Climate Change and Agriculture: Adaptation Strategies and Mitigation Opportunities for Food Security in South Asia and Latin America

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Abstract

During the past two centuries, the world has witnessed a remarkable increase in the atmospheric concentrations of the greenhouse gases (GHGs), namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as a result of human activities after 1750 (preindustrial era). During 1750 the concentrations for these gases were 280 ppm, 715 ppb, and 270 ppb, respectively which increased to 379 ppm, 1774 ppb, and 319 ppb, respectively in 2005. It showed an increase of 0.23, 0.96, and 0.12% annually. The same has further increased to 385 ppm, 1797 ppb, and 322 ppb, respectively in 2008 representing 1.6, 1.2, and 0.9% increase, respectively from 2005 levels at an annual increase of 0.53, 0.43, and 0.31%, annually. Increase in atmospheric CO_2 promotes growth and productivity of plants with C_3 photosynthetic pathway but the increase in temperature, on the other hand, can reduce crop duration, increase crop respiration rates, affect the survival and distribution of pest populations, and may hasten nutrient mineralization in soils, decrease fertilizer-use efficiency, and increase evapotranspiration. The water resources which are already scarce may come under enhanced stress. Thus, the impact of climate change is likely to have a significant influence on agriculture and eventually on the food security and livelihoods of large sections of the urban and rural populations globally. The developing countries, particularly in South Asia and Latin America, with diverse agroclimatic regions, challenging geographies, growing economies, diverse agricultural production systems, and farm typologies are more vulnerable to the effect of climate change due to heavy dependence on agriculture for livelihood. These regions also are demonstrating poor coping mechanisms to adapt to these challenges, and as a result there is evidence of negative impacts on productivity of wheat, rice, and other crops to varying extent depending on agroecologies.

Upscaling of modern technologies such as conservation and climate smart agriculture, judicious utilization of available water for agriculture through microirrigation and water saving technologies, developing multiple stress-tolerant crop cultivars and biotypes through biotechnological tools, restoration of degraded soils and waters,

promoting carbon sequestration through alternate production technologies and land use, and conservation of biodiversity must be promoted at regional and country level to ensure durable food and nutritional security. Reliable early warning system of environmental changes, their spatial and temporal magnitude, coupled with policies to support the diffusion of this information, can help interpret these forecasts in terms of their agronomic and economic implications for the benefit of farmers and to provide agriculture-dependent industries and policymakers with more informed options to support farmers. These countries need to formulate both short-term and long-term policies for improvement, sustenance, and protection of natural resources. There is an urgent need for capacity building through international collaboration in order to develop databases and analysis systems for efficient weather forecasting as well as preparing contingency plans for vulnerable areas. The objectives of this paper are to summarize the available information on adaptation strategies and the mitigation options for climate change to meet the food security in South Asia and Latin America.

1. INTRODUCTION

As per the estimates of the United Nations Census Bureau (UNCB), the present world population has exceeded 7 billion. This increase in population mainly comes from the developing world. The population in South Asia and Latin America has increased by about three times, in Africa by more than three times, and in the world as a whole by more than two times during the past 50 years (Fig. 1).

Of the total world population, only 16% live in developed world (Northern America, Europe, and Oceania), while 84% live in developing world. This figure will be 15 and 85%, respectively by 2020 but the most significant fact will be that 856 million additional people will be living in developing countries as compared to 34 million in developed countries (Hisas, 2011). So far, the increase in food production has matched the phenomenal increase in population growth. During 2010, there were 2208 million tons (MT) of cereals produced (including 651 MT wheat, 672 MT rice, and 844 MT corn), and a further production of 609 MT fruits and 966 MT vegetables (FAOSTAT, 2010). South Asia with a population of 1704 million (Table 1) had 47.3% of its population working in agriculture on 309 million ha of arable land, resulting in a ratio of just 0.1 ha per person. India, while being the largest agricultural producer in South Asia, has irrigation on 35.2% of its agricultural land (http://data.worldbank.org/indicator/AG.LND.IRIG.AG.ZS-2010) and along with other Asian countries produces 40 and 90% of the total wheat and rice production in the world

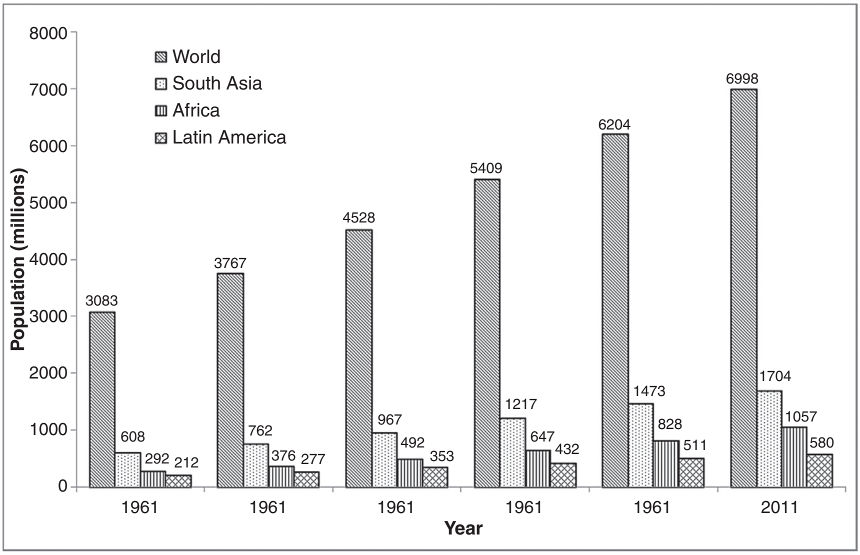

Figure 1 Population (million) of South Asia, Latin America, Africa, and the World from 1961 to 2011. *Source: Modified from FAOSTAT (2014).*

(FAO, 2009a–d). Total cereal, fruit, and vegetable production in South Asia in 2010 is summarized in Table 2.

Out of the total global production, about 66% of the wheat and 84% of the rice is utilized for food, and 82 and 94% of these were consumed in the country of origin (FAO, 2009a). In the case of maize, 12% of the global production is utilized as biofuel (ethanol), 60% as animal feed, and the remaining 28% as food (FAO, 2008).

The cereals invested as animal feed, plus extensive use of pasture, leads to the supply of about 282 MT of meat that is also consumed globally on an annual basis. Of this total, 48% originates from the rainfed mixed farming systems along with 53% of total global milk production.

There are, however, considerable differences in consumption between developing and developed population. The amount of the total food produced should be enough to feed the entire population, however, due to poor distribution system and the inability of the poor to purchase sufficient food, about 15% of the world's population, mainly in the developing countries, is undernourished. In recent years there has been volatility and increase in food prices, and over one billion people still go to bed

Table 1 Population land availability for agriculture in South Asia and Latin America.

		Agricultural population			Land availability (2009), percent agriculture land				
Region	Total population in 2010 (million)	Total (million)	% of total	Total land area (m ha)	Permanent crops	Arabic crops	Pasture	Total	Arable land/ person (ha)
South Asia	1704.1	806.2	47.3	640.0	2.6	33.5	12.2	48.3	0.1
Latin America	590.1	93.2	15.8	2024.1	1.0	7.4	27.3	35.7	0.3
World	6894.8	2619.0	32.3	13003.5	1.2	10.6	25.8	37.6	0.2

Source: From FAOSTAT (2010).

Table 2 Production (MT) of essential food items in South Asia and Latin America in 2010.

Regions	Wheat	Rice	Maize	Cereals (rice milled equivalent)	Fruits	Vegetables
South Asia	111.0	185.7	20.7	277.0	98.2	713.5
Latin America	25.8	24.3	119.7	185.6	107.1	38.4
World	650.9	672.0	844.4	2208.4	609.2	965.6

Source: From FAOSTAT (2010).

undernourished. The underlying causes of the increases in food prices are complex, and include poor harvests due to an increasingly variable climate (drought, flood, etc.); use of food crops as biofuel; higher energy and fertilizer prices; low availability of food stocks per capita; and policies that restrict the movement of cereals and other foods. Ever increasing population and global warming may lead to the future agriculture becoming evermore vulnerable.

The goal of affordable nutritious food for all, and that is being produced in an environmentally sustainable manner is achievable but it will require a new agricultural revolution, with a more rational use of scarce land and water resources, an equitable trade regime, as well as widespread recognition and action on climate change. The trends in population growth suggest that the food production, particularly in developing countries, is unlikely to satisfy future demand under predicted climate change scenarios. In developing countries where agroecosystems are already fragile, investment in agriculture is limited, the land holdings are shrinking, and climate change is predicted to have its most devastating effects.

Particularly vulnerable are regions that are dependent on snow and glacier melt. For example, the "water towers" of the Himalayas and The Andes have been vital sources of water for the Indo-Gangetic Plain (IGP) and the western coast flatlands of South America. Snow-capped mountains play a critical role in downstream water supply by retaining much of the precipitation falling at high elevation as snow, and ice in mountain glaciers, before gradually releasing it over time. Snow accumulations and glaciers therefore act as critical buffers against highly seasonal precipitation and provide water for domestic, agricultural, or industrial use during the dry season, when rainfall is low or absent. This environmental service is often taken for granted, yet projections indicate that it is being threatened by future climate change. With rising temperatures, the snow melts away, and

the snow cover begins to disappear. However, snow melt is initially compensated by melting glaciers higher up in the mountains. When the glaciers finally melt away, it can result in severe water scarcity. A World Bank study (Vergara et al., 2007) indicates that less than 2% of the snow and glacier melt flows east from the Andes, where most of the population lives, the rest flows toward the Amazon, and that the 18 glaciers in the country have already lost 22% of their surface in the last 35 years. The glaciers in The Himalayas are also receding, but possibly because of their higher elevation may be more resilient. A recent study (Immerzeel et al., 2013) concludes that total water flow from the Himalayan ranges may not diminish until at least 2050.

In the future, the availability of good quality water, deteriorating soil health and the climatic abrasions will most significantly impact food production. In general, the projected climate change is expected to have more impact on agriculture in low-latitude regions (between 30 degree N and S of the equator) due to reduced water availability and negative water balance on account of change in precipitation (IPCC, 2007a; FEU-US, 2011). In mid-latitude regions (between 30 and 60 degree N and S) the impact on agriculture will be due to degradation of soil and water resources. Increased global temperature will alter rainfall pattern causing drought and flood and also increase demand for irrigation water thereby affecting water balances.

The growing impact of climate change is coinciding with the growth of the middle class in many developing countries, placing even greater strains on food systems. A study by the McKinsey Institute (Beinhocker et al., 2007) concludes that the middle class in India will expand significantly from 5% of the population in 2005 to 41% in 2025 representing 583 million Indians with increased incomes. A separate study (Mansharamani, 2011) concludes that the rising Indian middle class will reach an inflection point at a per capita GDG of around US$ 5000 and that at that point the country's animal protein consumption takes off, and in turn raising demand for grain to feed livestock. Total expenditure on food in India will increase but will fall as a percent of total expenditure, and over time, move steadily toward branded products.

Similarly, in Latin America the middle class expanded by 50% from 2003 to 2009 to a total of 152 million (Ferreira et al., 2013). The rise of a middle class also changes the distribution and sale of food. In the 1980s, supermarkets represented 10–20% of food sales in Latin America, and by 2000 this share had grown to 50–60%. In one decade Latin America has experienced

the growth of supermarkets that took the USA six decades to achieve (Reardon et al., 2003). Thus, the challenge of climate change on food production includes changes in the distribution channels, marketing, and consumption of food products.

South Asia and Latin America are rich in natural resources and have strong potential as food producing regions, but are highly vulnerable to climate change. This paper highlights major adaptation strategies and mitigation options for climate change to meet the food security needs of these two regions.

2. CLIMATE CHANGE SCENARIO IN SOUTH ASIA AND LATIN AMERICA

The earth's climate has remained dynamic throughout the 4.5 billion years of its history, and climate has periodically changed following a natural cycle. These climatic changes in the past geological time had profound influence on sea level, rainfall patterns, and temperature-related weathering processes. However, temperature increases in the late 20th century seem unique, and seem to provide evidence that a greenhouse effect has already established itself, above the level of natural variability of the last 1000 years and that is greater than the best estimate of global temperature change for the last interglacial.

The global warming potential (GWP) of carbon dioxide was estimated by the Swedish chemist Svante Arrhenius, and subsequently many researchers concluded that human consumption of fossil fuels was leading to significant increase in atmospheric CO_2 and global average temperature (Callender, 1938). Huang et al. (2000) reported that the 20th century is going to be the warmest of the past five centuries, and later Huang (2004) stated that the 20th century warming is a continuation to a long-term warming started before the onset of industrialization. Later the 4th Assessment Report of Intergovernmental Panel on Climate Change (IPCC, 2007a) also mentioned that the change in earth's climate has been in an unprecedented manner during the past 40,000 years, but greatly accelerated during the past century. This was mainly due to indiscriminate destruction of the natural environment and rapid industrialization. The IPCC (2007b,c) also reconfirmed that the global atmospheric concentrations of greenhouse gases (GHGs) namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), have increased markedly as a result of human activities since 1750

Table 3 Level/concentration of GHGs in atmosphere during different years.

Years	CO_2 (ppm)	CH_4 (ppb)	N_2O (ppb)	References
1750	280	715	270	IPCC (2007a)
2005	379	1774	319	IPCC (2007a)
2008	385	1797	322	WMO (2009)

(preindustrial era) when their concentrations were 280 ppm, 715 ppb, and 270 ppb, respectively and these values increased to 379 ppm, 1774 ppb, and 319 ppb, respectively in 2005. The same increased (WMO, 2009) to 385 ppm, 1797 ppb, and 322 ppb, respectively in 2008 (Table 3) representing 1.6, 1.2, and 0.9% increase, respectively from 2005 levels.

The GWP of N_2O is 298 times, while that of CH_4 is 25 times compared to that of CO_2 in a 100-year time horizon (Forester et al., 2007; Solomon et al., 2007). Anthropogenic activities result in emissions of four principal GHGs at various proportions (Fig. 2) mainly from developed countries.

Share of 41 industrialized countries to total anthropogenic GHG emission is 46% as compared to 54% from 153 developing countries (IPCC, 2007c). The CO_2 concentration in the atmosphere is gradually increasing from 315.97 ppm in 1959 to 391.57 ppm in 2011 (Fig. 3) and the decadal increase is from 0.86 to 1.99 ppm/year which is the highest ever (www.CO_2now.org).

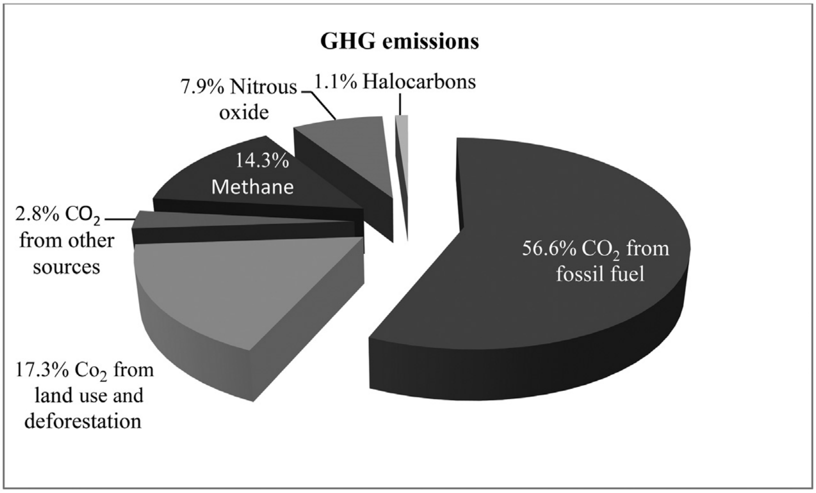

Figure 2 Types of GHG emissions (IPCC, 2007a,b).

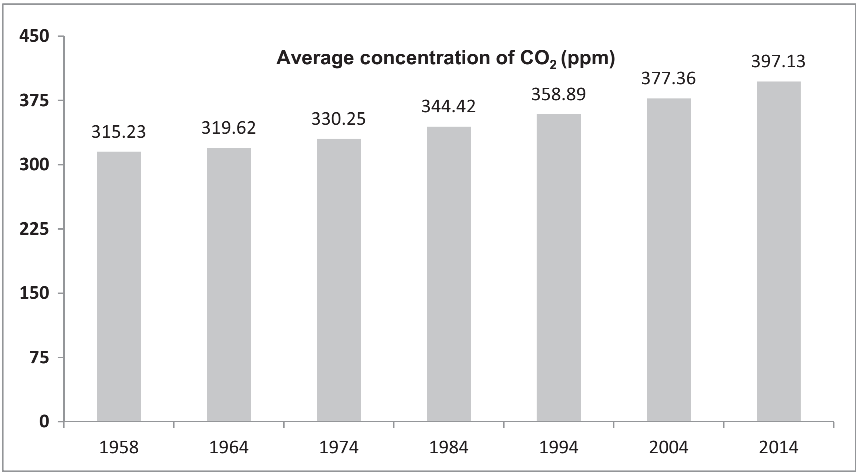

Figure 3 Average CO_2 concentration in the atmosphere during 1958–2014. *Source: http://CO₂now.org*

The projections suggest that global temperatures may rise by 0.6–2.5°C by 2050 and 1.4–5.8°C by 2100 (IPCC, 2007a). For South Asia, a 0.5–1.2°C rise in temperature is projected by 2020, 0.88–3.16°C by 2050, and 1.56–5.44°C by 2080, with the variation depending on the scenario of future development (IPCC, 2007a,c). Overall, the temperature increases are likely to be much higher in the winter season than in the rainy season, while precipitation is likely to increase in all time scales in all the months except during Dec.–Feb. when it is likely to decrease (Aggarwal, 2008; Reynolds, 2010; FCCC, 2012a,b).

Observed trends at low-altitude locations in South Asia suggest that these sites can normally expect future changes in temperature extremes that are consistent with broad or macroscale warming. High-elevation sites appear to be more influenced by local factors and, hence, future changes in temperature extremes may be less predictable for these locations (Kumar et al., 1994; Revadekar et al. 2013). Climate change projections to 2100 AD for India indicate an overall increase in temperature by 2–4°C (Table 4) with no substantial change in precipitation (Kavikumar, 2010). At an all India level, there is no definite trend that can be established in the monsoon rainfall during last 100 years, but there are some regional patterns. Areas of increasing trend in monsoon rainfall are found along the west coast, north Andhra Pradesh and adjoining areas, north-east India and parts of Gujarat and Kerala (−6 to −8% of normal over 100 years). The warming trend in India over the

Table 4 Projected changes in climate in India (2070–99).

Region	Jan.–Mar.	Apr.–Jun.	Jul.–Sep.	Oct.–Dec.
Change in temperature (°C)				
Northeast	4.95	4.11	2.88	4.05
Northwest	4.53	4.25	2.96	4.16
Southeast	4.16	3.21	2.53	3.29
Southwest	3.74	3.07	2.52	3.04
Change in precipitation (%)				
Northeast	−9.3	20.3	21.0	7.5
Northwest	7.2	7.1	27.2	57.0
Southeast	−32.9	29.7	10.9	0.7
Southwest	22.3	32.3	8.8	8.5

Source: From Kavikumar (2010).

past 100 years (1901–2007) was observed to be 0.51°C with accelerated warming of 0.21°C every 10 years since 1970 (Kumar, 2009).

The spatial distribution of temperature changes indicates a significant warming trend along the west coast, central India, the interior Peninsula, and over northeast India. However, a cooling trend has been observed in the northwest and in some parts in southern India. Records over the past 130 years do not show any significant long-term trend in the frequencies of large-scale droughts or floods in the summer monsoon season. The frequency of cyclonic storms that form over Bay of Bengal has remained almost constant over the period 1887–1997. The magnitude of the impact of climate change is likely to vary in different parts of India. Parts of western Rajasthan, Southern Gujarat, Madhya Pradesh, Maharashtra, Northern Karnataka, Northern Andhra Pradesh, and Southern Bihar are likely to be more vulnerable in terms of extreme events (Mall et al., 2006).

The results of a recently published study conducted over the Cauvery Basin of Tamil Nadu, India, using PRECIS and RegCM3 regional climate models (RCMs) showed an increasing trend for maximum temperature, minimum temperature, and rainfall (Geethalakshmi et al., 2011).

In a study (DARE, 2003) using maximum and minimum temperature data (1901–2004), it was found that about 75% of the locations in the Southern zone of India showed increasing trends in maximum temperature, while in the north only 20% of the locations showed an increasing trend. Nevertheless, for minimum temperatures, most of the stations showed the increasing trend. It is also projected that by the end of the 21st century, rainfall in the region will increase by 15–40% (NATCOM, 2004).

