of food from the shrinking land resources due to increasing competition for land from the nonagricultural sectors is becoming even more challenging due to the fact that South Asia is among the most vulnerable regions to the impact of climate change. The IPCC projections for South Asia are: 0.5–l.2°C rise in mean annual temperature by 2020, and l.56–5.44°C by 2080, depending upon the scenarios of future develop- ments (Solomon et al., 2007). The absolute amount of precipitation is likely to decrease during December to February, when wheat is grown in northern parts of the region. The assessment of the Fourth Assessment Report of the IPCC (IPCC-AR4) for South Asia still holds in IPCC-AR5 (Hijioka et al., 2014a).

Temperature, precipitation, and enhanced CO_2 level in the atmosphere, the three climate change drivers are not only going to influence growth of crops like wheat directly at the plant level but also through indirect effects at the system level, for instance through changes in properties and processes in soils being used as medium for plant growth, shifts in nutrient cycling, crop–weed interactions, insect pest occurrence, and plant diseases. Several simulation models have projected reduced wheat yields in the emerging climate change scenarios. A meta-analysis based on such studies (Easterling et al., 2007) shows that mean response of wheat was yield reduction to warming beyond 1.5°C and robust yield reductions beyond 2°C of local warming. However, projections of temperature changes with global climate models become increasingly uncertain at scales below roughly 600 horizontal miles and regional changes in precipitation are even more challenging to predict, with estimates becoming highly uncertain at scales below roughly 1200 miles (https://phys.org/news/2016-08-global-climate-easily-downscale-regional.html#jCp). Thus, predicting the impact of anthropogenic climate change on regional scale wheat productivity is not an easy task because along with large uncertainty in regional changes in temperature and precipitation, the impacts on productivity may depend more on the magnitude and timing of extreme temperatures. Occurrence of an extreme heat event around senescence can lead to crop models to underestimate the effects of heat on senescence by as much as 50% for some sowing dates for 2°C rise in mean temperature.

As soils are intricately linked to the atmospheric–climate system through the C, N, and hydrologic cycle, altered climate affects soil processes and properties and in turn productivity of wheat. Although, study of the effects of climate change on soil processes and properties is still nascent, but it is becoming increasingly clear that climate change will impact soil organic matter dynamics, including soil organisms and the multiple soil properties that are tied to organic matter, soil water, and soil erosion. Soil moisture and temperature are primary determinants of nutrient availability and root growth and development so that C allocation to roots governs nutrient acquisition. Warmer conditions stimulate soil N availability through higher rates of mineralization. It may lead to increased productivity but also to higher N losses from the system, particularly if N demand by the plant is not synchronized with N supply. Thus fertilizer management in wheat is also going to be governed by emerging climate change scenarios. Similarly, analysis of the impacts of climate change on net irrigation water requirements, gross agricultural water withdrawals for irrigation, and renewable water resources revealed that higher temperatures and altered precipitation regimes will determine the net irrigation water requirements. The exact direction and magnitude of those impacts will be dependent on the amount of change in atmospheric gases, temperature, and precipitation amounts and patterns.

Very few climate change impact studies directly focus on soils or soil functions. Research specifically aimed at soil functions under climate change is recommended. How climate change will affect the N cycle and, in turn, how the N cycle will affect C sequestration in soils is a major research question. What are the implication for N inputs to meet soil C sequestration targets such as that of the French 4P1000 given C:N stoichiometry? Equally important is the need to understand soil water–CO_2 level–temperature relationships. Knowledge of the response of plants to elevated atmospheric CO_2 given limitations in nutrients like N and P, as well as associated effects on soil organic matter dynamics is a critical need. A better understanding of how soil organisms will respond to climate change is urgently needed because the organisms are incredibly important in a number of soil processes, including the C and N cycles. Since in recent years, there has been a lot of emphasis on achieving climate change mitigation via transforming C into the inert pools in the soil (e.g., through biochar), there is urgent need to define balance between active and inert C pools in soil because the former are critical to nutrient cycling and plant production.

Soil, climate, vegetation, and water are intrinsically linked and as such a meaningful assessment of climate impacts on soil functions requires integrated, holistic modeling studies considering all of these and other elements. Changes in crop yield could readily be linked to impacts on soil organic matter, moisture status, and nutrient cycling. Thus, wherever possible, climate change impacts research not directly focused on soils should incorporate a consideration of possible soil effects. Considerable funding and research effort need to be directed into developing a suite of modeling tools for various soil functions and processes. Studies are not available that consider the impacts of uncertainties in climate prediction and soil process model formulation. Future research into soil functions under climate change should therefore attempt to deal with uncertainty analysis wherever possible. Considerable effort is involved in maintaining long-term experiments in South Asia and elsewhere. Where relevant, these should be used as fully as possible for benchmarking and for guiding new monitoring work to assess climate change impacts on soil functions.

Kirkham (2013) has discussed in details the research needs for agriculture under elevated CO_2 levels expected under the emerging climate change scenarios. Questions that are relevant to soil processes and wheat cropping in South Asia and need to be answered by conducting research in the future are: How do water, aeration, temperature, and mechanical impedance interact with elevated CO_2 levels to affect crop growth? How much is the increase in water-use efficiency and how will irrigation recommendations for wheat change under elevated CO_2? Optimal concentration of CO_2 in the air also needs to be worked out for adequate growth of wheat. The location of soil organic matter within the soil matrix has a much stronger influence on its turnover than its chemical composition both in the context of fertility of soil and climate change mitigation. Stabilized C with long residence times may accumulate in deep soil horizons via continuous transport, temporary immobilization, and microbial processing of dissolved organic C within the soil profile (Kaiser and Kalbitz, 2012) and/or efficient stabilization of root-derived organic matter within the soil matrix (Rasse et al., 2005). As soil C is the centerpiece in the food security/climate change mitigation/ adaptation debate, helping designing options will require substantial investments in data, and models for systematic investigations in soil organic matter/ soil carbon permanence vs climate change in wheat-based cropping systems.

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CHAPTER FIVE

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