Climate change forecasts for Latin America project an increase in temperature and a corresponding decrease in soil humidity, which would result in the tropical rainforest on the eastern side of the Amazon region being gradually replaced by savannahs (IPCC, 2007a; AGRIFOR, 2009). Further, the semi-arid vegetation will gradually be replaced by arid land vegetation; significant losses in biodiversity in tropical areas; crop productivity would decrease leading to decrease in productivity of cattle farming. Central American countries and small islands states are considered to be the most vulnerable areas due to their geographical locations. A strip of land surrounded by the Atlantic and Pacific oceans makes the region subject to the greater frequency and intensity of extreme climate phenomenon, like intense rainfall, which has increased abruptly since 1995 and 4 out of 10 strongest hurricanes occurred during the last one decade as the surface seawater temperature has increased between 1 and 2°C (AGRIFOR, 2009). The rise in sea level will make the area more susceptible to floods and the risk of salinization of neighboring aquifers. The northern regions of Mexico would be affected by drought. The central Andean region observed temperature rise of 0.34°C between 1974 and 1998 which was 70% higher than the global average increase for the same period (AGRIFOR, 2009). Similarly, the rise in temperature and long periods of drought in Amazon Basin may cause massive death of the trees affecting carbon dioxide absorption leading to the danger of converting the rainforest ecology into the savannah ecology. Once this process is noticeable, we could expect some humans to see advantages in the declining tree cover, and to move in seeking to establish new farm and pasture land, accelerating the process.

No doubt such climatic changes will affect agriculture through their direct and/or indirect effects on crops, soils, water, livestock, and pests. Temperature rise will have a greater impact on agricultural production in South Asian countries as a large part of it is situated in the tropical regions (10 degree S to 28 degree N). The recent negative effect of heat waves on wheat yields in many countries has indicated the serious implications of climate change on food security. The damage to crops due to increased occurrence of cyclones and floods has drawn greater attention to the need for climate change research.

3. EMISSION OF GREENHOUSE GASES FROM AGRICULTURE

A major challenge for agriculture is its environmental footprint and climate change. According to an estimate, agriculture is responsible for about

14% of total GHG emission, and these projections can become as high as 30% of total anthropogenic GHG emission if deforestation due to expansion of the agricultural frontier is included (IPCC, 2007a). On the other hand, the mitigation potential of agriculture (estimated upper limit if best management practices are widely adopted) has been calculated as 5.5–6 Gt of CO_2 eq. per year by 2030 (IPPC, 2007a). This potential is extremely large, especially relative to emissions from the sector. About 89% of this potential could be achieved through soil carbon (C) sequestration.

Soils can be a net sink or source of CH_4, depending on different factors, such as water content, N level, organic material application, and type of soil (Gregorich et al., 2005; Liebig et al., 2005). Soil as a sink for CH_4 is far less important than as a source of N_2O (Bavin et al., 2009; Chan and Parkin, 2001; Johnson et al., 2010). Paddy fields have been found to be a significant source of CH_4 and N_2O emissions, which have attracted considerable interest due to their contribution to global warming (Bouman et al., 2007a,b; Hadi et al., 2010).The main GHGs in wheat and maize cropping system are mainly N_2O and CO_2. In the case of N_2O, N fertilizers are the direct source of emissions in the field and an indirect source through fossil fuel energy consumption associated with the manufacturing and transportation of fertilizers.

The two main processes of the N cycle that determine the production of N_2O are nitrification and denitrification. The latter occurs under anaerobic conditions where nitrate is reduced to various N forms. Any management system that creates anaerobic condition, including flooding especially in heavy textured soils when nitrate is present, will lead to increased N_2O emissions (Ball et al., 1999). These emissions can be reduced by aerating the soil as proven by reduced emissions in permanent raised beds (Patino-Zuniga et al., 2009). The N_2O is also released from soils to the atmosphere during nitrification of ammonia, and in ammonia producing fertilizers under aerobic condition.

Annual global consumption of N fertilizers is expected to exceed 100 MT, 50% of which is used for wheat, maize, and rice production. Approximately, only half of the applied N is taken up by the crops (Matson et al., 1997; Heffer, 2009; Ladha et al., 2005). The remaining N can take on many forms, with various consequences for ecosystems and public health. One of the forms of N that is lost to the atmosphere is N_2O. Water-filled pore space, temperature, and soluble C and N availability have a dominant influence on N_2O emissions (Lee et al., 2006; Ortiz-Monasterio et al., 2010). These factors can be manipulated by tillage

(Venterea et al., 2005), residue management, irrigation (Qian et al., 1997), and the application of N fertilizers (Smith et al., 1997). However, the amounts emitted depend on the interaction between soil properties, climatic factors, and agricultural practices (Granli and Bockman, 1994), therefore, it is difficult to draw general conclusions (Snyder et al., 2007).

Timing of fertilizer application is a critically important factor in N_2O emission. In both wheat and maize preplant application has been documented as being the most inefficient method of applying N fertilizer (Mahler et al., 1994; Randall et al., 2003; Ortiz-Monasterio et al., 2010). Any prolonged period when NH_4-based fertilizers can undergo nitrification, without competition from plant uptake, is likely to increase emission of NO and N_2O (IFA/FAO, 2001). It has been reported by Snyder et al. (2007) that application of N fertilizer when crop N uptake begins will significantly reduce N losses as N_2O.

4. WATER RESOURCES: CURRENT AND FUTURE SCENARIO

4.1 Water Resources in South Asia

Climate change is likely to affect water availability significantly. The water resources available in terms of rainfall, renewable water, and that utilized in various sectors in South Asian countries is presented in Tables 5 and 6. The *per capita* water availability in the region is less than the World average except for Bhutan and Nepal where water use is limited mainly to the agriculture sector (≥94%). Bangladesh being downstream, and a deltaic country of a huge watershed, suffers from the hazards of quantity and quality of water. Nepal, though currently water rich, is facing increasing water demand. Bhutan has a high spatially variable precipitation, 76% of which goes as runoff. The sufficient per capita water availability (2582 m^3) in Sri Lanka is expected to decline to 1900 m^3 by 2025 (FAO, 2007). Afghanistan, though having low rainfall, is rich in water resources due to the snow cover in nearby mountain ranges [55 billion m^3 (BCM)]. India, home to 1/6th of world's population has only 1/25th of the world's available water resources. Pakistan has the lowest rainfall (494 mm) in the region, and that also varies temporally and spatially.

Nepal has a cultivated area of 2.64 million ha (18% of its land area). Out of this, two-thirds (1.8 million ha) is potentially irrigable. At present, 42%

Table 5 Water resources in terms of rainfall and renewable water in South Asia.

Country	Total renewable water resources (BCM/year)	Per capita total renewable water (m^3/year)	Total internal renewable water (BCM/year)	Per capita total internal renewable water (m^3/year)	Withdrawal for agriculture (%)	Average annual precipitation (mm)
Bangladesh	1,211	7,934	105	688	96.0	2320
Bhutan	95.0	39,716	95.0	39,716	—	2200
India	1,897	1,729	1,261	1,149	87.0	1170
Maldives	0.03	88.8	0.03	88.8	—	1972
Nepal	210	7,996	198	7,539	97.0	1500
Pakistan	223	1,382	52.4	325	96.0	494
Sri Lanka	50.0	2,582	50.0	2,582	95.0	1712

Source: From FAO (2007).

Table 6 Water utilization in different sectors of South Asian countries.

Country	Total water withdrawal (million m^3)	Agriculture (%)	Municipality (%)	Industry (%)	Sources GW (%)	Sources SW (%)
Bangladesh	35,870	88.0	10.0	2.0	79.0	21.0
Bhutan	338.0	94.0	5.0	1.0	100	—
India	761.0	89.0	7.4	2.23	97.1	2.9
Maldives	5.9	—	94.9	5.08	79.2	20.8
Nepal	9,787.0	98.2	1.5	0.3	100.0	—
Pakistan	183.4	93.97	5.3	0.76	100.0	—
Sri Lanka	12,950	87.36	6.2	6.42	100.0	—

GW, ground water; *SW*, seawater.
Source: From FAO (2007).

of the cultivated area has irrigation but only 17% of the cultivated area has year-round irrigation (ie, only 41% of the irrigated area gets year-round irrigation). In the Terai, 82% of the total irrigated area (0.9 million ha) is through surface irrigation and the remaining 18% through groundwater. Most of the irrigated area is situated in the fertile lowlands of the Terai. It is estimated that the existing irrigation schemes contribute approximately 65% of the country's current agriculture production (WECS, 2003).

Most land area in Bangladesh is low-lying floodplain formed by the alluvial soil deposited by three great rivers; the Brahmaputra/Jamuna, the Ganges, and the Meghna. About 25% of the country is flooded to varying degrees each year during May through Sep. when over 60% of the cereals are produced. Recurrent flooding severely restricts the farmers' choice of cropping to traditional low-yielding broadcast variety of rice that can thrive in deep water. The real production potential of the alluvial soils is not harnessed due to flooding.

Bangladesh experiences four main types of floods: monsoon floods from the major rivers; local flooding due to drainage congestion, flash floods in the eastern and northern rivers; floods caused by high tides combined with storm surges in the coastal areas. During the Jun.–Sep. monsoon, Bangladesh receives about 80% of its annual precipitation, averaging 2300 mm, but varying from as little as 1200 mm in the West to over 5000 mm in the East. Runoff from adjacent riparian is generated by rainfall which averages 5,000 mm over the Himalayas, and exceeds 10,000 mm over the Meghalaya plateau north to Sylhet. Together, inflows and rainfall cause peak floods in the Ganges, Brahmaputra, and Meghna rivers in the period of Jul.–Aug., and on average 22% of the country is flooded

annually. On the other hand, scarcity of irrigation water during Mar.–Apr. limits the cultivation of high-yielding varieties of rice which account for about 36% of total rice production. This is because Bangladesh receives only the residual flow from the major rivers after diversion and upstream use during the dry season. Reduced stream flow is also aggravating salinity intrusion and environmental degradation. Drought is not only confined to the dry season, and decreased rainfall can take place during the monsoon, as happened in 1994. This phenomenon of reduced monsoon rainfall can also severely affect floodplain fisheries and late monsoon "aman" rice.

Of the three sources of water in Pakistan, namely, rainfall, groundwater, and surface water, groundwater contributes about 40% of the total water supplies. There are 0.9 million privately owned tube wells that annually extract 59 BCM of water. Surface water is the largest source of irrigation water and provides about 171 BCM of water annually. Pakistan has two big dams, Tarbela and Mangla, with water storage capacity of 10.38 and 5.90 BCM of water, respectively. A canal irrigation system has 48 major canals, which deliver irrigation water to the farmers' fields through 1,70,000 water courses extending over a length of 1.6 million km (ASP, 2011). Average annual rainfall varies from a meagre 125 mm in the South East to over 750 mm in the North West of Pakistan. Rainfall can be erratic and is received in two rainy seasons; about two-thirds of the annual rainfalls during the monsoon season (Jul. to mid-Sep.) and the remaining one-third in the winter season (Jan. to Mar.). Fresh water sources in the country are becoming scarce and degraded while their demands for agriculture, domestic, industrial, environmental, and recreational uses are on a continuous rise. Over a 50-year-period (1950–2000), per capita water availability has been reduced by 77% in Pakistan (WWAP, 2009).

The water shortages in Pakistan registered during the past few years were as high as 40–50%. The total inflow of the western rivers during the monsoon season fell to 93.48 BCM in 2001 from 143.16 BCM in 1998, while in winter season it dropped to 19.06 BCM in 2001–02 from 27.82 BCM in 1998–99. The total inflow of the western rivers fell to 112.54 BCM in 2001–02 from 196.14 BCM in 1992–93. On the basis of current water shortages and rapidly increasing future demands, the experts have foreseen that this situation would simply be unsustainable for agriculture. Acute shortage of irrigation water motivated farmers to exploit groundwater reservoirs. The number of tube wells in Pakistan has increased from 374,099 in 1992–93 to 1,070,375 in 2009–10 (ASP, 2011). Intensive exploitation of

Table 7 Rainfall received in different geographical regions of India.

Rainfall (mm/year)	Geographical area (10^6 ha)	Rainwater received (10^6 ha-m)
100–500	52.1	15.6
500–750	40.3	25.2
750–1000	65.9	57.6
1000–2500	106.4	205.9
>2500	32.6	95.7
Total	297.3	400.0

Source: From Bhaskar (2002).

groundwater initially benefited the farmers and helped them to attain higher production with consequences of increases in soil salinity and a decrease in the depth of the water table. Currently over 16 million ha of land is affected by varying levels of salinity and waterlogging (ASP, 2011).

India is endowed with large renewable water resources, but is faced with the issues of regional imbalance, poor seasonal distribution, and vulnerability to changing climate. As much as 139 M ha of land area receives >1000 mm/year, of which 33 Mha receives > 2500 mm/year of rainfall (Table 7).

The total annual rainfall received in India is about 400 million ha-m, of which, only 150 million ha-m (37.5%) infiltrates into the soil, 180 million ha-m (45%) is lost as surface runoff, and 17.5% is lost as evaporation (Bhaskar, 2002). Therefore, conservation, management, and recycling of rain water are crucial for reducing wastage and for enhancing the production of rain-fed agriculture. Drought management is an important strategy to enhance production from rain-fed agriculture in India.

4.2 Water Resources in Latin America

Latin America is relatively well endowed with water resources. However, population growth and rapid urbanization are putting considerable pressure on the water available for irrigation. Annual average rainfall varies considerably in different regions from 550 (Argentina) to >2500 mm in Colombia, Costa Rica, Guadeloupe, and Guatemala. Based on the information on rainfall data collected by Ringler et al. (2000) the countries in the Latin American region can be placed in four groups (Table 8). Most of the regions (except Argentina, Chile, and Mexico) receive more than 1000-mm rainfall, which is substantial moisture for agriculture although there is substantial variation within countries.

Table 8 Range of annual rainfall in Latin American countries.

Annual rainfall range (mm)	Countries
500–750	Argentina, Chile, Mexico
1000–1500	Bolivia, Cuba, Dominican Republic, Haiti, Paraguay, Peru, Uruguay
1700–2500	Belize, Brazil, Ecuador, El Salvador, Guyana, Honduras, Jamaica, Nicaragua, Puerto Rico, Venezuela
2500–3000	Colombia, Costa Rica, Guadeloupe, Guatemala

Source: From Ringler et al. (2000).

Besides rainfall, there are 58 rivers and lakes in Latin America whose drainage basins are shared by two or more countries. South America, Central America, and the Caribbean have a combined annual renewable water supply of about 13,120 BCM, which represents 30.8% of the global total of 42,655 BCM. This generous endowment is shared by only 8.5% of the world's population that lives in 15% of the world's land area (Ringler et al., 2000).

But water resources are distributed unequally, with more than half of the renewable water supply for the region concentrated in one river, the Amazon, which covers 7.1 million km^2 and has a mean annual flow of 252,000 m^3/s. It is the world's largest concentration of surface flow and provides, on its own, one-fifth of the world's total volume of fresh water. The Orinoco River has a catchment area of about 1.05 million km^2 and a mean annual flow of 30,000 m^3/s ; while the River Plate has a drainage basin covering 2.8 million km^2 and a mean annual flow of 18,000 m^3/s (WMO/IDB, 1996; Ringler et al., 2000). Most of the rivers are of pluvial origin and flows vary over the year according to the rainfall pattern. It is estimated that three quarters of the total water flow in Latin America (generated over 56% of the territory) comes from international basins, in which water systems are shared between two or more countries.

In Latin America, as elsewhere, agriculture is the major user of fresh water (Table 9).

Total reservoir capacity in the region is 1097 BCM; about half of this is in Brazil alone and Brazil, Venezuela, Argentina, and Mexico combined together have 87% of the total reservoir capacity of the region. Brazil also has the largest number of dams (594), closely followed by Mexico with 536 dams. Of the 1568 large dams in the region that are registered with the

Table 9 Water withdrawals and consumption (BCM) by different sectors in Latin America.

Sector	1990 Withdrawals	Consumption	2025 Withdrawals	Consumption
Agriculture	96.7	74.2	112.0	84.7
Industry	15.9	1.2	56.5	6.2
Municipalities	28.1	5.0	64.5	7.8
Reservoirs	11.0	11.0	24.0	24.0
Total	151.7	91.4	257.0	122.7

Note: Agriculture includes livestock watering, industrial use includes thermal power plant cooling, municipal use includes domestic uses in urban and rural areas, and reservoirs withdrawal represents the amount of water lost to evaporation in reservoirs.
Source: Modified from Ringler et al. (2000).

International Commission on Large Dams (ICOLD, 1998), almost half have irrigation as an important component and 532 dams in the region have been solely built for irrigation purposes (Ringler et al., 2000). Mexico ranks first for irrigation dams with 387 dams followed by Brazil and Chile with 48 and 46 dams, respectively. Moreover, 19 large dams in Argentina and 16 in Peru are only used for irrigation.

In the last four decades, the growth in the irrigated area in the region averaged below 2.5%/year, and only in Brazil and El Salvador was it 5.5% or slightly more, and in Colombia, Costa Rica, Nicaragua, and Uruguay it was between 4 and 5%. In 1996, the total irrigated area in Latin America and Carribbean stood at about 17 million ha, out of an agricultural area of 155 million ha (FAOSTAT, 1999). Even though the agricultural frontier in the region has increased substantially, there is still a large agricultural area without irrigation or sufficient water availability. Overall, the picture for the development of irrigation and water resources in the region shows a slowdown in the expansion of irrigated areas, declining investment in irrigation, rapid increases in demand for water in nonagricultural uses, increasing development costs, and substantial degradation of water and soil quality.

The main constraint in the performance of and future prospects for irrigation development include the market and price prospects of the crops that may be grown with irrigation, and the high capital costs of irrigation. In order to pay for future investments, irrigated agriculture needs to produce high-value crops for both local consumption and exports into competitive world markets. These trends pose significant challenges for future water management policy, which can be addressed through expansion of water

availability through investment in new sources of supply; and reforms in water demand management, including efficient reallocation of water to meet increasing demands, improved water quality, and reduce water-related environmental degradation (Ringler et al., 2000). The key elements of an appropriate water policy would include:

- integrated water management at the river basin level;
- irrigation management transfer and user-managed irrigation;
- water rights, pricing, and markets; and
- reform of groundwater management.

5. IMPACT OF CLIMATE CHANGE ON CROP PRODUCTION AND FOOD SECURITY IN SOUTH ASIA AND LATIN AMERICA

5.1 South Asia

Agriculture is one of the largest contributors to the GDP in South Asia, besides being the main source of employment for a labor force of millions. As three-fifths of the cropped area in this region is rain-fed, the agricultural economy is centered on the behavior of monsoon. Global warming is projected to have a significant impact on conditions affecting agriculture, including temperature, CO_2, glacier runoff, precipitation, and the interaction of these elements. These conditions in turn determine the carrying capacities of different ecosystems to produce enough biomass including food for human population and domesticated animals. The overall effect of climate change on agriculture will depend on the balance of these effects. Climate change is predicted to have severe consequences on agriculture and the rural poor in South Asia. It has been identified as one of the most disaster-prone regions in the world. This is critical in view of the fact that increased frequency of extreme weather events like droughts and floods can have severe impacts in these countries (IPCC, 2007a). Given that approximately three-fifths of the cultivated area in South Asia is rain-fed, the onset, duration, spatial extent, and total precipitation during the monsoon is the most critical factor in determining the livelihoods of a large majority of the population in rural areas. Moreover, resilience is typically low in rural areas as the existing asset base is limited and services are often insufficient. Global warming is likely to affect all these factors (Sterrett, 2011).

India is the second largest producer of rice and wheat in the world. In addition, 4% of the soybean (9.1 MT) and 23% of maize (19.7 MT) in the world is grown in India (FAOSTAT, 2010). Crop growth and yield are largely determined by weather during the growing season. With slight variations from normal weather, the effectiveness of externally supplied inputs decreases and consequently yields are affected. Increasing CO_2 concentration in the atmosphere and predicted higher atmospheric temperature are also expected to have an effect on crop production through changes in plant growth and transpiration (Mall et al., 2006). Increased temperature reduces the grain yield due to faster development, increased respiration losses, and decreased time of grain growth in food crops. Yield reduction in wheat, rice, and corn in the region due to temperature rise during winter is expected (Challinor and Wheeler, 2008; Challinor et al., 2008).

The possible scenarios and impacts are unique to each country and are largely influenced by its geographical profile. Bhutan and Nepal have fragile mountainous ecosystem; Bangladesh and Sri Lanka have low-lying coastal areas, while India and Pakistan depend on cultivation in river plains, deltas, arid and semiarid lands. Key impacts of climate change would be an increase in temperature particularly during post monsoon and winter, increased frequency of floods during the monsoon, decreases in winter precipitation, and lower number of rainy days all affecting crop growth and production.

Increases in atmospheric temperature and annual rainfall result in frequent floods and cyclones in Bangladesh, whereas increased temperature would shift the cultivating zone further into higher elevations in the mountain ranges of Nepal, Bhutan, and India. Coastal region inundation or intrusion of seawater is a likely cause of a loss of the cultivated area in Bangladesh. With extreme weather events and encroaching salt water, the impacts on rice yield may vary between −6 to + 14% depending on different climate change scenarios (Mahmood et al., 2004). On an average during the period 1962–88, Bangladesh suffered a loss of about 0.5 MT of rice production annually as a result of floods, accounting for nearly 30% of the country's average annual grain imports.

Increased frequency of monsoonal storms and flooding in the Himalayas could aggravate the occurrence of landslides in Nepal. In addition to the danger to life and property, some of the generated sediments may be deposited in the agricultural lands or in irrigation canals and streams, which will contribute to deterioration in crop production and in the quality of agricultural lands. There will be an increase of 0.6–1°C in mean temperature in coastal areas in Pakistan; increase in summer and winter rainfall in northern

Pakistan and 10–15% decrease in the coastal belt and arid plains. The warming trend in India over the past 100 years (1901–2007) was observed to be 0.51°C, with accelerated warming of 0.21°C every 10 years since 1970 (Kumar, 2009).

Spatial and temporal variation projected changes in the temperature and rainfall, are likely to lead to differential impacts in the different regions (Byjesh et al., 2010). The IPCC reports, and a few other global studies, indicate a probability of a 10–40% loss in crop production in India with increase in temperature by 2080–2100 (Rosenzweig and Parry, 1994; Rosenzweig et al., 2002; Fischer et al., 2002; IPCC, 2007b; Majumdar, 2008). Studies conducted in India (Aggarwal and Sinha, 1993; Rao and Sinha, 1994; Lal et al., 1998; Saseendran et al., 2000; Mall and Aggarwal, 2002; Aggarwal, 2003, 2008) have confirmed similar declining trends in agricultural productivity due to climate change. For every 1°C increase in temperature, the yields of wheat, soybean, mustard, groundnut, and potato are expected to decline by 3–7% (Aggarwal, 2009a,b) and in rice by 6% (Saseendran et al., 2000; IWMI, 2007). Projections indicate the potential loss of 4–5 MT of wheat with every rise of 1°C temperature throughout the growing period with current land use in India alone (Aggarwal, 2008). Losses were also significant in other crops, such as mustard, peas, tomatoes, onion, garlic, and other vegetables and fruit crops (Samra and Singh, 2004; Aggarwal, 2009a). Various districts in the western Rajasthan, southern Gujarat, Madhya Pradesh, Maharashtra, northern Karnataka, northern Andhra Pradesh, and southern Bihar are also highly vulnerable to climate change. Sorghum yields are predicted to vary from + 18 to −22% depending on a rise of 2–4°C in temperature and increase by 20–40% of precipitation (Mall et al., 2006). Rain-fed areas are likely to be more vulnerable in terms of extreme events (Mall et al., 2006). Aberrations in the South–West monsoon could include a delay in the onset of the monsoon, long dry spells, and early withdrawal, etc., adversely affecting the productivity (Lal, 2001). This increase in variability could make it more difficult for resource-poor farmers to take decisions on investing on inputs and new technologies (Pandey et al., 2000).

Climate change is expected to accelerate the hydrological cycle. In India and Pakistan, winter precipitation is projected to decline and this is likely to result in a greater demand for water during the Rabi season. During the monsoon season, the intensity of rains is projected to increase, which will imply more frequent and severe floods and a lesser recharge of groundwater (Jain, 2012). The flow of Indus river basin is also likely to affect cotton

production in Pakistan, the main cash crop of the country. Further, water for agriculture is becoming increasingly scarce, and climate change-induced higher temperatures will increase crops' water requirements, so shortages will become more serious in the coming decades. By 2025, 15–20 million of the world's 79 million ha of irrigated rice lowlands, which provide three-quarters of the world's rice supply, are expected to suffer some degree of water scarcity (IWMI, 2007). It is also estimated that to eliminate hunger and undernourishment of the world's population by 2025, the additional water requirements may be equivalent to all freshwater withdrawn and used today for agricultural, industrial, and domestic purposes (SIWI, 2005).

In Nepal, soil loss is a major cause of the decline in agriculture production due to the steep terrain. The effects of climate change may further aggravate this situation. Glacier lake outbursts; floods due to glacial melt and soil loss due to floods are also predicted. Sri Lanka will be affected in a different way due to the extreme events of the rise in temperature and changes in rainfall patterns with a 0.2°C/year increase in central highlands, and an increasing trend in rainfall in Feb. and decreasing trend in Jun. More intense floods, increased temperature, and prolonged dry spells will decrease the coarse grains, tea, and coconut production (Oxfam, 2011). Many studies (IPCC, 2007b) have reported a significant increase in runoff in many parts of the world including South Asia. This, however, may not be very beneficial unless the storage infrastructure for water is vastly expanded. The extra water in the wet season, on the other hand may lead to an increase in the frequency and duration of floods. The increased melting and recession of glaciers associated with global climate change could further add to the dimensions of the runoff scenario. Himalayan glaciers have shown an overall deglaciation of 21% reducing the area from 2077 km^2 in 1962 to 1628 km^2 in 2007 (Kulkarni et al., 2002). Such increases in glacier melt in the Himalayas could affect the availability of irrigation especially in the (IGPs), which is turn would have consequences on food production (Aggarwal, 2008) and livelihood security.

5.2 Latin America

The Latin American region has the highest biodiversity on the planet. Two important contrasting features characterize the region: having the biggest tropical forest of the planet and possessing the largest potential for agricultural expansion during the next decades. The region also has multiple

stressors on natural and human systems derived in part from significant land-use changes and exacerbated by climate variability/climate change. In Central and South America 613 climatological and hydrometeorological events occurred in the period 2000–13, resulting in 13,883 fatalities, 53.8 million people affected, and economic losses of US$52.3 billion (Intergovernmental Panel on Climate Change, Magrin et al., 2014).

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Magrin et al., 2014), over the last decades increases in precipitation were observed in southeastern South America, northwest Peru, and Ecuador, while decreases were registered in southern Chile, southwest Argentina, southern Peru, and western Central America. It is estimated that mean warming for Latin America at the end of the 21st century could be 1–4°C, with rainfall anomalies (positive or negative) in the tropical part of Latin America. The report concludes that the future impacts for the region include: "significant species extinctions, mainly in tropical Latin America (*high confidence*); replacement of tropical forest by savannas, and semiarid vegetation by arid vegetation (*medium confidence*); increases in the number of people experiencing water stress (*medium confidence*); probable reductions in rice yields and possible increases in soy yields in southeastern South America, and increases in crop pests and diseases (*medium confidence*), with some coastal areas affected by sea level rise, weather and climatic variability and extremes (*high confidence*)."

Among the regional projected changes summarized in this report are the following (Magrin et al., 2014): selected regional projected changes in temperature, precipitation, and climate extremes in different sectors of Central America and South America are summarized in Table 10.

In summary, the Intergovernmental Panel on Climate Change concludes that South America could lose between 1 and 21% of its arable land due to climate change and population growth, and in addition, Mexico's landbase could be threatened, already marginal for two of the country's major crops; maize and beef.

Mexico is one country that has been concerned with evaluating the impact of climate change. Climate change studies have been conducted for over 20 years at the Centro de Ciencias de la Atmosfera, UNAM (CCA-UNAM). A series of studies summarizes the current and projected impact of climate change in Mexico. In forestry (Diaz et al., 2011), the potential of climate change was considered for 16 species that have economical importance. In every case, the suitable area for each species decreased

Table 10 Selected regional projected changes in temperature, precipitation, and climate extremes in different sectors of Central America and South America.

Variable and region	Projected changes
Air temperature by 2075 and 2100 in Central America	+2.2°C by 2075, +3.3°C by 2100
Precipation by 2100 in Central America	−24 to −48%
Air temperature by 2100 in Southeastern South America	+2.5 to +3.5°C
Precipitation by 2100 in Southeastern South America	+20 to +30%
Drought frequency, intensity, and duration in Southeastern South America south of 20 degrees S for 2011–40 relative to 1979–2008	Frequency increase of 10 to 20%, increase in severity of 5–15%, and reduction in duration of 10–30%.
Air temperature by 2100 in the Altiplano of The Andes	+3.0°C
Precipitation by 2100 in the Altiplano of The Andes	−10 to −30%
Air temperature by 2100 in the Amazon region	+5 to +7°C
Precipitation by 2100 in central and eastern Amazonia	−20 to −30%

with climate change, with some species projecting decreases of suitable area of over 75%. In general terms, the results showed that the species from temperate regions will be most affected, and that the species in arid and semiarid zones will be the most resilient. In maize, (Rivas et al., 2011), according to the Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca y Alimentacion (SAGARPA, 2007) maize growing occupied 51% of the entire cultivated and harvested surface during the period 1996–2006. The study concluded that only 63.1% of the area planted was suitable for maize, and that under climate change projections, the suitable areas would be the most affected. For livestock, two independent studies on the impact of climate change on livestock were conducted. A study (Rivas et al., 2011) focusing on outdoor range livestock feeding found that the drier regions were most at risk of losing their animal-carrying capacity, while the more tropical regions would be able to maintain their carrying capacity. However, the second study (Hernandez et al., 2011) found that the increasing temperature–humidity index in a tropical area would become more critical in the future, reaching levels considered dangerous for animal health. The vulnerabilities of fisheries to climate change were assessed

(Arroyo et al., 2011) in different ecosystems and habitats. Among the impacts of climate change that are foreseen are rising sea temperatures, rising sea levels, increased incidence of strong hurricanes, changes in precipitation and run-off, changes in surface sea currents, increases in CO_2 concentration, and habitat compression due to falls in oxygen concentration or nutrient availability. Fisheries that depend on coral reefs will be most threatened by the impact of increased temperatures and frequency and intensity of hurricanes. The estuarine species with less tolerance to salinity changes will also be affected by changes in discharge from land as well as by sea-level rise. The Guayalejo-Tamesi river basin was studied (Esqueda et al., 2011) to evaluate the impact of climate change. The study concludes that the water resource is already overexploited, and that unless improved water-management practices and policies are implemented, climate change can only make a bad situation worse. Biodiversity (Trejo et al., 2011) was included in the climate change evaluation. The most noticeable change is expected to be the reduction of the area covered by coniferous forests and the increase of favorable conditions for the tropical dry forest. In general by 2050 nearly half of the mammalian species studied (N=30) will lose 50% or more of their current distribution areas, 9 species are expected to lose more than 80% of their historic area of distribution, and only 13 species are expected to increase their geographic range.

The impact of climate change on urban areas was also evaluated, with a particular focus on cities with a population of over 1 million (Tejeda et al., 2011; Martinez et al., 2011). The urban climate differs from the surrounding rural areas because of the way in which the net energy trapped in the surface/atmosphere interface is dissipated, and this produces phenomena like the "heat island." For example, cities in middle and subtropical latitudes can be about 2°C in the city center than in its surroundings. The study concluded that cities in the higher elevations and in the winter will have milder winters. Nevertheless, the energy demands for cooling across the warmer months is expected to increase in all cities, with per capita consumption increasing for some tropical cities by over 35% by 2030 and 60% by 2050 in the warmer months, and even increasing in the cooler cities by near 5% per capita by 2030 and near 10% by 2050. Different municipalities of Mexico were evaluated (Rivas et al., 2011) for their resilience to climate change, taking into consideration their existing infrastructure, indicators of land capacity, and local projections of climate change. Overall, the drier municipalities in the north of the country were found to be the most vulnerable to climate change, with municipalities

with a lack of soil degradation as providing the best resilience against climate change. The study calls for promoting soil improvement and conservation activities.

A separate study analyzed the impact of crop yields on migration from Mexico to the USA (Feng et al., 2010). The key conclusion was that a 10% reduction in maize crop yields leads to an additional 2% of the population to emigrate. The study further concludes that by 2080, with climate change, an estimated 1.4–6.7 million adult Mexicans will emigrate as a result of declines in agricultural productivity alone.

The impact of climate change on agriculture in other Latin American countries can be summarized more briefly. In Colombia (World Bank, 2014a,b,c,d), weather disruption is increasing with increased excessive rains caused by the climatological effects of El Niño, and a more recent weather oscillation called La Niña, resulting in a decrease of 2.1% of GDP in 2010–11. In 2008, El Niño reduced yields by an average of 5% in the 17 most important crops in the country. Agriculture is expected to be increasingly challenged by decreases of precipitation of 10%, particularly affecting rice production. Peru (World Bank, 2014a,b,c,d) is one of the countries most impacted by hydrometeorological phenomena associated with El Niño and ocean atmosphere disturbances in the equatorial Pacific Ocean. Climate-change projections indicate that changes in temperature and more frequent El Niño events can be expected. Climate change has already been evidenced by species migration (eg, native potato now being produced in higher areas) and shifts in pest and disease distribution. Significant differences are expected in weather patterns across Peru, with temperatures rising more in the north than the south of the country, and decreases in precipitation in the central area strongly affecting maize, and potato production, and decreases in water availability in other regions affecting rice and coffee production. Costa Rica (World Bank, 2014a,b,c,d) is less exposed to drought and extreme weather events than most of Central America. It is located just south of the hurricane belt, and only its north-west provinces are in the Central American Dry Corridor. Nevertheless, Costa Rica is already being affected by more erratic rainfall. Costa Rica depends heavily on food imports, and its food security is threatened by price volatility and the production of staples, such as beans, for which it depends heavily on neighbors more heavily affected by climate change. El Salvador (World Bank, 2014a,b,c,d) lies within the Central American Dry Corridor, meaning rainfall is frequently scarce over large parts of the country. The country is vulnerable to cyclones from both the Atlantic and Pacific oceans and these

have been increasing in frequency and intensity. Coffee in the highlands and agricultural production in the flood-prone coastal areas are considered at most risk from climate change.

Studies in Brazil summarize both the impact of climate change on agriculture and the impact of agriculture on climate change. The Brazilian Amazon is the largest tropical forest in the world, and has attracted attention and concern that large-scale conversion of tropical forests into pastures or annual crops could lead to changes in climate. One study (Nobre et al., 1991) concluded that when Amazonian tropical forests were replaced by degraded grass (pasture), surface temperatures increased by 2.5°C, there was a 30% decrease in annual evapotranspiration, a reduction of 25% in precipitation in the dry season, and there was an increase in the length of the dry season. An additional Amazon study (Malhi et al., 2008) found that the human use of fire to facilitate large-scale conversion of tropical forests into pastures or annual crops was further undermining tropical forest resilience. Fire use for land management is nearly ubiquitous in rural Amazonia. Fire is used to clear the area for agricultural use. Yet the native tropical trees lack adaptation to survive fires, which more temperate tree species can have, and the native tropical trees burn out and die. The tropical trees are replaced by grasses, which often become a fuel for repeated burns, eliminating any opportunity for recovery by the native tropical trees.

In Latin America, conservation agriculture (CA) has been adopted mainly in Brazil, Argentina, and Paraguay, and in other countries, adoption of CA is still incipient (<0.1 m ha) or extremely low compared to the total agricultural area. In Mexico, the experimental results demonstrated that there were significant advantages to zero tillage (ZT) over either conventional or minimal tillage. When minimal tillage was applied on steep slopes, improved erosion control was demonstrated than that produced using conventional tillage. Differences of 400% more erosion with conventional tillage in comparison to ZT were found under slope and Andosol conditions in the first years (Tiscareño et al., 1997). On cultivated lands on steeper slopes in southern Veracruz, it was found that producing a kilogram of maize with conventional tillage caused 27 kg of soil loss, while under ZT the loss was reduced to less than a kilogram of soil per 4-year average (Uribe, 1998). Over a 100 experiments done by the national program during a 5-year period showed that ZT reduced the erosion rate by nearly 80% in maize, and by nearly 95% in wheat, in comparison to conventional tillage. The use of ZT on a more continuous basis tends to increase the soil protection even more (Osuna, 1997; Velasquez et al., 1997).

Costa Rica has an extremely small surface under conservation tillage (less than 100,000 ha), but it has developed advanced legislation on conservation tillage to integrate into its agriculture. El Salvador, despite a protracted civil war which ended in 1992, is one of the conservation tillage pioneers in Latin America. El Salvador has demonstrated that conservation and productivity can be successfully associated within a productive system. One initiative was launched in 1970 to incorporate conservation tillage into the traditional maize–sorghum association. This traditional system was manually sown in the Guaymango region involving nearly 5000 ha with very steep (40–90%) slopes. Small producers keep working their fields manually with some having access to animal traction. Before adopting conservation tillage, they had already adopted hybrid seeds and chemical nitrogen and phosphorous fertilizers. They had also stopped burning crop residues to leave part of them on the soil. During the following 16 years, maize production increased from 0.7 to 3.23 t/ha, and that of sorghum from 0.6 to 2.1 t/ha. (Sain and Barreto, 1996; Erenstein, 1999). Brazil is the most advanced and largest conservation tillage adoption case in Latin America, and it is a good example for the world as a whole. Favorable circumstances for the adoption have been: versatility of ecological environments where the conservation tillage is used, interest of farmers from small to large producers, the cleverly made machinery available that has been designed for either animal or mechanical energy, and the ample catalog of imaginative technologies that have been offered, and are applied extensively. The surface covered with conservation tillage is nearly 12 million ha, representing nearly a third of the total land cultivated in the country. That surface has been increasing by more than a million hectares per year during the last 4 years of the 1990s (Derpsch, 1999).

The use of conservation tillage in Brazil started in the states of Parana and Rio Grande do Sul during the 1970s, after some Brazilian agriculturists visited the University of Kentucky and became interested in the technologies demonstrated there. At the beginning they had difficulties due to the lack of direct sowing machines and they had to import them. However, the limitation was solved by adapting the conventional sowing machines they already had to direct sowing. Another important constraint was the scarcity and high price of herbicide. A partnership was forged in the 1970s that included state research, commercial companies, and international agencies. The state of Parana became a diffusion center for new technology in Southern Brazil. Later, conservation tillage was diffused to other regions, including maize and soja bean producers cultivating large extensions in Central West Brazil (Da Veiga, 1997; Derpsch, 1998).

One of the most important characteristics of the adoption of conservation tillage in Brazil is that it integrated other complementary practices such as: green manure, crop association, and rotation. The use of number of legumes was incorporated to increase the nitrogen content available in the soil. Furthermore, the new practices included were extended to include cereals, such as very short-cycle millet, and black oats, which have been very popular crops in Southern Brazil. Crop rotation, alternating cereals and legumes was proven to be the most practical remedy to solve the soil problems caused by monocropping (Da Veiga, 1997). Another very important focus of conservation tillage in Brazil has been the integration of agricultural, animal production, and forestry systems within a watershed. This wider perspective has made it easier to secure support for longer term programs financed nationally and internationally (CEPA/SC, 1999). These successes have been achieved due to the producers' collaboration who have contributed with work and other resources, as well as the dedication of managers, technicians, researchers, and service providers, who have organized very efficient teams.

Argentina is the second largest adopter of conservation tillage in Latin American. Argentina initiated its research and practical conservation tillage implementation by producers in 1974. Initially, the bottleneck was also either lack, scarcity, or high price of herbicides and sowing machines. Agricultural producers had reached a high organization level with conventional tillage and this same competence was applied to reach an excellent organization level on conservation tillage matter. The surface under conservation tillage in Argentina increased from 25,000 in 1988 to 7 million ha to date. The initial constraint on machinery and herbicides in Argentina has been overcome, and by the end of the 20th century, there were 30 national suppliers of direct sowing machines and herbicides that had been produced in the country (Derpsch, 1998).

Although in both Brazil and Argentina conservation tillage is widely used, there are some differences between these two countries: whereas in Brazil conservation tillage has also been embraced by small farms, in Argentina the leaders of conservation tillage are extensive, and well-organized rural enterprises. Furthermore, in Argentina agriculture depends mainly on mechanical energy, whereas Brazil includes animal traction. In addition, Argentina's application of conservation tillage has not been integrated green manure, the crop rotations, and the watershed management as in Brazil.

Paraguay is an exceptional case, due to the speed of change from conventional to conservation tillage. In Paraguy small farms predominate, and

many of these face the unfavorable characteristics of tropical countries. First attempts at conservation tillage were made during early 1980s, but failed due to the low quality of the machinery available and lack of herbicides. Later, the government associated to Japan's JICA, promoted a new conservation tillage initiative, and later received additional support from the Germany GTZ. In 1992, there was a surface of only 20,000 ha under conservation tillage. In 1998 there were 80,000 ha under conservation tillage, most of it cultivated with soja beans. Conservation tillage now covers more than 50% of the country (Derpsch, 1998, 1999). The success in Paraguay has been facilitated by research networks, such as RELACO and CAAPAS. This last one is a federation of Latin American sustainable agriculture associations, and has achieved such a high prestige, that some other associations from other world regions have joined.

6. ADAPTATION STRATEGIES AND MITIGATION OF CHANGING CLIMATE IN AGRICULTURE

Promoting agricultural practices that mitigate climate change by reducing GHG emissions is important; but those same practices also have to improve farmer's production and income and buffer the production system against changes in climate. South Asia and Latin America being large areas with diverse agroclimatic regions, the adaptation and mitigation strategies have to be location specific and cost effective. Changes in land-use management sustaining the production, development of multiple stress-tolerant varieties, and evolvement of new agronomic management strategies are some of the adaptation strategies that are being talked about. Suitable resource-conservation technologies (RCTs) and proper contingency plans for temperature and rainfall-related risks need to be developed. Agroforestry systems and other biological carbon capture systems can also help in reducing the carbon emissions. Already large numbers of efficient water- and fertilizer-management practices that reduce emission of CH_4 and N_2O are available for paddy and wheat cultivation. Water harvesting and supplemental irrigation for drought-proofing areas, improved drainage and flood control measures in high rainfall regions, and techniques for conservation of resources are of immense importance for mitigating the adverse effect of climate change. Similarly, knowledge-based decision support systems for translating weather information into operational-management practices are required as adaptation mechanisms. These adaptations

can be at the level of individual farmer, society, farm, village, watershed, or at national and regional level.

There are a large number of options in soil-, water-, and nutrient-management technologies, which contribute to both adaptation and mitigation. Much of the research done in rain-fed agriculture relates to conservation of soil and rainwater (Sharma et al., 2009; Venkateswarlu et al., 2009, 2012). Important technologies include: CA (tillage, residue, and nutrient management), in situ moisture conservation, rainwater harvesting and recycling, efficient use of irrigation water, energy efficiency in agriculture, use of poor-quality waters, alternative land uses, and agroforestry on degraded lands. Agriculture systems will have to be more robust and resilient to extreme weather events, that is, drought and flooding. It is important that new agricultural practices will have to prevent further soil degradation (Sharma et al., 2005, 2008, 2011 and Sharma and Jat, 2012), through increased soil organic matter, improved water-use efficiency (WUE) and nutrient-use efficiency and increased biodiversity (Hobbs and Govaerts, 2010).

The improvement in rice-production technology and livestock/manure management can help in mitigation of 9% of the total anthropogenic CH_4 and better crop-land management can mitigate about 2% of the total N_2O emission from agriculture. The majority of the potential (70%) can be realized in developing countries (Smith et al., 2007). The core challenge of climate change adaptation and mitigation in agriculture is to produce more with higher efficiency, under more volatile production conditions, and with net reductions in GHG emissions. Elimination or reduction of trace gas fluxes from soil would significantly impact carbon-equivalent impacts of agriculture (Gaunt and Lehmann, 2008). Recently, the concept of climate-smart agriculture has been proposed to overcome the adverse effects of climate change on agriculture. This concept includes many of the field-based and farm-based sustainable agricultural land management practices, such as conservation tillage, agroforestry, residue management, and water management (FAO, 2011; Nelson et al., 2010a,b; Pye-Smith, 2011; World Bank, 2011). Most of the focus of climate-smart agriculture has been on the implementation of these field and farm practices, and the ways in which they can be improved in the context of a changing climate.

The potential to offset GHG emissions from agricultural sources is largely based on studies documenting the GHG mitigation potential of production systems. It is important, however, to consider the net result of fluxes for all three major biogenic GHGs (ie, CO_2, N_2O, and CH_4) on radiative forcing, which is essential for understanding agriculture's impact

on the net GWP. Soil-management practices are known to affect the CO_2, CH_4, and N_2O (Ball et al., 1999; Omonode et al., 2007). Some of the most important adaptation and mitigation approaches with high potential have been reviewed here.

6.1 Conservation Agriculture-based Crop Management Technologies

In recent years, CA, defined as minimal soil disturbance and permanent organic soil cover combined with efficient and economically viable rotations (FAO, 2009a–c), has emerged as an important cropping system management strategy to address climate-related challenges in agriculture. The CA is designed for optimizing crop yield and reaping economic and environmental benefits by simultaneously conserving the soil, water, and nutrient resources. The problems of soil and water erosion, pests and disease problems, climatic problems like drought, limited water availability, and unfavorable profit margin are the most important motivations for the farmers to adopt CA (Chauhan et al., 2000; Sharma et al., 2004a,b, 2007a,b; Chhokar et al., 2007; Jat et al., 2009a,b,c; Saharawat et al., 2010).

Studies showed that CA can enhance soil carbon sequestration at a rate ranging from about 0.2–1.0 t/ha per year depending on the agroecological location and management practices (Corsi et al., 2012). The carbon sequestration to soil organic carbon (SOC) would: (1) help mitigate greenhouse gas emissions contributing to global warming and (2) increase soil productivity and avoid further environmental damage from the unsustainable use of intensive tillage systems. However, most of the soil carbon sequestered is not permanent and can be lost if the improved management practice is stopped. The effect of the same management practice on SOC is expected to be different in different locations with different soil types and climatic regimes (rainfall and temperature). Hence, regional methods of assessment will be necessary. CA can also substantially reduce CO_2 emissions through reduced diesel use and increased sequestration of C in the soil, and by reducing or eliminating the burning of crop residues. The key for the implementation of CA as a GHG-mitigation strategy is the understanding of the combined effects of practices on all GHGs and developing the necessary component technologies and fertilization practices to reduce the emissions of N_2O, since any gains in reduction of CO_2 and CH_4 emissions may be offset by increased N_2O emissions (Hobbs and Govaerts, 2010).

The CA practices which are also referred to as win–win agriculture have been adopted and are rapidly expanding in tropical, subtropical, and

temperate regions of the world under both rainfed and irrigated systems, globally occupying about 125 M ha in all continents and all agricultural ecologies (Friedrich et al., 2012). At present adoption has been low (4.72 M ha) in Asia, particularly in South Asia where the awareness and adoption of CA is on the increase (Friedrich et al., 2012). Largest area with 49.6 million ha (46.6% of total global area) under CA is in South America followed by North America (40 million ha, 37.5%), Australia and New Zealand (12.2 million ha, 11.4%), Asia (2.6 million ha, 2.3%), Europe (1.5 million ha, 1.4%), and Africa with 0.5 million ha, 0.4% (Kassam et al., 2009).

Several studies (Derpsch et al., 1991; Pretty et al., 2006; Landers, 2007; Erenstein et al., 2008; FAO, 2008; Hengxin et al., 2008; Rockstorm et al., 2009; Hobbs and Govaerts. 2010; Jat et al., 2010, 2011a,b; Sharma et al., 2008 and many others) have shown crop yield and/or soil-health improvement under CA as compared to tillage systems. The yield differences in the range of 20–120% between CA systems and tillage systems have been reported in Asia, Latin America, and Africa. In addition, the benefits of CA have also been reported in the form of reduced infestation of insects like termite, weeds, and important diseases like powdery mildew and Karnal bunt (Sharma et al., 2004a,b, 2007a Chhokar et al., 2007).

Permanent ground cover is a critical aspect of CA and it is important for several reasons. The presence of residue at the soil surface prevents aggregate breakdown by direct raindrop impacts as well as by rapid wetting and drying of soil (LeBissonnais, 1996). Results from rainfed and irrigated long-term trials in Mexico have shown that not ZT as such, but the combination of ZT with retention of sufficient soil-surface crop residue resulted in improved physical, chemical, and biological soil quality (Hobbs and Govaerts, 2010; Govaerts et al., 2009a,b). Moreover, it has been reported that ZT without residue retention results in deteriorated soil beyond the conventional tillage practices (Govaerts et al., 2005, 2006a,b, 2007a,b). However, the long-term experiments in the subtropical climate of India have shown the benefits of ZT wheat after manually harvested paddy, leaving only a small amount of anchored residue, on soil physicochemical properties (Sharma et al., 2005) and significant improvement in SOC (Sharma et al., 2008) and associated physical, chemical, and biological soil quality when wheat and/or paddy crop residue was left on the surface or incorporated into the soil. Changed temperature patterns and increased soil temperature especially at seeding and seedling emergence can negatively affect crop production. Therefore, in tropical hot soils mulch cover reduces soil peak temperature significantly

(often between 2 and 8°C during day) in zero-tilled soil favoring biological activities and initial crop growth (Acharya et al., 1998; Oliveira et al., 2001).

CA practices increased water stable aggregates, reduced soil strength, enhanced water-holding capacity, and infiltration rate, hence reduced runoff resulting in lower soil erosion, increased soil penetrability of roots, and increased microbial population including earthworms (Li et al., 2007a,b; Kladivko, 2001; Govaerts et al., 2007a,b, 2009a; Hobbs and Govaerts, 2010; Sharma et al., 2005, 2008). Soil sodicity and salinity can be ameliorated by CA practices. Under permanent raised-bed planting with residue retention, sodicity was reduced significantly reducing Na concentration by 2.64 and 1.80 times in 0–5 cm and 5–20-cm layer, respectively compared to conventional tilled raised beds (Govaerts et al., 2007c). Compared to conventional tillage, values of exchangeable Na, exchangeable Na percentage, and dispersion index were lower in an irrigated vertisol after 9 years of minimum tillage (Hulugalle and Entwistle, 1997).

The CA-based RCTs improve resource- or input-use efficiency (including water, air, fossil fuels, soils, inputs, and people) and provide immediate and demonstrable economic benefits such as reductions in production costs, savings in water, fuel and labor requirements, and timely establishment of crops leading to improved yields. Laser land leveling, bed planting, ZT, direct drilling in surface-retained residue, direct seeding of rice (DSR), residue management to avoid burning, alternate wetting and drying (AWD) in rice, site-specific nutrient management, diversification/intensification, and alternative land uses/agroforestry are some innovative CA-based RCTs, which are able to quickly respond to critical needs that address the concerns (eg, farm economics and climate change) faced by South Asian agriculture (Sharma et al., 2002; Barclay, 2006, Ladha et al., 2009; Saharawat et al., 2012). The RCTs are increasingly being adopted by farmers in the rice–wheat belt of the IGPs in South Asia because of several advantages like labor saving, water saving, and early planting of wheat (Chauhan et al., 2000; Sharma et al., 2005; Gupta and Sayre, 2007; Gupta and Seth, 2007; Saharawat et al., 2010). In wheat–rice cropping system of IGP across India, Pakistan, Nepal, and Bangladesh, there is large adoption of zero-till (ZT) wheat (~5 M ha), but only marginal adoption of permanent no-till systems and full CA. Yields of rice and wheat in heat and water-stressed environments can be increased significantly by adopting CA-based RCTs, which minimize unfavorable environmental impacts (Kataki, 2001; Pathak and Wassmann, 2007). Potential benefits of some of the CA-based RCTs in terms of climate change adaptation are listed in Table 11.

Table 11 Potential benefits of the key CA-based RCTs in terms of climate change adaptation relative to conventional practices.

CA-based RCTs	Potential benefits relative to conventional practices
ZT	Reduced water use, C sequestration, similar or higher yield and increased income, reduced fuel consumption, reduced GHG emission, more tolerant to heat stress
Laser-aided land leveling	Reduced water use, reduced fuel consumption, reduced GHG emissions, increased area for cultivation, increased productivity
Direct drill seeding of rice	Less requirement of water, time saving, better postharvest condition of field, deeper root growth, more tolerance to water and heat stress, reduced methane emission
Diversification	Efficient use of water, increased income, increased nutritional security, conserve soil fertility, reduced risk
Raised-bed planting	Less water use, improved drainage, better residue management, less lodging of crop, more tolerant to water stress
Leaf color chart (LCC) for N management, nitrification inhibitors	Reduces fertilizer N requirement, reduced N loss and environmental pollution, reduced nitrous oxide emission
Crop residue management	Moderates soil temperature, improves soil quality, reduces soil erosion, reduces evaporation losses and conserves soil moisture, increases C sequestration, avoids burning and reduces environment pollution, increases tolerance to heat stress, reduces weed infestation.
Sprinkler/drip irrigation	Increases water and nutrient-use efficiency, reduces GHG emissions, increased productivity

Source: Adapted from Wassmann et al. (2009a,b).

The adoption of RCTs and CA have the potential to reduce the release of GHGs especially carbon through its sequestration in soil as well as reduction in the use of external inputs. To evaluate the GWP one must take into account the GHG emissions from soil, carbon sequestration, fuel used for farm operations, and the production of inputs (West and Marland, 2002;

Robertson et al., 2000). To assess the GWP of RCTs, Pathak et al. (2011a,b, 2013), Pathak and Aggarwal (2012) and Saharawat et al. (2012) used InfoRCT (Information on Use of Resource-Conserving Technologies) simulation model in India. In China, Wang et al. (2012) used a process-based Denitrification and Decomposition (DNDC) model to assess the long-term impact of various management alternatives on GWP for the rice–wheat rotation. The DNDC model provided a sound basis for comprehensive understanding of the effect of alternative management practices on soil C and N cycles involved in global warming. They reported that SSNM followed by no-tillage scenario could mitigate global warming without decreasing crop yield in rice–wheat system.

Overall, CA systems have higher adaptability to climate change because of the higher effective rainfall due to higher infiltration rate and soil moisture holding capacity, therefore, minimum flooding and soil erosion (Table 11). Derpsch et al. (1991) and Sharma et al. (2005) illustrated that soil moisture conditions in rooting zone under CA remains better than under minimum and conventional tillage throughout the growing season leading to extended crop cycle and longer period of nutrient absorption resulting in increased WUEs and nutrient-use efficiencies. In well-managed CA systems in Brazil, infiltration rate was far superior (120 mm/h) than traditional tillage (20 mm/h), which could maximize effective rainfall, recharged ground water, and reduced the risk of flooding (Landers, 2007). In rain-fed condition in the semiarid high lands of Mexico, Verhulst et al. (2011) observed that ZT with residue retention resulted in a good topsoil structure including higher earthworm biomass as compared to ZT with residue removal and conventional tillage. At the start of the dry spell, ZT with residue retention had 50 mm more water stored in the soil profile than the other practices.

Govaerts et al. (2006a, 2009a,b) reported that GWP of the GHGs was lowest in ZT with removal of crop residue. However, this practice is not a sustainable option for farmers, since it degrades soil quality and results in low yields compared to when residue is retained. Pathak et al. (2011b) reported that GWP of different RCTs differed among ecoregions. For example, in the ZT technology, GWP was 111 kg CO_2 ha^{-1} in the upper-IGP and negative (-61 kg CO_2 ha^{-1}) in the lower-IGP. Similarly, in the lower-IGP, ZT in wheat resulted in the negative GWP, which is not the case in upper-IGP. All the RCTs reduced GWP by 13–38%. Although GWP of many technologies was less than conventional management, all of them were not feasible in terms of their economic return. Among different RCTs (mid-season drying in rice, DSR on raised beds, transplanted rice on raised beds, ZT-DSR

and ZT transplanted rice followed by ZT wheat), the lowest values of GWP were recorded for DSR on raised beds and the maximum in CT (Pathak et al., 2009).

6.1.1 Zero Tillage

The work on ZT in India was initiated with the import of two ZT machines imported from New Zealand during the year 1992. The machine was too heavy for the tractors being used at that time and the first Indian version was made during 1993. The initial trials conducted, during 1993–95, with a time difference of 7–10 days showed yield gains of about 8% mainly due to time difference (Anonymous, 1996; Sharma et al., 2005). However, when time of seeding was the same, the yield was higher in wheat following direct-seeded rice (DSR) compared to puddle transplanted and tillage in wheat gave similar results (Anonymous, 1995) except in wheat under ZT following transplanted rice. Since the sowing time was not an issue in the northern IGP, the subsequent experiments and farmers' field trials showed that yield levels are similar under both ZT and conventional till drill sown but about 10% higher than farmers' practice of broadcast sowing after conventional tillage (Sharma et al., 2004c, 2005). In addition, there are huge savings (about 90%) on energy, time, and tillage cost in wheat production with about 3–5% savings on water (Anonymous, 2000; Chauhan et al., 2000; Sharma et al., 2004c, 2005). Many studies conducted across the production systems under varied ecologies of South Asia (Gupta et al., 2002, 2003; Malik et al., 2005; Gupta and Sayre, 2007; Gupta and Seth, 2007; Chandra et al., 2007; Jat et al., 2009a,b, 2010, 2011a,b; Sidhu, 2010; Gathala et al., 2010, 2011; Parihar et al., 2011; Chauhan et al., 2011; Saharawat et al., 2012) have revealed the potential benefits of the previously mentioned RCTs (Table 12), which also play an important role in mitigating climate change (Table 13). In India, the adoption of no-till practices by farmers has occurred mainly in the wheat portion of the wheat–rice double-cropping system.

The ZT has also been promoted as a practice capable of offsetting GHG emissions because of its ability to sequester carbon in soils (Six et al., 2004). Emission of CO_2 is often lower in ZT than in conventional tillage (Almaraz et al., 2009; Sainju et al., 2008), although the opposite has also been reported (Oorts et al., 2007). Dendooven et al. (2012a) reported that net GWP was near neutral or negative for ZT with crop-residue retention (40 kg CO_2-C/ha per year), whereas in the other management practices it was approximately 2000 kg CO_2-C/ha per year. Tillage and residue management had little effect on GHGs emitted from the soil. As such, the difference in GHGs

Table 12 Effect of different CA-based crop management technologies on yield gain, water saving, and increase in water productivity (WP) over conventional practice in IGPs.

Technologies	Crop/ cropping system	Yield gain (kg/ha)	Water saving (ha-cm)	Increase in WP (kg/m^3)	References
Laser leveling	Rice–wheat	750–810	24.5–26.5	0.06	Jat et al. (2009a,b)
	Rice	750	22.0	—	Sidhu (2010)
No till	Wheat	150–140	2–4	0.10–0.21	Malik et al. (2005)
	Wheat	610	2.2	0.28	Saharawat et al. (2010); Gathala et al. (2011)
	Maize	150	8	0.21	Parihar et al. (2011)
No till with surface residue	Rice–wheat	500	61	0.24	Gathala et al. (2010)
	Wheat	410	10	0.13	Jat et al. (2009c)
DSR	Rice	120	25	0.08	Jat et al. (2006a)
	Rice	510	13	0.09	Gill et al. (2006)
	Rice	62	18	0.10	
Raised-bed planting	Maize	324	12	0.80	Jat et al. (2006b)
	Wheat	310	16	0.58	Jat et al. (2011a,b),
	Wheat	270	5	0.50	Chandra et al. (2007)

Source: From Chauhan et al. (2012).

between ZT and CT due to machinery use became an important factor. Zero till reduced the C emission of farm operations with 74 kg C/ha per year compared to CT. ZT cultivation also saves fossil-fuel consumption by more than 90% and the CO_2 released only from fuel consumption for field preparation in conventionally cultivated wheat was more than 200 kg/ha compared to only around 15 kg/ha in zero-till sown wheat (Chauhan et al., 2000; Sharma et al., 2005). Using ZT for wheat on 1 ha of land in the rice–wheat cropping systems of the IGP can save 1 million L of irrigation

Table 13 Grain yield and simulated GHG emissions (CO_2 equivalent) in rice–wheat system with different tillage and crop establishment practices in IGPs.

Technology	Grain yield (t/ha)[a]		Net income (US$)	[b]GHG emissions-CO_2 eq. (kg/ha)		
	Rice	Wheat		Rice	Wheat	Total
Rice transplanted after conventional puddling, wheat broadcasted after conventional tillage	6.4	4.8	621 ± 31	3286	597	3884
Rice transplanted in unpuddled fields/wheat drill-sown in zero tillage (ZT)	6.7	4.8	645 ± 20	3174	576	3750
Transplanted rice on raised beds/wheat drilled on same beds after reshaping	5.8	4.8	578 ± 10	2209	591	2799
Transplanted rice with zero till/wheat drill sown in ZT	6.45	4.8	639 ± 18	2491	542	3033
Direct drill-seeded rice/ZTW	6.2	4.8	674 ± 23	2482	564	3046

[a]Means of 2 years.
[b]Including soil, fertilizer, machine, biocide, etc.
Source: From Saharawat et al. (2012).

water and 98 L of diesel as well as reducing carbon dioxide emissions by 0.25 t (Reeves et al., 2001; Pathak et al., 2009; Pathak, 2010). While the amount of C that can be sequestered in soil is finite, the reduction in net CO_2 flux to the atmosphere by reduced fossil-fuel use can continue indefinitely (West and Marland, 2002). The C sequestration in ZT with residue retention was approximately 2 t C/ha per year higher than in practices involving tillage or ZT with residue removal.

Adopting ZT allows rice–wheat farmers to sow wheat crop sooner after a rice harvest, wherever the sowing is getting delayed facilitating the crop to mature before the onset of premonsoon hot weather. As average temperature in the IGP region rises because of climate change, early sowing will become even more important for wheat (Aggarwal and Pathak, 2009). Erenstein and Laxmi (2008) reported a 5–7% yield increase, mostly due to timely planting of wheat and Sharma et al. (2005) reported a yield gain of about 8% when sowing is advanced by 7–10 days for ZT wheat after rice compared to CT in the IGP of South Asia.

Although fertilizer application is the largest contributor to N_2O emission from soil, studies conducted in different parts of the world have indicated contrasting results on the impact of ZT on N_2O emission, with lower (Beheydt et al., 2008; Ussiri et al., 2009; Patino-Zuniga et al., 2009; Jacinthe and Dick, 1997; Xiao et al., 2007), or have no effect (Lemke et al., 1999; Jantalia et al., 2008; Johnson et al., 2010), or higher (Rochette et al., 2008; Robertson et al., 2000) emissions compared to conventional tillage in different cropping systems. However, Rochette et al. (2008) demonstrated that in heavy soils average N_2O emissions in ZT were more than double than conventional tillage and further observed that N_2O emissions only increased in poorly drained and finely textured soil under ZT located in humid region, but not in well-drained aerated soil. Six et al. (2004) reported that in both humid and dry climates, differences in N_2O emissions between the two tillage systems changed over time. During the first 10 years, the N_2O fluxes were higher in ZT regardless of climate, while in 20 years, N_2O emissions in a humid climate were lower in ZT and were similar in tillage systems in dry climates. Emission of N_2O is a result of many interacting processes and it is difficult to predict how tillage practice will affect it. It can be speculated that lower temperatures, better soil structure, and less compact soils in ZT than in conventional tillage will reduce emissions of N_2O, while increased soil organic matter, water content, and mineral N contents will favor emissions of N_2O.

It has been reported (Harman et al., 1998) that the elimination of the presowing irrigation in a ZT system results in water savings of 25% compared to conventional tillage systems for maize and sorghum in the Texas High Plains. Because ZT takes immediate advantage of residual moisture from the previous rice crop, as well as cutting down on subsequent irrigation requirements, water use is reduced by about 10 cm or approximately 1 million L/ha (Malik et al., 2002). However, it had been contested (Sharma et al., 2004c, 2005) that this contention is misplaced as the residual moisture can be used for field preparation and seeding of wheat and irrigation water savings for subsequent irrigations for growing wheat is about 3% indicating a savings of about 0.12 million L/ha.

6.1.2 Furrow Irrigated Raised-bed Planting System

The raised beds cultivation of irrigated wheat in the rice–wheat system of the IGP was inspired by the success of beds for wheat–maize systems in Mexico (Sayre and Hobbs, 2004; Akbar et al., 2007; Lumpkin and Sayre, 2009). Raised-bed planting not only reduces irrigation water use by 12–60%

(Balasubramanian et al., 2003; Gupta et al., 2003; Hossain et al., 2003; Jehangir et al., 2002) and improves drainage but also reduces CH_4 emission. Singh et al. (2003) reported that compared to transplanted rice, DSR on flatland and on raised beds reduced total water input during crop growth by 35–42% when the soil was kept near saturation and by 47% when the soil dried out to 20-kPa moisture tensions in the root zone. Most of the water savings were caused by reduced percolation losses. There are several reports of reduced irrigation amounts or time by up to 30–40%, with similar or higher yields for wheat on raised beds compared to conventional tilled wheat (Anonymous, 2001; Connor et al., 2003; Dhillon et al., 2000; Bhardwaj et al., 2009; Ram et al., 2011a,b; Sharma et al., 2005). In the rice–wheat systems of IGP, irrigation water saving ranged from 18 to 50% with adoption of bed planting system (RWC-CIMMYT, 2003; Gupta et al., 2002; Jat et al., 2005). In addition, there were savings of about 25% nitrogen and 25–50% seed (Anonymous, 1999, 2000, 2001), indicating much higher nitrogen and WUEs in bed planting compared to conventional flat plating of wheat. Crops on beds with residue retained on surface are less prone to lodging and more tolerant to water stress, thereby making it more adaptable to unfavorable climate.

Permanent bed systems are forms of irrigated CA, which would conserve both natural resources, water and soil, but conflicting reports for rice–wheat systems deter farmers' interest in north-western India (Singh et al., 2008b,c; Kukal et al., 2008). It is more so due to much lower rice yields of direct dry seeded and transplanted rice even under ZT (Anonymous, 2010), especially, in light to medium textured soils. In nonrice-based cropping systems, water-logging can also be minimized under this method. There are a number of reports suggesting significantly higher maize grain yields under bed planting than under conventional or ZT on the flat on fine-textured soils with poor drainage prone to flooding (Anonymous, 1999; Cox et al., 1990; Dhadli et al., 2009, Jat et al., 2013).

In cotton, planting on raised beds of 76.5 cm gave 44% higher yield compared to flat beds with similar spacing (Anonymous, 1999) and broad beds with spacing of 135 cm and planting cotton in furrows in paired rows increased yield by 44% and saved 40% of irrigation water compared to normal row spacing of 67.5 cm in flat bed system (Hira, 2009) and planting potatoes on both sides of a narrow bed increased tuber yields (24 t/ha) by 25% and saved 20% of irrigation water as a compared to ridge-planting method. Earlier, Aujla et al. (1991) reported a saving of 100–150 mm of water in cotton planted on ridges with no yield loss compared with flood irrigation on flat land.

6.1.3 Dry Direct-seeded Rice

Conventional puddled transplanted rice (PuTPR) consumes a large quantity (120–180 cm) of water (Chauhan et al., 2012). Dry direct seeded rice (DSR) is considered a viable agrotechnology to cope with the looming crisis of water supply that threatens the sustainability of irrigated rice-production systems (Bouman and Tuong, 2001; Sharma et al., 2002; Bouman et al., 2007a,b). Bouman et al. (2005) reported that, on average, DSR required 190-mm less water for land preparation and had 250–300-mm less seepage and percolation losses than a PuTPR field. Overall, DSR needs 25–57% less water than conventional lowland rice. It has been reported to produce similar or lower grain yields in many studies conducted in South Asia (Anonymous, 2010; Gupta et al., 2003; Kumar and Ladha, 2011; Humphreys et al., 2010; Lampayan et al., 2010; Singh et al., 2003, 2008b,c; Farooq et al., 2009; Mahajan et al., 2011a,b,c). The lower yields are generally recorded on coarse-textured well-drained soils whereas almost similar yields are recorded in fine textured and poorly drained soils.

Since DSR crop does not require continuous soil submergence, thereby it either reduces or totally eliminates CH_4 emission. Moreover, the deeper root growth of DSR crop provides better tolerance to water and heat stress. Pathak et al. (2013) reported that DSR saved 3–4 irrigations compared to the transplanted rice, and without any yield penalty. Human labor use was reduced by 45%, and tractor use was reduced by 58% in the DSR compared to PuTPR. Total GWP of DSR was lower (1.5–2.9 t CO_2 eq./ha) than the PuTPR (2.0–4.6 t CO_2 eq./ha). If 50% area is converted to DSR in Indian Punjab, which seems a distant possibility owing to generally well-drained coarser textured soils, GHG emission will be reduced by 16.6% of the current emission. However, authors emphasized the need for optimal fertilizer N management to minimize N_2O emissions that can increase under resulting aerobic conditions. Using InfoRCT model, Pathak et al. (2011b) demonstrated that the major effect of RCTs was on the reduction of emission of CH_4 and CO_2 in rice and the lowest emissions were recorded in DSR on beds and the highest in PuTPR.

6.1.4 Crop-residue Mulching

Based on the mean residue to grain ratio for different crops, annual production of crop residues is estimated at 3440 MT in the world, while residues from grain cereals constitute about 73.5% of the total residues (Lal, 1997). In India, more than 140 MT of crop residues are disposed off by burning each year of which 22 MT (rice residue) is burned in Indian Punjab to clear the

fields for timely sowing of wheat (Singh et al., 2010d). In IGP of South Asia, where rice–wheat is the main cropping system, there are few options for rice straw because of the poor quality for forage, bioconversion, and engineering applications. Farmers burn the rice straw to establish the wheat crop rapidly since the labor availability is limited. The field burning of crop residues is a major contributor to reduced air quality (particulates, GHG), human respiratory ailments, and the death of beneficial soil fauna and microorganisms. During burning of crop residues around 80% of the carbon is lost as CO_2 and a small fraction is evolved as CO. Burning involving incomplete combustion can also be a source of net emissions of many GHGs including CO, CH_4, SO_2, and N_2O. Apart from loss of carbon, up to 80% of N and S, 25% of P, and 21% of K losses occur during burning of crop residues (Ponnamperuma, 1984; Singh et al., 2005).

Rice straw can be managed successfully in situ by allowing sufficient time between its incorporation and sowing of the wheat crop (Singh et al., 2005). The incorporation of rice residue into the soil typically had a small effect on wheat yield during the short term of 1–3 years, but the effect appeared in the fourth year of incorporation (Singh et al., 2005, 2008a; Gupta et al., 2007). Crop residues when applied to soil have significant effects on soil organic matter, and physical, chemical, and biological properties of soil (Bhatnagar et al., 1983; Kumar and Goh, 2000; Singh et al., 2005, 2008a; Chauhan et al., 2012; Sharma et al., 2008).

Another solution to avoid burning of rice straw would be to use it as soil mulch in wheat cultivation to improve crop yields, conserve soil moisture, and saving of irrigation water. However, there are problems with direct drilling of wheat into combine harvested paddy fields. Loose straw accumulates and drags with the seed-drill furrow openers, the seed-metering drive wheel loses traction due to the presence of loose straw and the depth of seed placement is nonuniform due to frequent lifting of the implement under heavy trash conditions. Two new machines, known as the "Happy Seeder" and Rotary Disc Drill, are now available, which are capable of direct drilling (ZT) wheat into heavy rice or other type of residues in a single operation. Wheat yield for ZT with mulch plots was similar or more than the conventionally sown wheat (Sharma et al., 2008; Sidhu et al., 2007, 2011). Additional advantages like less weed infestation (Chhokar et al., 2009), water savings, improved soil health, and reduced GHG emissions were also noted under ZT with residue retention (Mandal et al., 2004; Singh et al., 2005; Sharma et al., 2008; Alvarez and Steinbach, 2009). Residue mulch lowered canopy temperature by about 2.9°C at the grain-filling stage to mitigate the

terminal heat effects in wheat (Jat et al., 2009c; Gupta et al., 2010), and significantly improved C sustainability index (Jat et al., 2011b).

Mulching in nonflooded crops has significant effect on soil water conservation in reduced and no-tillage systems and the effect was more pronounced during dry periods (Rahman et al., 2005; Singh et al., 2008a; Verhulst et al., 2010, 2011). Singh et al. (2011) reported that rice straw mulch in wheat in rice–wheat system in the IGP of India, reduced evaporation by 42–48 mm during wheat growing season. Chakraborty et al. (2010) reported that compared to no-mulch, mulches produced 13–21% higher grain yield and more roots (25 and 40% higher root weight and root-length densities) in subsurface (>0.15 m) layers, probably due to greater retention of soil moisture in deeper layers. Mulches were effective in reducing 3–11% of crop water use and improved its efficiency by 25%. Experiments conducted by Sidhu et al. (2007) suggest that mulching might reduce the irrigation requirement of wheat during the growing season due to reduced soil evaporation, and some anecdotal reports indicate a saving of one irrigation (OFWM, 2002). Savings in irrigation water in mulched upland crops can be attributed to suppression of soil evaporation.

A third option for rice straw management is its collection from the paddy fields manually, or using a baler, for application as surface mulch for summer crop production. Straw mulching has shown a considerable promise to reduce loss of soil water by evaporation, regulate soil temperature, and suppress weeds. Apart from adjusting the growing period of crops as it has been done for rice in Punjab, mulching is the only practice that reduces evapotranspiration (ET) by decreasing evaporation. A number of studies carried out in India have reported substantial increase in economic yield with reduction of irrigation water requirement in several field and vegetable crops grown during spring and summer (Jalota et al., 2007; Sekhon et al., 2005). Jalota and Arora (2002) reported that straw mulching reduced evaporation by 15.8 cm in maize and 20 cm in cotton and sugarcane.

In contrast to the RW system in IGP, disposal of the wheat residue preceding rice crop is a major challenge in other places, particularly in China. There are few reports of evaluation of mulching in rice, apart from those from China, where considerable irrigation water savings (20–90%) occurred with straw mulch in combination with nonflooded conditions compared with continuously flooded transplanted rice, with no adverse effects on grain yield (Huang et al., 1999a,b; Lin et al., 2003; Pan et al., 2003; Shen and Yangchun, 2003; Fan et al., 2005; Qian et al., 2006). Zhang et al. (2008) demonstrated that straw mulch substantially increased

Table 14 Irrigation water applied and WUE for two rice cultivars under nonflooded mulching cultivations.

Treatment	Irrigation water (mm) Zhendao 88	Shanyou 63	WUE (kg grain/m^3) Zhendao 88	Shanyou 63
CF-NM	943a	962a	0.94c	0.96c
−25 kPa-NM	243b	248b	1.87b	2.28b
−25 kPa-SM	216c	191c	3.83a	4.04a

The CF indicates conventional flooding cultivation, and SM, and NM are wheat straw mulching and no mulching under nonflooded conditions. Values are averages across the five years (2003–07). Letters after the values indicate least significant difference *(LSD)* at the *P* =0.05 level within the same column and the same cultivar.
Source: From Zhang et al. (2008).

WUE compared to no mulch and maintained grain yield as high as from the traditional flooding (Table 14).

Residue-management practices may induce important changes in the N_2O emissions from agroecosystems, with additional impacts on CO_2 emissions. Abalos et al. (2013) reported that incorporation of maize stover increased N_2O emissions by about 105% over no residue. Dittert et al. (2003) found negligible CH_4 emission but increased N_2O emission when previous crop residue was used as mulch in rice crop. On the contrary, in an extensive review of the work carried out in Asia, Yan et al. (2005a) found that residue retention on surface caused a significant and often very large increase in CH_4 emission compared with residue removal. The more decomposed the residue is before flooding, the less is the CH_4 emitted. The decomposition of residue before soil flooding for rice production can be accomplished by (1) incorporating crop residue soon after harvesting a crop and allowing it to decompose aerobically before soil flooding for the next rice crop (Wassmann et al., 2000a,b,c,d; Yan et al., 2005a,b), (2) composting the residue off-field (Yagi and Minami, 1990; Corton et al., 2000), or (3) feeding the residue to cattle and returning it as manure (Setyanto et al., 2000; Wang et al., 2000).

6.1.5 Crop Diversification

Crop diversification is useful in providing higher protection against the risk associated with climate change, in addition to assured net returns to the farmers. Risk reduction through crop diversification related to climatic and biotic vagaries, particularly in fragile ecosystems, and commodity fluctuations will contribute to improved food security and income generation for resource-poor farmers and protect the environment (Behera et al., 2007). Rice–wheat cropping systems are the most important cropping systems for food security in South Asia, but the sustainability

Table 15 Net return, irrigation water applied, and electric consumption of different cropping systems under Trans-Gangetic plains of India.

Cropping system	Total variable cost (INR/ha per year)	Net return (INR/ha per year)	Irrigation WUE (kg grain/m^3)	Electricity consumption (units/ha per annum)
Maize–potato–onion	83,383	125,023	130	1,205
Maize–potato–pearl millet	64,250	78,588	105	973
Maize–wheat–pearl millet	48,255	72,797	92	853
Rice–wheat	39,318	59,742	212	1,963

Source: From Gangwar and Singh (2011).

of the system is threatened because of the shortage of resources such as water and labor (Ladha et al., 2003a,b). The farmers have taken the initiative to diversify agriculture by including short-duration crops such as potato, soybean, black gram, green gram, cowpea, pea, mustard, and maize in different combinations (Table 15) giving more profit and saving water significantly (Gangwar and Singh, 2011). However, lack of profits, price support, and marketing bottlenecks for the alternative crops are some constraints in adopting diversification. Inclusion of certain crops in sequential and intercropping systems has been found to reduce nutrient and water requirements, and also the population of some obnoxious weeds to a considerable extent (Chauhan et al., 2012).

Further, inclusion of legumes in cropping systems has been found to be effective in reducing nitrate leaching in lower soil profiles and legumes also play an important role in conserving groundwater and soil water (Chauhan et al., 2012). Replacing rice with cotton, maize, and basmati rice in summer season and wheat with oil-seed (rapeseed mustard) crops and chickpea in winter season can lower ET and reduce irrigation requirement (Jalota et al., 2009). Hira (2009) suggested reducing the rice area in Punjab by about 1 m ha and cultivating *Bacillus thuringiensis* (BT) cotton, *kharif* maize, soybean, and groundnut, which require only 2–5 irrigations. Water used in the maize-based system was less than the quantity of water used for the rice–wheat system, with corresponding savings in electricity consumption, thereby contributing to GHG reduction. Pathak et al. (2011b) reported that in crop diversification, where rice was replaced with an upland crop like maize with less water requirement, no CH_4 emission occurred. In other

places, shifting to a totally different mix of crops will be required to cope with dramatic changes in rainfall or temperature, and cropping systems will fundamentally change as a result.

6.1.6 Efficient Water Management

With the increased demand for water from other sectors, it is a must to improve WUE in agriculture. Adding climate change to this mix only intensifies the demands for efficient use of water in agriculture. Climate change will burden currently irrigated areas and may even outstrip the current irrigation capacity due to general water shortages. Farmers with no or less access to irrigation are clearly most vulnerable to climate change. Based on climate scenarios for 2020 and 2050 obtained from the HadCM3 model outputs using 1960–90 as the base line, a study carried out by Central Research Institute for Dryland Agriculture (CRIDA) (unpublished) on four crops grown in major districts of India, indicated a 3% increase in crop water requirement for wheat, maize, mustard, and groundnut by 2020 and 7% by 2050 across all the locations. Therefore, there is need for technologies and investments that improve WUE, access to irrigation water, or to find ways to improve income with less secure and more variable access to water.

Improving the inefficiencies in delivery system requires investment and farmers participation for integrated water management. There is need for rational pricing of surface and groundwater which can arrest its excessive and injudicious use in overexploited regions like Punjab, Haryana, and Tamil Nadu in India. The development of infrastructure could result in better utilization of groundwater in the regions with underutilized ground water like eastern India.

Rice is the greatest consumer of water among all crops and consumes about 80% of the total irrigated fresh water resources in Asia (Bouman and Tuong, 2001; Maclean et al., 2002). By the year 2025, it will be necessary to produce about 60% more rice than is currently being produced to meet the food needs of a growing world population (Fageria, 2007). In rice as well as in other crops, many ways of conserving water have been investigated and techniques such as 2-day drainage interval between irrigations following 2 weeks of continuous ponding after transplanting, AWD, deficit irrigation, and drip irrigation substantially save irrigation water without any reduction in grain yield and enhanced WUE (Zhang et al., 1998; Kang et al., 2000; Tabbal et al., 2002; Li et al., 2010; Bouman, 2007, Zhang et al., 2009; Sandhu et al., 1980). Kukal et al. (2005) demonstrated that irrigating transplanted rice based on soil water tension of 160 ± 20 cm enhanced water

productivity further compared to 2-day drainage interval practice earlier recommended by Sandhu et al. (1980). Other important practices responsible for saving irrigation water and increasing water productivity in rice include stopping irrigation 2 weeks before harvesting (Sandhu et al., 1982), and shifting rice planting date from high (mid May) to low (late June) evaporative demand periods, and replacing medium to long-duration varieties with shorter-duration varieties and hybrids which will contribute to substantial saving in irrigation water by reducing ET (Jalota et al., 2009; Sandhu et al., 2012). Narang and Gulati (1995) demonstrated that substantial irrigation water savings (25–30%) can be achieved by delaying transplanting from mid-May to mid-Jun.

In rain-fed areas, water conservation and water-harvesting techniques must be given due consideration for higher productivity and WUE. Watershed management is now considered an accepted strategy for development of rain-fed agriculture. A watershed approach has many elements, such as soil and water conservation works, farm ponds, and check dams which help both in adaptation and mitigation. This approach will moderate the runoff and minimize floods and soil erosion during high-intensity rainfall. Sharma et al. (2010) estimated that about 25 m ha of rain-fed area in eastern and central states of India has the maximum potential to generate runoff of 114 BCM which can be used to provide an additional supplemental irrigation in the entire 25-m ha area. Conjunctive use of surface and ground water is another important strategy for climate change adaptation and mitigation. Greater emphasis on water harvesting and improving the efficiency of regional as well as farm WUE could help face the uncertain rainfall. Appropriate policies are required to encourage farmers to conserve water and use it more judiciously.

Surface-irrigation methods are utilized in more than 80% of the world's irrigated lands and the field-level application efficiency is often 40–50% (von Westarp et al., 2004). Pressurized irrigation or microirrigation systems (sprinkler, surface, and subsurface drip) have the potential to increase irrigation WUE by providing water to match crop requirements, reducing runoff and deep drainage losses, reducing soil evaporation, and increasing the capacity to capture rainfall (Camp, 1998). There are few reports of the evaluation of these technologies in field crops in South Asia. Kharrou et al. (2011) reported that drip irrigation gave 28% higher wheat yield and 24% higher WUE compared to surface irrigation. Crop production per unit of water consumed by plant evapotranspiration is typically increased by 10–50%. Irrigation contributes to CO_2 emissions because

energy is used to pump water. Pathak et al. (2011b) reported that CH_4 emission was zero in the sprinkler irrigation technologies. In the sprinkler irrigation method, which resulted in no standing water in rice field, no CH_4 emission occurred. The average GWP of all the three GHGs with mid-season drainage was 1.9 Mg/ha and maximum global warming was because of CO_2, followed by nitrous oxide and methane. Emission of CH_4 from soil with mid-season drainage was only 0.1–0.3 Mg/ha CO_2 equivalent in the different districts of Punjab. They further observed that if the entire area under continuously flooded rice in the Indian Punjab is converted to mid-season drainage, the GWP will be reduced to 5.6 MT CO_2 eq. and would mitigate GWP by 16.7%. At a C trading price of 10 US$/t of CO_2 equivalent, this would bring US$28.0 million and US$14.0 million, respectively to the rice farmers of the state. However, the methodology for monitoring and transaction cost for processing the C trading have to be worked out.

With dwindling water availability, a "deficit irrigation" strategy, in which irrigation is applied at the drought-sensitive growth stages of a crop, can make a substantial difference in the productivity of areas having limited access to irrigation water. Within this context, deficit irrigation has been widely investigated as a valuable strategy for dry regions (Zhang and Oweis, 1999; English, 1990; Pereira et al., 2002; Fereres and Soriano, 2007) where the water is the limiting factor. Research results (compiled by Geerts and Raes, 2009) confirm that deficit irrigation is successful in increasing water productivity for various crops (Table 16) without causing severe yield reduction. Other water-saving technologies such as adoption of DSR and raised-bed planting have already been dealt with in the earlier sections.

In view of the decreasing water supplies, vigorous evaluation of utilizing industrial and sewage waste water in agriculture will be required. Such effluents, once properly treated can also be a source of essential plant nutrients. Since water has multiple uses and users, effective interdepartmental coordination is a must for the development of location-specific framework of sustainable management and optimum recycling of water.

6.1.7 Precision Land Leveling

Laser leveling of uneven fields can reduce evaporation and percolation losses by eliminating depressions and enabling faster irrigation (Jat et al., 2006). Hill et al. (1991) rated the development of laser land leveling as second only to breeding of high-yielding crop varieties for meeting the challenges of crop production and resource-use efficiency. Precision land leveling resulted in

Table 16 Summary of results on the sensitivity of different crops to drought stress during specific phonological stage and advisable deficit irrigation strategies as observed in some countries of South Asia and Latin America.

		Advisable deficit irrigation strategy		
Crop	**Location**	**Allow drought stress during**	**Avoid drought stress during**	**References**
Wheat	Ishwardi, Bangladesh	Maximum tillering and flowering	Crown root initiation and booting to heading	Ali et al. (2007)
Potato	Peshawar, Pakistan	Ripening	Establishment and tuber yield formation	Mohshin Iqbal et al. (1999)
Groundnut	Junagarh, India	Vegetative stage	Not reported	Nautiyal et al. (2002)
Tomato	Central Brazil	Vegetative stage	Fruit development and maturing	Marouelli and Silva (2007)
Cotton	Santiago del Estero, Argentina	Yield formation and ripening	Vegetative and bud formation	Prieto and Angueira (1999)
Common bean	Tumbaco, Ecuador	Moderate drought during ripening	Flowering	Calvache and Reichardt (1999)
Quinoa	Altiplano Bolivia	Vegetative, grain filling and ripening	Establishment, flowering, early grain filling	Geerts et al. (2006a,b 2008a,b)

irrigation water savings of 15–30% accompanied by increase in crop yield by 4–6% compared to traditionally leveled fields (Ahmed et al., 2001; Bhatt and Sharma, 2009; Rehman et al., 2009; Jat et al., 2009a,b,c, 2011a,b; Aggarwal et al., 2010a,b; Sidhu et al., 2010; Kaur et al., 2012). It also reduces fuel consumption due to efficient use of tractor and reduces GHG emission, particularly carbon dioxide. Currently this technique is being practiced in more than 1.5 million ha in South Asia (Jat et al., 2011a).

6.1.8 Nitrogen-use Efficiency

A primary requirement for the future is to produce higher yields with inputs that do not lead to environmental problems. Excessive nutrient additions degrade land, water, and air through leaching, eutrophication, and gaseous emissions (Vitousek et al., 2009). Generally, more than 50% of applied

N is not assimilated by plants (Ladha et al., 2005). Ideally nutrient additions (whether as mineral fertilizers or manures) and soil biota should be managed to deliver nutrients to crops in consonance with demand. The demand to reduce fertilizer inputs in South Asia (both due to the costs of chemical fertilizers, and concern over nutrient leaching to watercourses) may stimulate the adoption of rhizobacterial inoculants. Further research on rhizobacterial inoculation of major food crops seems warranted, given the demand for significant yield increments within a relatively short period of time, compared to the time required to develop new crop varieties (Dodd et al., 2011).

Emission of N_2O can be reduced by adopting management practices that improve N-use efficiency, including using slow or controlled release fertilizer or nitrification inhibitors which retard the microbial processes leading to N_2O formation (Robertson, 2004). The environmental impacts of increased N use are through nitrate leaching, the use of fossil fuels to manufacture, transport, and apply fertilizers, and N_2O emissions associated with denitrification (Foulkes et al., 2009). It is estimated that currently the production and use of 1 t of fertilizer N results in the emission of 1.9 t of CO_2 eq. (Mortimer et al., 2003). Improved fertilizer management can play an important role in reducing N_2O emissions from the field by increasing the fertilizer-use efficiency, thereby also reducing the emissions associated with manufacture and transportation. An important mitigation strategy for climate change is a reduction on the reliance of chemical inputs while maintaining yields. Since N_2O contributes to air pollution and the greenhouse effect, there is growing interest in identifying methods to reduce or optimize N application in agriculture, to develop crop varieties that are more responsive to N application (Vitousek et al., 1997) and are more efficient in its utilization from soil.

Large reduction in N_2O emissions and NO_3 leaching are possible with alternative management practices that match N fertilization with crop demand. It reduces N_2O emissions by more than 50% and NO_3 leaching by more than 60% without any reduction in N-fertilization rates (Matson et al., 1998). Further reductions were possible with the best alternative which also had lower application rates (Riley et al., 2001; Ortiz-Monasterio et al., 2010). The strategy to achieve this objective is the real-time N management using SPAD meter, LCC, and optical sensors. These new technologies optimize N rates and minimize the risk of excess fertilizer application and as a consequence less losses of N and N_2O emission (Shukla et al., 2004; Raun et al., 2009). For developing countries like South Asia, LCC provides a simple, quick, and nondestructive method of N-fertilizer application. A number of

studies conducted in South Asia (Singh et al., 2002, 2007a, 2010a,b,c, 2012) demonstrated that following LCC-based N management, fertilizer N use in rice can be reduced by up to 50%, without any reduction in yield, as compared to N used in farmers' practice and increased N-use efficiency by 20–35% in both rice and maize. Sensor-based N management in wheat and maize is a new technology that uses an optical sensor, optimizes N rates, and reduces the N losses and thereby less N_2O emission (Raun et al., 2009; Singh et al., 2012). Demand-driven N application using a LCC could reduce N_2O emission by 16% and CH_4 by 11% in rice (Bhatia et al., 2012). In wheat, reduction of N_2O using LCC was 18% as compared to the conventional method. Application of LCC-based N management did not affect carbon dioxide emission from soil in rice and wheat. The study showed that LCC-based urea application can reduce GWP of a rice–wheat system by 10.5%.

Nitrification inhibitors, reduce N_2O emission directly by reducing nitrification, and indirectly by reducing the availability of nitrate for denitrification (McTaggart et al., 1997; Castaldi and Smith, 1998). Several synthetic nitrification inhibitors are available but most of these are quite costly and are not effective in all ecoregions. Cost-effective indigenous materials such as Neem (*Azadirachta indica*) coated urea can be used to suppress nitrification in tropical and temperate production environments. Zu et al. (2002) observed lower emissions of both N_2O and CH_4 during rice growth using a combination of dicyandiamide (DCD) and hydroquinone. Nitrification inhibitors, nitrapyrin, and DCD, reduced the emission of N_2O by 12 and 63%, respectively (Pathak and Nedwell, 2001; Pathak et al., 2011a,b). Ma et al. (2013) demonstrated that using DCD and chlorinated pyridine (CP) as nitrification inhibitors increased the wheat yield by 9.7% and reduced N_2O–N emission by 67.7%. The treatment with CP produced the highest yield with the lowest N_2O emissions, thus leading to the lowest yield-scaled N_2O–N emission (0.15–0.17 kg N_2O–N/t grain yield) under both ZT and CT practices. Nutrient recycling through organic manures, crop-residue management, and leguminous green manures is important particularly in intensive rice–-wheat cropped systems to meet N requirement (Pannaullah et al., 2006; Timsna et al., 2006; Singh et al., 1991; 2008b,c; 2009a,b; Aulakh and Grant, 2008), which will help in reducing GHG emissions through C sequestration and saving in fertilizer use. The partial substitution of urea by pig slurry reduced net N_2O emissions by 46 and 39%, with and without the incorporation of crop residues, respectively (Abalos et al., 2013). The substitution of urea by organic sources can be considered a good management strategy to reduce N_2O emission from soils.

6.2 Effects of Climate Change on Pest Management

As a consequence of global warming, insect-pests and diseases will certainly change with climate change. Plant pests are particularly sensitive to warmer and wetter conditions. The rise in temperature could shorten dormant periods, speed up pest and disease growth and change their dynamics and resistance to pesticides. With the change in climate the insect pests are expected to expand their range and may find new and more vulnerable hosts. Since temperature directly affects many attributes of insect biology, population responses may vary dramatically in response to anticipated warmer climates. With increase in range and population of insect pests the use of pesticides may increase and there will be cascading effects on ecosystems and health. Researchers have shown that increased temperature can potentially affect insect survival, development, geographical range, and population size (Ramamurthy and Sharma, 2009). Many workers believe that as actotherms, insects will be far more sensitive to changes in temperature than to changes in all other environmental factors (Bale et al., 2002). It has been estimated that with an increase of 2°C temperature, insects might experience one to five additional life cycles per season (Yamamuira and Kiritani, 1998). Lower winter mortality of insects due to warmer winter temperatures could be an important factor in increasing their population.

Due to higher average temperature in temperate regions, some fruit crops like apple are able to grow in regions further up hills and it is likely that some insect pests of these plantations will follow the expanded crop areas. Researchers have shown that the diversity of insect species and the intensity of their feeding have increased historically with increasing temperature (Bale et al., 2002). Generally, CO_2 impacts on insects are thought to be indirect due to its effect on the host crop. Rising CO_2 can potentially have important effects on the natural ecosystems of which insects are one of the major components (Lindroth, 1996). In a controlled study when soybeans grown in elevated CO_2 atmosphere had 57% more damage from insects (primarily Japanese beetle, potato leaf hopper, western corn root worm and Maxican bean beetle) than those grown in present CO_2 atmosphere (Ramamurthy and Sharma, 2009). Therefore, inference may be drawn that with climate change scenario there will also be new dimensions in the insect pest ecology as there is direct correlation of climate change and vegetation, of which insect pests are one of the important components. Adoption of CA and RCTs will change the weed species and their dynamics in different cropping systems requiring new approaches and technologies for integrated insect-pests and disease management in future.

In recent years, increased attention toward nonchemical methods has been drawn because the chemical control is often not affordable for subsistence farming. Moreover, the chemicals which are available, pose a serious health risk due to lack of appropriate facilities, knowledge, and training. Biological control methods in turn are considered safe and viable. Integration of traditional technical knowledge, better storage devices, utilization of physical, cultural, mechanical, and biological controlling strategies along with advanced methods, namely, sterilization techniques and hormonal control are important for upliftment and advancement of agro- and forest-ecosystems (Thakur and Singh, 2009). Adoption of integrated pest management packages, which involves maintenance of a destructive agent (pest or weed), including insects at a tolerable level by the planned use of a variety of preventive, suppressive, regulatory tactics and strategies need to be developed and adopted for different crops and cropping systems that are ecologically and economically efficient and socially acceptable.

6.3 Developing Climate-resilient Genotypes

Superior varieties with increased resilience to abiotic (water, heat, and salinity) and biotic stresses will play an important role in adaptation to climate change (Easterling et al., 2007; Morison et al., 2008; Fedoroff et al., 2010) and have the potential to offset some of the yield losses linked to climate change (Lobell et al., 2008). Conventional breeding methods need to be combined with advanced breeding technologies such as marker-assisted selection (MAS) and genetic modification (GM) to develop climate resilient germplasm (Atlin and Lafitte, 2002; Babu et al., 2003; Cattivelli et al., 2008). The effectiveness of selection for secondary traits to improve yield under water-limiting conditions has been demonstrated in maize (Chapman and Edmeades, 1999), wheat (Richards et al., 2000), and sorghum (Tuinstra et al., 1998). This allows for more efficient selection of suitable germplasms across multiple traits and accelerates the breeding cycles. New efficient varieties and traits will also lead to less intensive use of other inputs such as fertilizers and pesticides.

The challenge is to develop water-efficient genotypes that produce higher yields with a limited water supply, and equal or greater yields than current varieties under favorable growing conditions devoid of stress. Developing short-duration varieties/hybrids is also an effective strategy for reducing seasonal transpiration and minimizing yield loss from terminal drought, as early maturity helps the crop to escape the period of stress (Kumar and Abbo, 2001). Rice breeding over the last decade has increased

water productivity by increasing yields together with reducing crop-growth duration, and hence reducing seasonal transpiration thus increasing WUE (Tuong, 1999; Fujita et al., 2007). Similarly, developing rice varieties for aerobic rice culture should possess moderate tolerance to moisture stress, improved lodging resistance and higher harvest index (Atlin and Lafitte, 2003).

Employing a molecular biology tool for locating important gene sequences and introgressing quantitative trait loci (QTL), or even selecting for genetically important QTLs to develop cultivars utilizing water more efficiently, strongly depends upon our understanding of yield-determining physiological processes (Kirigwi et al., 2007). Although there is little difference in photosynthetic rate among different commonly grown rice varieties, Peng et al. (1998) reported that WUE was some 25–30% higher for tropical *japonica* than for *indica* rice. This implies that significant variation exists in rice germplasm for higher photosynthesis-to-transpiration ratio, and this could be investigated further to enhance water productivity of rice.

Wheat yields decline at supraoptimal temperatures (Wardlaw et al., 1989; Reynolds et al., 1994) and significant breeding effort will be required for developing earlier maturing cultivars that escape terminal heat stress and encompass resistance to diseases associated with warm humid environments (Joshi et al., 2007). One of the most effective research strategies for wheat has been, and will continue to be, to change the phenological pattern of the crop so that critical growth stages do not coincide with stressful conditions or simply to complete the life cycle before the onset of stress conditions.

Another strategy is to genetically engineer plants to accumulate compatible osmolytes, such as amino acids, sugars, or sugar alcohols, resulting in decreased osmotic potential and avoidance of water deficit. Osmotic adjustment (OA) has been shown to enhance grain yield under water-limited conditions in several crops (Zhang et al., 1999). Transgenic approach can be applied to constitutively overexpress certain plant proteins, such as late embryogenic abundant (LEA) proteins that accumulate during seed desiccation and in vegetative tissues when plants experience water deficit. Among these, HVA1, group 3 LEA proteins from barley conferred tolerance to soil water deficit and salt stress in transgenic rice plants (Xu et al., 1996; Sivamani et al., 2000).

Another important approach to minimize the effects of water stress is through development of a deeper and extensive root system. This facilitates access of water from deeper soil profile in case of drought and heat stress, keeping the plants cooler by matching transpiration rates with the

evaporative demand, thereby permitting maximal carbon fixation (Reynolds et al., 2010). Intensive efforts are currently being directed to developing molecular markers for various traits such as maximum rooting depth (Champoux et al., 1995), the capacity of roots to penetrate hard pans (Ray et al., 1996), and ability of the plant to osmotically adjust to water deficit (Lilley and Ludlow, 1996). Many QTLs have already been detected for several root-related traits in rice (Ali et al., 2000; Ray et al., 1996; Yadav et al., 1997; Zhang et al., 2001).

Maize hybrids have been developed which have a yield advantage of up to 20% compared to commercially available hybrids (Banziger et al., 2006). However, further yield gains will be required to offset the potential effects of climate change. Emerging molecular breeding technology and phenotyping offers new high-throughput approaches to develop germplasm for future climates (Cabrera-Bosquet et al., 2012). Where limited genetic variation exists for biotic and abiotic stress tolerance, trans-genes will provide the opportunity to increase genetic variation into breeding programs (Juma, 2011). Large genetic variation exists within tropical maize for adaptation to heat stress and a breeding program can take advantage of this (Cairns et al., 2012). More research is needed on the interaction of heat and drought stress in cereals (Cairns et al., 2012; Barnabas et al., 2008).

For development of traits and varieties that help mitigate and adapt to climate change, agricultural biotechnology is a promising tool. Many promising traits and varieties developed owe their existence to biotechnology, including genetically modified crops with pest resistance (eg, Bt) and herbicide tolerance (eg, Roundup Ready) and conventionally bred varieties that benefit from breeding tools such as marker selection and tissue culture. The drought and salt tolerant traits identified in maize and other crops are largely the product of biotechnology, including the Water Efficient Maize for Africa and other partnerships between public research institutes and private agricultural biotechnology firms (Cairns et al., 2012). Crops, varieties, and traits that are resistant to pests and diseases will improve the ability to adapt to climate change. These varieties reduce the carbon emissions by decreasing pesticide demand as well as the number of in-field applications.

Since a substantial proportion of the GHGs produced are attributable to the production and application of nitrogen fertilizer alone (Stern, 2006), developing N-use efficient genotypes could substantially mitigate emissions in agriculture. Large genetic variation for NUE exists within maize (Bertin and Gallais, 2001; Gallais and Coque, 2005; Gallais and Hirel, 2004; Lafitte et al., 1997), canola (Good et al., 2005), and rice (Bi et al., 2009). Thus, it

may be important to exploit landraces within NUE breeding programs to develop varieties with superior NUE or introgressing NUE traits into elite germplasm. In addition to exploiting existing genetic variation, introduction of novel genes through GM offers an additional, targeted approach to improve NUE in crop plants.

6.4 Alternative Land-use Systems/Agroforestry

In the current climate-change scenario, agroforestry systems have attracted special attention in climate-change mitigation and adaptation discussions. These farming systems yield multiple benefits, such as sustainable production, meeting household requirement through diversified food products, resource conservation, groundwater recharge, employment generation, social equity, and above all the environment improvement.

Agroforestry has been recognized as having high potential for sequestering carbon, adaptation and mitigation of climate change (IPCC, 2007a; Lal, 2011; Dagar et al., 2012). On an average, carbon storage by agroforestry land-use system has been estimated to be around 9, 21, 50, and 63 t C/ha in semiarid, subhumid, humid, and temperate regions, respectively (Schroeder, 1994). For small holder agroforestry systems in the tropics, potential carbon sequestration rate ranges from 1.5 to 3.5 t C/ha per year (Montagnini and Nair, 2004).

It is well known that agroforestry plays a vital role in utilizing the degraded habitats for agricultural production in terms of providing fodder, fuel wood, food, medicinal and aromatic plants, and carbon sequestration. Globally, soil degradation processes affect about 1216 million ha area (Table 17), out of which about 121 million ha of degraded land is in India. Most of these degraded soils are also low in SOC content. Soil restoration, by planting trees or sowing vigorously growing cover crops, would enhance

Table 17 Estimates of soil degradation in the world and in India.

Process of degradation	World (million ha)[a]	India (million ha)[b]
Water erosion	751	82.6
Wind erosion	280	12.4
Chemical degradation	146	24.7
Physical degradation	39	1.1
Total degraded land	1216	120.8

[a]Estimates of soil degradation in world at moderate level (Lal, 2004).
[b]ICAR (2010).

Table 18 Changes in soil properties (0–30 cm) in 5 years under different tree-crop combinations on partial reclaimed alkali soil.

Cropping system	Organic carbon (%)	Available nitrogen (kg/ha)
Sole crop	+0.07	+10
Eucalyptus tereticornis based	+0.12	+21
Acacia nilotica based	+0.20	+31
Populus deltoides based	+0.17	+25

Source: From Singh et al. (1995).

SOC content and lead to improvement in soil quality under different agroforestry systems as compared to sole crops (Table 18).

Afforestation of marginal soils or degraded soils has a large potential of biomass production and carbon sequestration as estimated for different types of degraded soils in India (Table 19). Most of the agroforestry systems are site specific and may differ, in terms of species and their potential of C sequestration (Table 20) both in wood and underground root systems, in different agroclimatic regions. Thus, adoption of a restorative land use through agroforestry and efficient management practices on degraded soils can reduce the rate of enrichment of atmospheric CO_2 while having positive impacts on food security, agroindustries, water quality, and the environment.

The C-storage capacity varies from region to region and also depends upon the growth and nature of tree species involved in the system (Table 21). Economically also, agrihorticultural systems have been reported to give highest benefit to cost ratio in comparison to other land-use systems (Table 22) under rain-fed conditions. Many studies (Lal et al., 1995; Lal,

Table 19 SOC sequestration potential through restoration of degraded soils in India.

Degraded process	Area (million ha)	SOC sequestration rate (kg/ha per year)	Total SOC sequestration potential (Tg C per year)
Water erosion	32.8	80–120	2.62–3.94
Wind erosion	10.8	40–60	0.43–0.65
Soil-fertility decline	29.4	120–150	3.53–4.41
Waterlogging	3.1	40–60	0.12–0.19
Salinization	4.1	120–150	0.49–0.62
Lowering of water table	0.2	40–60	0.01–0.012
Total			7.20–9.82

Compiled from various sources.

Table 20 Carbon storage (t/ha per year) in different agroforestry system.

Location	AF system	C seq (t/ha per year)[a]	References
Raipur	*Gmelina arborea* based system	2.96	Swamy and Puri (2005)
Chandigarh	*Leucaena leucocephala* based system	0.87	Mittal and Singh (1989)
Jhansi	*Anogeissus latifolia* based system	1.36	Rai et al. (2002)

[a]Includes soil carbon storage of 0.42 t/ha per year (up to 60-cm depth).

2004, 2005, 2011; Hooda et al., 2007; Yadava, 2010, 2011; Dagar et al., 2014) have shown the carbon-storage potential of agroforestry systems from 1.8 to 35.13 t/ha in different climatic regions.

Although there are variations in the estimation of area under agroforestry and C stock there are good indications of agroforestry gaining popularity for mitigating climate change. The desired tree cover can only be achieved by including trees in farm fields, especially on bunds.

Table 21 Carbon sequestration potential of different agroforestry systems in IGPs.

Species	Nature of plantation	Carbon sequestration potential (t C ha^{-1} per year)	References
Eucalyptus hybrid	Boundary	0.34–0.88	Yadava (2010, 2011)
E. tereticornis	Boundary	0.84	Kanime et al. (2012)
Populus deltoides	Block	12.02	Singh and Lodhiyal (2009)
	Block	2.01–2.54	Gera et al. (2006, 2011a,b)
	Boundary	1.33–1.42	
	Block	1.98	Hooda et al. (2007)
	Block	9.42–11.87	Rizvi et al. (2011)
	Boundary	3.86–4.56	
	Block	2.06	Yadava (2010)
	Boundary	0.52	
	Block	2.75	Kanime et al. (2012)
	Boundary	0.43	
Dalbergia sissoo	Block	1.04	Yadava (2011)
	Block	2.73	Kanime et al. (2012)
Litchi chinensis	Block	0.94	
Mangifera indica	Block	1.43	

Table 22 Benefit:cost ratios of different alternative land-use systems in rain-fed conditions of Indian continent.

Agroforestry system	Period (years)	Benefit: cost ratio
Arable farming	1	1.34
Agroforestry (with sorghum + pigeon pea)	10	1.65
Agrihorticulture	30	5.53
Silviagriculture (with castor intercrop)	10	1.99
Silvopastoral	10	2.45

Reclaiming waterlogged, salt-affected lands which are low in organic carbon, through fast-growing plantations is a useful strategy for carbon sequestration. Increase in soil carbon through plantations may also act as an important carbon sink. The present stock of carbon in Indian soils is estimated to 63.19 Pg (Velayutham et al., 2000) (1 Pg = 10^{15} g), which is just 4.2% of the world and the C-carrying capacity of Indian soils is estimated at 85.04 Pg (Dagar and Swarup, 2003), therefore, there is a scope of additional C sequestration of 21.85 Pg.

Introduction of canal irrigation in arid and semiarid regions without provision of adequate drainage causes a rise in the ground water table, leading to waterlogging and secondary salinization. The impact of block plantations of *E. tereticornis* on reclamation of waterlogged areas has already been tested and found effective at the Indira Gandhi Nahar Project (IGNP) sites in India (Heuperman et al., 2002; Ram et al., 2007, 2008). On these sites, it has been established that the transect of trees such as species of *Eucalyptus, Acacia, Populus, Prosopis, Casuarina, Pongamia, Terminalia, Syzygium, Dalbergia*, etc. when planted along canals can successfully check seepage and help mitigate waterlogging. To control seepage and rise in water table, tree species such as *Eucalyptus, Casuarina*, and *Populus* may act as biological pumps.

In one study (Ram et al., 2011a) the average above ground oven dry biomass obtained from *Eucalyptus* trees planted in paired rows on bunds was 24.0 t/ha from 5 years 4-month-old 240 surviving trees, and the below ground oven dry biomass of roots was 8.9 t/ha. The carbon content was 15.5 t/ha, which was equivalent to 56.7 t/ha of CO_2 (Table 23).

Agroforestry land-use systems also have great relevance to the coastal and island ecologies, particularly in the scenario of climate change. These ecosystems are more prone to natural calamities (such as cyclones and Tsunamis) as well as anthropogenic interferences. In recent times, due to significant research inputs, agroforestry has gained new dimensions in improving the productivity and the livelihood security of coastal populations. Tropical

Table 23 Carbon and CO_2 sequestered by 5 years and 4-month-old trees of clonal *E. tereticornis*.

Tree components	Oven dry biomass (t/ha)	Carbon (%)	Carbon content (t/ha)	CO_2 content (t/ha)
Timber	22.1	47.0	10.39	38.10
Fuelwood	0.8	43.5	0.34	1.25
Twigs and leaves	1.1	43.9	0.47	1.74
Roots	8.9	48.0	4.26	15.63
Total	32.8	182.4	15.47	56.72

Source: From Ram et al. (2011a).

home gardens with high agrobiodiversity have high potential for C sequestration, especially under changing environments. The rate of average global C sequestration was estimated to be 33.8 and 33.2 g C/m^2/year, respectively, by changing land use from agriculture to agroforestry or grassland (Post and Kwon, 2000). The carbon sequestration in humid and subhumid areas in different land uses/practices such as CA, agroforestry, and afforestation ranged 0.3–0.8, 0.2–3.1, and 4.0–4.8 t C/ha per year, respectively. The aboveground C stock of mixed tree species (>20-cm girth) in 839 home gardens of the Western Coast ranged from 16.3 to 35.2 t/ha with a mean of 24.3 t/ha (Kumar and Takeuchi, 2009; Kumar, 2011).

Mangroves have very dense root systems and are very large C sinks and protect the shore from the damage caused by the natural disasters. Besides mangroves littoral species such as *Pandanus* spp., *Thespesia populnea, Scaevalia taccada, Tournefortia ovata, Hibiscus tiliaceus*, and *Salvadora persica* may also play important roles in protecting the shores and beaches. Multipurpose trees (MPTs) such as *Calophyllum inophyllum, Pongamia pinnata, Heritiera littoralis, Terminalia catappa*, and *Manilkara littoralis*, which are found growing luxuriously along beaches, may be planted on degraded low-lying areas. These belts protect the shores/beaches, provide valuable forest products and also give shelter to wildlife.

6.5 Improved Risk Management Through Early Warning System and Crop Insurance

An important step for climate resilient agriculture is agroadvisories based on weather forecasts, and the development of weather indices. Access to accurate weather data is critical to formulate and disseminate agroadvisories at the microlevel (district, block, village, etc). The Indian Council of Agricultural Research (ICAR) has successfully implemented a vulnerability assessment program through 100 vulnerable *Krishi Vigyan Kendras* (KVKs), installing

automatic weather stations which are measuring meteorological parameters at 30 min intervals. The data flows to the central server established at the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad and is available online (web site: http://www.aicrpam-nicra-aws.in). If weather-related information is available in advance, farmers can plan and manage their farming accordingly, thereby minimizing the risk of extreme climate events. In view of these climatic changes and trade scenarios, it will be very useful to have an early warning system of environmental changes and their spatial and temporal magnitude. Continued investments in remote sensing and weather forecasting are as important as ever and modern tools of information technology could greatly facilitate this. Improvements in sensing and communication technology and in modeling techniques have brought sophisticated short-term forecasts to many parts of the world. More must be done to improve longer-term seasonal forecasts and to develop more effective forecasts of slow onset events such as drought. Policies to support the diffusion of this information and to help interpret these forecasts in terms of their agronomic and economic implications are required to help farmers.

The increasing probability of floods and droughts and other uncertainties in climate may seriously increase the vulnerability of resource-poor farmers to global climate change. In such cases, adaptation to environmental change could be in the form of crop insurance, subsidies, pricing policies, and changes in land use. Necessary provisions need to be included in the development plans to provide protection to the farmers, if their farm production is reduced due to natural calamities.

6.6 Use of Frontier Biotechnological Tools for Improved Biotypes

Increasing agricultural productivity requires the use of frontier technologies through investments in breeding programmes which could spark substantial yield gains coupled with crop-management programmes in adapting to climate change. Therefore, future breeding and crop-management efforts would need to address multiple stresses like heat and drought tolerance, salinity tolerance, and pest resistance cultivars to cope with threats posed by changing climate. This would require extensive breeding and crop-management efforts, which will depend on the collection, conservation, and sharing of appropriate crop genetic material among plant breeders, and sharing the finished products with other researchers, for fine tuning the management options for greater productivity. The genetic resources, especially landraces from the areas where past climates mimicked the projected future climates,

could serve as the serving pool for building genes for tolerance coupled with developing appropriate package of practices. Further, there is a need for a better understanding of wild relatives, landraces, creating trait-based collection strategies, and establishing prebreeding as a public good for providing a suitable response to challenges of global climate change. A combination of conventional, molecular marker directed mutational and transgenic breeding approaches will be required to evolve the desired cultivars and varieties.

Among the major cereal crops, rice, sorghum, and maize are relatively well adapted to high temperatures. To meet the ever-increasing requirement of food, and keeping in view the limitation that we cannot increase the arable land for cultivation, we would have to focus on crop improvement and improved resource-management options, for higher yield under stress conditions. Breeding programs are already geared up to deliver germplasm that will be productive in warmer than average years (Braun et al., 2010) and the appropriate allocation is a must to gear up the natural resource management programme as well. The wide range of environments in which wheat, rice, and maize are now grown indicates that the genetic variability exists within these species to cope with the large and rapid climate shift.

To explore the possibility of identification of the most suitable germplasm, we require more integrated and multidisciplinary collaborative approaches to evaluation and exchange of seed and information at global levels (Lantican et al., 2005; Reynolds and Borlaug, 2006; Dixon et al., 2007; Braun et al., 2010). Modern crop cultivars developed by seed companies or international crop research centers often exhibit a very wide geographical range of environmental adaptation. For example, the popular rice varieties "Swarna" and IR64 are grown on millions of hectares in several Asian countries, and the maize inbred line CML 312 has contributed to hybrids throughout the Latin America subtropics (Braun et al., 2010). For wheat, the cultivars that spearheaded the green revolution such as "Siete Cerros" (also named "Mexipak" and "Kalyanasona") were grown on millions of hectares from North Africa to South Asia; and selections from the CIMMYT cross "Verry" were released in more than 40 countries (Skovmand et al., 1997). Selection in both the wet and the dry seasons in the IRRI irrigated rice breeding program (Wassmann et al., 2009a) and drought screening in maize, wheat, and rice have all contributed to the development of more stress-tolerant cultivars (Banziger et al., 2006). The Central Soil Salinity Research Institute (CSSRI) in India has developed high productive and salt-tolerant varieties of rice (CSR 10, CSR 13, CSR 30, CSR 33), wheat (KRL-4, KRL 220, KRL 230), and mustard (CS 54, CS 56).

All of these techniques and more extensive sharing of information and well-characterized germplasm are key tools that will be needed for adaptation to a changing climate. CIMMYT uses the concept of megaenvironment for developing improved wheat germplasm for use in diversified situation in developing countries covering about 110 million ha (Lantican et al., 2005). The wheat-growing area in the world was assigned to 12 mega environments of which each one tends to be associated with a characteristic set of abiotic and biotic stresses (Braun et al., 1996, 2010).

The adaptive mechanism in rice for different hydrological environments was described by Mackill et al. (1996). Over time, rice farmers have adapted germplasm and management techniques for different ecohydrological environments. In unbunded fields, at the top end of the topo-sequence, farmers grow short duration, drought-tolerant upland rice varieties established by direct seeding. These varieties are usually tall, unimproved, and of the *aus* varietal group (in South Asia) or tropical *Japonica* (in South-East Asia). In upper bunded fields, farmers tend to grow short duration, photoperiod insensitive, modern early flowering varieties, escaping late season drought stress. In well-drained mid topo-sequence fields, farmers usually grow semi-dwarf high-yield potential varieties developed for irrigated conditions and established by transplanting. In lower and flood-prone fields, farmers usually direct-sow tall, photoperiod-sensitive varieties that flower as the rains cease and stagnant water begins to decrease. An important example of specific adaptation to a hydrological stress is submergence tolerance in rice grown on millions of hectares in eastern India and Bangladesh where rice fields are subject to flash flooding that completely submerges the plants. Several landraces tolerate up to 2 weeks of complete flooding and the key trait associated with this tolerance is growth inhibition during submergence (Braun et al., 2010). A highly tolerant Indian landrace FR/3A was used as a donor for the trait in genetic analysis that identified a single major quantitative trait locus, designated *sub1*, which controlled 60–70% of phenotypic variations for the trait in the screening system (Xu and Mackill, 1996).

The adaptation to environment in maize is affected primarily by day length, average temperature, seasonal rainfall, subsoil pH, soil N fertility, and foliar diseases (Banziger et al., 2004). Ongoing efforts to genetically improve maize (Banziger et al., 2006), rice (Wassman et al., 2009a,b), and sorghum under water-deficit condition will need to be intensified to maintain and increase productivity (Reynolds et al., 2010). Temperate cereals such as wheat and barley are relatively well adapted to drier environments and are being grown widely in semiarid regions. Ongoing breeding work has

made steady progress in improving performance (Ammar et al., 2008). However, performance of cereals is substantially less at high temperature and a significant breeding effort will be required to maintain their productivity under warmer conditions (Reynolds et al., 1994, 2010). There is some evidence for C3 cereals (wheat, barley, rice), that increased CO_2 will partially offset the effects of higher temperature and drought through improvements in the WUE (Reynolds et al., 2010), but, the extent of impact on productivity is still not clear (Leakey et al., 2006).

The National Bureau of Plant Genetic Resources (NBPGR), India has screened the entire germplasm of wheat (about 22,000 accessions) comprising *Triticum aestivum*, *Triticum durum*, and *Triticum dicoccum* against biotic stresses under the National Initiative on Climate Resilient Agriculture (NICRA) project and conserved it in the National Bank. In addition, protocols have been standardized for *in vitro* callus transformation in variety HD 2967 for developing transgenic wheat with enhanced heat tolerance. Proteome analysis of nitrogen-efficient cultivars at elevated CO_2 conditions were also carried out and final results will be available shortly. The evaluation of key rice germplasm for tolerance to submergence, drought and salinity was also carried out and the tolerant cultivars were identified (Table 24).

Table 24 Rice cultivars for tolerance to different stresses.

Stress	Cultivars
Waterlogging	AC 1125-A, AC 1781, AC 1996, AC 813, AC85, AC 39416A
Anaerobic germination	AC 34245, AC 34280, AC 40331-A, AC 40346, AC 416222-A, AC 41647, AC 41644-A, AC 41644-B, AC 39397, AC 394418, AC 39416-A
Complete submergence for 20 days better than Swarna-sub-1	AC 38575, AC, 37887, IC 258990, IC 258830, AC 42087, AC 20431-B
Vegetative stage drought	IC 568083, IC 568112, IC 568065, IC 568016, IC 568030, IC568083, IC 568112, IC 568065, Mahulata, IR77298-14-1-2-10
Reproductive-stage drought	CR 143-2-2, IR 55419-04, IR 80461-B-7-1
Seedling-stage salinity	Pokkali (AC 41485), Chettivivippu (AC 39389), AC 39394
Tolerant to both anaerobic germination and salinity	Kamini, Ravana, Talmunga, Paloi, Longmutha, Murisal, Rashpanjor, AC 39416 (A)
Tolerant to anaerobic germination salinity and waterlogging	AC 39416 (A)

Source: From Venkateswarlu et al. (2012).

To assess the performance under higher temperature as summer season experienced 3–4°C higher than the growing season, popular rice varieties (six short-duration and seven medium- and long-duration) of Cauvery Basin (India) were grown during summer. Among the varieties tested (Geethalakshmi et al., 2011), ADT 38, ADT 48, CO 43, ADT 36, ADT 37, and BPT 5204 withstood higher temperature and gave higher yields compared to others. This indicates that these varieties can be recommended for a warmer climate.

7. MITIGATION STRATEGIES/OPTIONS

The global climate change is the consequence of human behavior, which, if left unchecked could be catastrophic. Besides adaptation measures, we need to have a look at mitigation strategies in agriculture. Improved agricultural management enhances resource-use efficiencies leading to often reduced emissions of GHGs. The effectiveness of these practices depends on factors such as willingness of the human being to change, climate, soil type, input resources, and farming systems. About 90% of the total mitigation arises from sink enhancement (soil C sequestration) and about 10% from emission reduction (Ortiz-Monasterio et al., 2010). To better understand the influence of different management practices on C sequestration, Barker et al. (2007) and Govaerts et al. (2009a,b) reviewed the literature extensively and assessed the mitigation potential in different promising agricultural management options (Table 25).

In most agricultural soils biogenic formation of N_2O is enhanced by an increase in available N. Therefore, optimizing nitrogenous fertilizer-application rates and synchronizing them with crop requirement will reduce the costs with similar or higher yields coupled with reduced emissions of N_2O (Singh et al., 2012; Matson et al., 1998; Verhulst et al., 2011).

7.1 Mitigation of Greenhouse Gases Through CA-based Management Options

Minimal soil disturbance (zero/reduced tillage) results in less exposure of the soil organic matter to oxidation and lower CO_2 emissions to the atmosphere as compared to tilled soils. CA-based practices significantly reduce energy consumption (eg, fuel and electricity) and thus lower CO_2 emissions (Erenstein et al., 2008). In IGPs, it has been found that farmers adopting

Table 25 Assessing mitigation potentials in agriculture.

Mitigation option	MT CO_2 eq. per year[a]
Restoration of cultivated organic soils	1260
Improved cropland management (including agronomy, nutrient management, tillage, residue management), water management (including irrigation and drainage), and set-aside/agroforestry	1110
Improved grazing land management (including grazing intensity, increased productivity, nutrient management, fire management, and species introduction)	810
Restoration of degraded land (using erosion control, organic amendments, and nutrient management)	690
Improved rice management	210
Improved livestock management (including improved feeding practices, dietary additives, breeding, and other structural changes and improved manure management (improved storage and handling and anaerobic digestion)	260

[a]Assuming C prices up to US$100 per t CO_2 eq. by 2030.
Source: From Barker et al. (2007).

ZT save from 35 to 74 L of diesel/ha for land preparation thus contributing to reduced CO_2 emission by 98–190 kg CO_2 eq. per ha (Sharma et al., 2005; USEPA, 2009). Moreover, a 70% fuel saving was reported in CA (FAO, 2008) and 92% in ZT in north western IGP of India (Chauhan et al., 2000; Sharma et al., 2005). In Mexico, under intensive tillage agriculture and with monoculture systems, the carbon liberation into the atmosphere was found to be about 1.8 t/ha per year of C_2O (FAO, 2001).

The effect of tillage practices and crop-residue management on the net GWP was evaluated by Dendooven et al. (2012b). They reported that tillage and residue management had little effect on GHGs emitted from the soil and that the maximum difference between the agricultural systems was 242 kg equivalent C/ha per year. Due to an improved growing season moisture regime and soil storage of water and nutrients, crops under CA require less fertilizer (Kassam et al., 2009) although some researchers have reported similar (Sharma et al., 2005) or higher (Gathala et al., 2011) N requirement under CA during initial years.

During the decomposition of organic matter, especially when organic material with large C:N ratio is added to soil, decomposition may limit microbial activity thereby decreasing the CO_2 flux (Lavelle et al., 1993; Reicosky, 2008; Nelson et al., 2009).The largest contribution to reducing

the CO_2 emissions associated with agricultural activities is made by the reduction of tillage operations. West and Marland (2002) reported estimates for C emission from agricultural machinery averaged over maize, soybean, and wheat crop of 69.0, 42.2, and 23.3 kg C/ha per year, respectively. It was reported by Grace et al. (2002) that incorporation of crop residue could increase the population of aerobic bacteria and fungi while the burning of these residues led to the loss of a considerable amount of N, P, K, and S and led to emission of GHGs significantly, and the destruction of beneficial microflora of the soil (Jat and Pal, 2000; Timsina and Connor, 2001). It is estimated that 1 t of straw on burning releases 3-kg particulate matter, 600-kg CO, 1460-kg CO_2 (or 398-kg C), 199-kg ash, and 2-kg SO_4 (Gupta et al., 2005). The significance of these emissions have been explained by Levine (1990), Andreae and Crutzen (1997), Cheng et al., (2006), Tsai and Chyan (2006), Hirota et al. (2007), Sahai et al. (2007, 2011) and many others.

Together with the addition of mulch as well as through root exudation of carbon compounds directly into the soil during crop growth (Jones, 2007), there is a reversal from net loss to net gain of C in the soil, hence commencement of long-term process of C sequestration (Blanco-Canqui and Lal, 2008). Moreover, the soil is not tilled and exposed, which otherwise leads to faster decomposition and depletion of SOC. Thus, CA has the potential to slow/reverse the rate of emission of CO_2 and other GHGs by agriculture.

7.2 Mitigations Through Water Management Techniques

Reduction in CH_4 emission from agriculture can, to a large extent, be accomplished by changing rice production system from anaerobic to aerobic, AWD of rice field, planting rice on beds, using surface or subsurface micro-irrigation practices, and increasing water percolation. Optimizing irrigation scheduling in the field by introducing practices such as additional mid-season drainage accounted for 70–80% of CH_4 emission reduction compared to continuous flooded rice (Wassmann et al., 2000c). A single mid-season drainage reduced seasonal CH_4 emission from rice fields but increased the emissions of N_2O (Bronson et al., 1997). Irrigation water should be applied after the soils have dried to where fine cracks appear (Ortiz-Monasterio et al., 2010). This not only reduces the amount of water application but also reduces CH_4 emissions (Hobbs and Govaerts, 2010). Raised-bed planting may be another strategy to optimize water management thereby reducing GHG emissions. Although most of the recent studies (Anonymous, 1999; Chauhan et al., 2000;

Humphreys et al., 2008a Singh et al., 2008c, 2009b; Kukal et al., 2008, 2010; Chauhan et al., 2012) have shown that there is no yield advantage of growing crops on raised beds compared to flat beds, there is definite advantage in water saving (Sharma et al., 2005), and in reducing GHG emissions Saharawat et al. (2012) as compared to other cultivation methods.

7.3 Sequestering C in Farming Systems

It is known that farming alters the C cycle, and that the management of cropping systems will determine the amount of CO_2 emissions to the atmosphere as well as the potential for C sequestered in the soil. Maland et al. (2003) distinguished four sources of CO_2 emissions in agricultural systems: (1) plant respiration, (2) oxidation of organic C in the soil and crop residues, (3) the use of fossil fuel in agricultural machinery, and (4) the use of fossil fuels in the production of agricultural inputs such as fertilizers and pesticides. Therefore, C sequestration in soil, C storage in crop residues and CO_2 emissions from all farming activities should be considered as well as the indirect CO_2 of energy use and C emission from primary fuel, electricity, fertilizers, lime, pesticides, irrigation, seed production, and farm machinery (Wang and Dalal, 2006). C levels in soil are determined by the balance of inputs (such as crops residues, organic amendments, etc.) and C losses through organic-matter decomposition as has been determined for India (Fig. 4) by Maheswarappa et al. (2011).

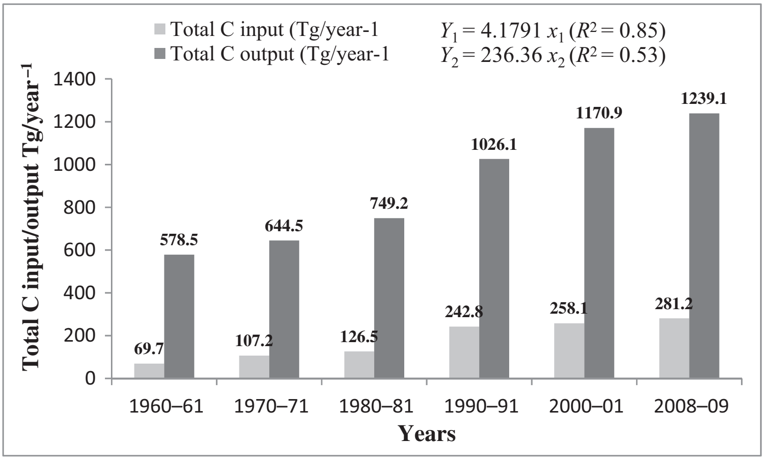

Figure 4 Trends in C-based inputs and outputs in Indian agriculture (Y_1 and Y_2 are Tg C and x_1 and x_2 are years). *Source: Modified from Maheswarappa et al. (2011).*

Table 26 Feasibility of carbon sequestration by different technological options (Lal, 1997).

Technique	Global C sequestration rate (Pg/year)	Global increase in SOC content to 1-m soil depth (%/year)
Crop residue management	0.20	0.001
Conservation tillage	0.125	0.002
Soil restoration by afforestation	3.0	0.01

There are several strategies for carbon sequestration in the soil and the most effective are based on proper land use and soil management. Adoption of improved and science-based agricultural practices can be an important strategy to bring about a quantum jump in per capita productivity, yet enhancing environmental quality and mitigating greenhouse effects. Crop residues are important and renewable resource nutrients, enhance soil fertility, improve soil structure, sequester carbon, and mitigate the greenhouse effect (Table 26).

The SOC in the 0–60-cm layer was affected strongly by tillage and crop-residue management. The SOC content was 118×10^3 kg C/ha in ZT with residue retention, approximately 40×10^3 kg C/ha per year higher than in practices involving tillage or ZT with residue removal. In 20-years duration, approximately 2000 kg C/ha per year was sequestered in the soil in zero till with residue retention compared to other practices (Dendooven et al., 2012b). West and Post (2002) reported that a change from conventional tillage to no till can sequester 57 ± 14 g C/m^2 per year. Barker et al. (2007) found that crop-rotation systems in CA accumulated about 11 t/ha of carbon in 9 years.

There lies a potential for C sequestration through the management of crop residue. Assuming the mean carbon content of 45%, total carbon assimilated annually in the crop residue will be about 1.5 Pg in the world. If 15% of the carbon assimilated in the residue can be converted to humus fraction, it may sequester C at the rate of 0.2 Pg/year or 5.0 Pg of cumulative C sequestration up to the year 2020. If we assume soil bulk density of 1.5 t/m^3 in world arable land of 1500×10^6 ha to 1-m depth, this would increase the mean SOC content of 0.001%/year (Lal, 1997).

Among several solutions being debated to mitigate climate change, carbon (C) sequestration is one of the key options (Lal, 2011) and agroforestry systems can help ameliorate global climate change by sequestrating carbon in

their live biomass as well as in the soil. Several studies have shown that inclusion of trees in the agricultural landscapes often improves the productivity of systems while providing opportunities to create carbon sinks (Maikhuri et al., 2000; Pandey, 2002, 2007; Albrecht and Kandji, 2003; Ram et al., 2011a,b). More details of C sequestration (mitigation of climate change) in different agroforestry systems under different situations have been discussed earlier in Section 6.5.

7.4 Developing Climate Smart Germplasm

Different species of a genus and different cultivars of the same species differ in their stress tolerance. This has been proven through several agronomic trials across different agroclimatic regions. The cultivars which have greater adaptations for multiple stresses are usually also resilient to higher temperature and hence climate change. This fact has been exploited in developing cultivars emitting less GHG. For example, the role of rice cultivars on methane emission from flooded fields was investigated by Adhya et al. (2000). Among the four modern improved rice cultivars tested Lalat gave the highest CH_4 seasonal flux (44.4 kg/ha) followed by IR72 (25.84 kg/ha), Gayatri (22.58 kg/ha), and Tulsi (20.21 kg/ha). The cultivars Gayatri and Tulsi had lower CH_4 flux, thereby producing 13 and 22% less CH_4 than IR72. As mentioned under adaptation, several crop varieties give higher yields under stress and higher temperature and we need to evaluate these for their GHG emission status through multilocation trials.

8. MODELING IMPACT OF CLIMATE CHANGE ON CROP PRODUCTION

8.1 Crop Simulation Models for Climate Change Impacts on Crops

Future climate change is projected to be one of the major challenges for global agricultural production (IPCC, 2007a). Therefore, the key vulnerabilities and risks from future climate change have been a considerable concern (IPCC, 2007a) in terms of agricultural production and food security. Due to the complexity of climate change (CC) and the inherent lack of empirical basis, modeling can represent a useful resource to assess the effect of CC on agricultural systems and guide in the development of alternative cropping systems for increased adaptive capacity to CC.

Empirical and process-based models have been developed in the past decades to simulate the potential impacts of climate change on agricultural production and natural ecosystem. Empirical models statistically corelate past weather variables to crop performance to identify the most important climatic drivers of crop production and, using projected future weather, assess the impact of CC as well as identify possible alternatives for adaptation. Process-based crop and crop-soil models formalize known mechanism for crop growth and soil dynamics to evaluate the performance of crop and cropping systems. Contrary to empirical models, these models can take into account increased CO_2 concentration in the atmosphere as well as simulate yields for future climatic situations where empirical knowledge from past trends does not exist. The interactions between crops and climate should be studied as a coupled system in which feedbacks may be important for the accurate simulation of both the climate and the crop. Further, modeling the effect of soil degradation or climate change on crop production should include all possible processes within a consistent framework. For example, the effect of draught or soil nutrient mining on crop production can only be assessed if the model is able to account for the processes governing nutrient and water limitation. Similarly, GHGs from soils can only be calculated if the nitrogen and carbon removed by crop growth are adequately considered. However, many simulation models often focus on limited aspects of the agricultural plant-soil system and the consideration of specific processes related to the earlier mentioned dynamics, and measurement for the parametrization of models, are still lacking. Despite these challenges, crop simulation models are the only tools for large area impact assessment of climate variability and change on crop yield (Challinor et al., 2004; Olesen and Bindi, 2002; Parry et al., 2004) and simulations have been the major data sources for Intergovernmental Panel on Climate Change (IPCC) assessments for agriculture.

A large number of models have been developed not only to optimize agricultural management strategies, but also to investigate the effect of climatic variability and soil hydrology on crop yields. These models employ detailed representations of plant phenology and physiology as well as soil and climate processes requiring laborious parameterization and calibration. Some examples of crop-growth models include CERES (Ritchie et al., 1991), WOFOST (Supit et al., 1994), APSIM (Keating et al., 2003), and CROPGRO (Hoogenboom et al., 1992). These models have been applied over a wide range of scales, from lysimeter studies with WOFOST (Eitzinger et al., 2004) to regional and subcontinental modeling studies with CERES (Saarikko,

2000) and WOFOST (Boogaard et al., 2002). The EPIC model (Sharpley and Williams, 1990) was originally developed to study the impact of soil erosion on yields, but includes a detailed description of crop growth as well. Statistical approaches (eg, Schlenker and Roberts, 2009; Lobell et al., 2011) are gaining in prominence for assessing climate-change impacts on crop production due to their ability to rapidly assess large and diverse datasets.

Another group of models focuses on soil biogeochemistry and nutrient cycling, for example, RothC (Jenkinson et al., 1991) for organic carbon turnover, CENTURY (Parton et al., 1988) for carbon, nitrogen, phosphorus, and sulfur cycles, CASA (Potter et al., 1993) for N_2O emissions, and MEM (Cao et al., 1995) for CH_4 emissions. These models pay more attention to soil processes, such as decomposition, nitrification, and denitrification. Further, there are efforts to improve the representation of crop growth in such models (Zhang et al., 2002). Reviews about the general features and mechanisms of process-based crop models are provided by Tubiello and Ewert (2002) with a focus on the effects of elevated CO_2 concentrations and by Lipiec et al. (2003) with a focus on crop growth, water movement, and solute transport. Assessments of climate-change impacts on global food production and supply rely heavily on process-based modeling (Rotter et al., 2011). These are the types of models that use our understanding of physical and biological processes (such as how given crops respond to increased carbon dioxide, reduced water supply, warmer growing seasons, or changed crop management) to forecast how farm-level productivity may change in the future. Scaled up to larger regions, in combination with projections of future population, trade and commodity prices, this information can help us to estimate the future of the overall system such as how much food we can grow in a warmer world.

To examine the full range of climate change impacts on agriculture, both biophysical and economic aspects need to be considered and combined (Hillel and Rosenzweig, 2010). As mentioned earlier biophysical effects of climate on crop yield can be assessed by employing statistical models (eg, Lobell and Burke, 2010) as well as process-based dynamic crop-growth models (eg, Keating et al., 2003; Brisson et al., 2003; Jones et al., 2003; Van Ittersum and Donatelli, 2003; Challinor et al., 2004). For simulating the combined biophysical and economic effects of climate change on agriculture, a coupled biophysical and economic simulation model designed for integrated assessment of economic, technological, policy, and environmental changes at regional or global scales (eg, Rosenzweig and Parry, 1994; Hermans et al., 2010; Nelson et al., 2010a,b) are used.

The mechanics of simulating crop responses to climatic variability may appear straight forward: one provides the model with initial field conditions (eg, for soil moisture and nitrogen status), crop information (cultivar characteristics, planting arrangement, and fertilization and irrigation, if any), the daily weather and CO_2 data corresponding to the historic, current, or future scenarios of interest. The simulation is then run, and the outputs are compared to those of other simulations where different initial conditions, management practices, or weather and CO_2 scenarios were used. Methodological differences employed by different models, however, limit the comparison and aggregation of results of such modeling initiatives. Inconsistent and divergent results from multiple crop and economic models sometimes reduce the ability of the government to plan responses to climate change in relation to agriculture and food security.

To address these challenges of modeling climate-change impact in agriculture, a group of international agricultural modelers formed Agricultural Model Intercomparison and Improvement Program (AgMIP) in 2010 (www.agmip.org). AgMIP aims to significantly improve agricultural models and scientific and technological capabilities for assessing impacts of climate change and variability on agriculture, food security, and poverty at local to global scales. The major activities of this agricultural modeling platform include intercomparison of multiple agricultural models, evaluation and model improvement, development of improved methodologies for integrated assessments of impacts and adaptation, and the performance of integrated assessments at local to regional to global scales. It brings together world leaders in climate, crops, livestock, and economic modeling to form cutting-edge framework to understand climate impacts on food security. This platform dramatically increases the rigor of scientific information to help decision-makers better understand how climate change will reverberate through complex agricultural systems and markets.

Through this initiative, the impact of climate change on food security, income, and poverty can now be assessed for current farming systems and types of farming systems that are likely to occur in future. Through integration of climate models into crop, livestock, and economic models, it is possible to perform multimodel climate-change impact assessments as well as yield, income and poverty outcomes from adaptation packages. The design of the intercomparison allowed AgMIP to characterize uncertainty thus highlighting the need for continuing rigorous model evaluation and improvement. AgMIP has successfully demonstrated an honest collaboration across previously competing modeling groups, providing a productive space

to undertake challenging research endeavors. International AgMIP community activities are designed to undertake state-of-the-art assessments of climate impacts on food security at local, regional, and global scale.

8.2 Climate Predictions and Potential Benefits

In the last several decades, human activities have induced climate change and the climate will continue to change regardless of any mitigation strategy (IPCC, 2007a). The increase in atmospheric carbon dioxide concentrations and several other trace gases is well established. Although it is not possible to be sure of the exact magnitude and distribution patterns of future climatic change, global climate models suggest that the changes may be larger than anything experienced in human history. If carbon dioxide emissions continue at present levels, atmospheric concentration will be doubled by the middle of the next century. This may lead to an average global temperature increase of 1.5–4.5°C. Together with temperature, other weather factors may change, such as rainfall amounts and frequencies, cloudiness, and solar radiation pattern (Meehl et al., 2005). But how the plants and crops will react to the elevated concentration of carbon dioxide and associated temperature, rainfall, etc., is still a matter of debate.

Climate change as projected for the 21st century may significantly alter crop production (Rosenzweig and Hillel, 1998). Referring to the IPCC's Special Report on Emissions Scenarios, Parry et al. (2004) estimated that while global production is likely to remain stable for most of the century, regional differences could grow stronger through time, with only developed countries possibly benefiting from climate change. Worldwide the impacts of climate change upon crop yield and food security are predicted to be significant. Positive regional differences in the response of crop productivity to climate change are likely to emerge in Europe. As reported by Olesen and Bindi (2002), climate change is expected to have positive impacts only in the Northern countries, and areas of crop suitability may expand northward (Olesen et al., 2007). Southern areas, on the other hand, will likely have to face decreased crop yields.

9. THE WAY FORWARD

The impact of climate change is projected to have a great influence on agriculture, and eventually on the food security and livelihoods of a large section of the rural population. Droughts, floods, tropical cyclones, heavy

precipitation events, hot extremes, and heat waves are known to negatively impact agricultural production and the livelihood of the farmers. Further, the climatic changes will affect agriculture through their direct and indirect effects on crops, soils, livestock, and pests. Under the changed climatic scenario, the following approaches and tools should be part of climate smart agriculture policy to adapt to and mitigate the changing climate:

The drivers of vulnerability to build the resilience of climate-related stresses, poverty reduction, gender initiatives, and livelihood diversifications.

Capacity development to handle climate change related issues, including weather monitoring, reforestation, and efficient natural resources management.

Managing climate change related risks, specially disaster-planning activities and technological measures such as the use of drought-resistant crops and agronomical tools, climate proofing, and water-saving measures, etc.

Confronting climate change, for example, rehabilitation of communities in response to weather calamities, sea-level rise, glacial melts, and developing infrastructures to face drought, frost, and other unexpected climate-related events.

Ecosystem-based approaches for building resilience to conserve and protect biodiversity, improve economic livelihood and human well-being; sustainable restoration, conservation and management of ecosystems; utilization of traditional knowledge of local people; and recognizing the importance of ecosystem services and integrating them to cost-effective management of natural resources.

Promotion of RCTs for climate-smart agriculture such as laser-assisted precision land leveling, no-tillage or minimum tillage, integrated nutrient and pest management, crop-residue management, raised-bed planting, DSR, deficit water use, microirrigation methods, in situ and ex situ moisture conservation, judicious use of poor-quality waters, reclamation of degraded lands, modern agroforestry practices, and community-based natural resources management.

Adaptation of techniques for restoring soils involving revitalizing biological tillage, reducing compaction, increasing infiltration, protection of natural drainage through the soil profiles, increasing water-storage capacity, naturally improving soil nutrient status, and biodrainage for controlling waterlogging.

Management of coastal ecosystems including mangrove ecosystems, developing opportunities for alternative livelihoods, creating "climate proof" coastal infrastructure, restoring of coastal wetlands and beaches, restoration of abandoned village/fish ponds, providing local communities with customized information on flood risks, and integrating traditional

knowledge of local communities to maintain ecosystems with scientific and technical informations.

Approaches to address residual risk through insurance contracts, catastrophe bonds, grants to farmers against crop failures due to climatic catastrophes, crop insurance against natural calamities, and meaningful, appropriate, and applicable legislation.

The climate-smart village (CSV) concept of CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is a good example of making synergies in investments for climate-smart agriculture interventions as well as raising the awareness of the farming community for climate literacy using a community-based approach and can be used as a case for accelerated adoption of climate-smart agriculture.

10. CONCLUSIONS

Climate change is threatening the food security and livelihood of millions of people in the developing countries including South Asia and Latin America. Models generally predict that rising temperatures, increased climatic variability, and extreme weather events could significantly impact upon food production. Consistent warming trends and more frequent and intense extreme weather events have been observed across these countries in recent decades. Climatic events like cold wave, heat wave, drought, and floods have significantly influenced the production of food crops. Therefore, scientific intervention coupled with indigenous wisdom of the farmers is a must to enhance the resilience of modern agriculture in the face of climate change. Development of multiple stress-tolerant varieties, efficient cropping systems, RCTs, water harvesting, and supplemental irrigation for drought proofing in rainfed areas can help in building resilience against the adverse climatic variability. Alternate land-use systems like agroforestry and other biological carbon capture systems can also help in both adaptation and climate-change mitigation. Accurate and reliable forecasting of environmental changes will be of immense importance, and policies to support the dissemination of this information are required to help the farmers. Researchers, planners, and policy makers must develop comprehensive adaptation and mitigation strategies to cope with the adverse impact of climate change. Policy decisions for promotion of climate-smart agriculture, promoting CA including the availability of suitable machinery, precise land leveling, water harvesting, judicious use of water, rehabilitation of degraded

lands, site-specific nutrient management, integrated weed and pest management, development of multiple stress-tolerant crops, and capacity building for weather and risk-forecasting mechanisms, index-based insurance, ICT-based agroadvisories must be in place both in an integrated and community-based approach at local and regional level to meet the ever-increasing food demand in the face of burgeoning population pressure, in general and, in these areas, in particular.

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