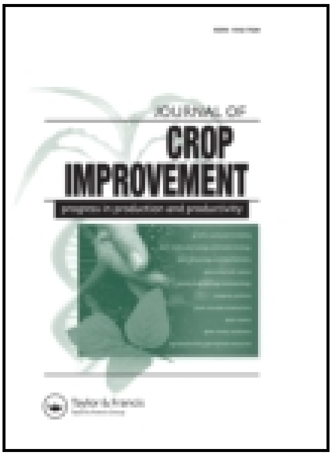

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Global Agriculture and Climate Change

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Global Agriculture and Climate Change

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Climate change, caused by anthropogenic activities, is a universal phenomenon across the globe. There is general consensus that combating climate change will require a set of internationally coordinated policy interventions for reducing greenhouse gas (GHG) emissions besides addressing regional or global vulnerabilities, development patterns, equity distribution, and technology transfer. Agriculture is both a victim and an abettor of climate change. Serious attention is thus required, not only to enhance its adaptation capacity but also to exploit its mitigation potential as a carbon sink. A sustainable policy shift toward enhanced food security, preservation of freshwater resources, prevention of soil degradation, and maintenance of biological diversity and ecosystems remain the hallmark of mitigation strategies. Improved adaptive capacity relative to climate-resilient agriculture needs to be integrated with global developmental paths aimed at reducing social inequalities and alleviating poverty. The United Nations' Millennium Development Goals provide an excellent backdrop for integrating adaptation and sustenance into global development polity. World essentially requires a climate closest to which all forms of life have adapted during their evolution. Deceleration of carbon emissions and a shift to a long-term and sustainable growth paradigm are essential imperatives, notwithstanding the associated economic costs. Research has shown that benefits of reducing methane emissions alone would be to the tune of US$700–US$5000 per metric ton, whereas the abatement costs have been estimated to be less than US$250.

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INTRODUCTION

Earth's climate is undoubtedly changing; both global warming and rising sea levels are a reality. Globally, average temperature for May 2012 marked the second warmest May since recordkeeping began in 1880. May 2012 also marks the 36^{th} consecutive May and the 327^{th} consecutive month with a global temperature above the 20^{th} century average. According to the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center, the global land surface temperature was 2.02°F (1.12°C) above the 20^{th} century average of 46.4°F (8.1°C), making it the fourth warmest March–May on record. Record April and May warmth in the Northern Hemisphere led to the warmest spring on record with a temperature departure of 2.48°F (1.38°C) above the long-term average. Warmth was most pronounced across central Eurasia and most of North America. It was cooler than average across Alaska in the Northern Hemisphere and Australia in the Southern Hemisphere. The March–May global sea surface temperature was 0.39°C (0.70°F) above the 20^{th} century average of 16.1°C (61.0°F), tying with 2011 as the 11th warmest March–May on record. The margin of error is ±0.04°C (0.07°F). The average Arctic sea ice extent during May was 3.5% below average, resulting in the 12^{th} smallest May sea ice extent on record since satellite recordkeeping began in 1979. On the opposite pole, Antarctic sea ice during May 2012 was 2.4% above average and ranked as the 15th largest May sea ice extent in the 34-year period of recordkeeping.

CAUSES OF CLIMATE CHANGE

Climate change is directly or indirectly related to human activity. Greenhouse gases (GHGs) (carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]) are, among others, said to be the causes of global warming or climate change. Tropospheric ozone and black carbon are the only two agents known to cause both warming and degraded air quality (Shindell et al. 2012). Ozone precursors, including CH_4, also degrade air quality.

Agricultural activities release significant amounts of CO_2 (decomposition of soil organic matter or burning of plant materials), CH_4 (under oxygen-deprived conditions; e.g., wetlands, flooded rice, and digestion by livestock), and N_2O (microbial processes in soils and manures, and fertilizer applied in excess of needs) into the atmosphere. The Intergovernmental Panel on Climate Change (IPCC 2007) concluded that agriculture accounted for 10%–12% of total global anthropogenic emissions of GHGs. Although CO_2 emissions from agriculture are relatively small, almost 60% of all N_2O is reportedly emitted from soils and about 50% of CH_4 is generated by enteric fermentation (Smith et al. 2007a,b). More increases in agricultural emissions are expected as population and economic growth derives food demand, which, in turn, would increase the use of nitrogenous fertilizers. Between 1990 and 2005, methane and nitrous oxide emissions increased by 17%; these emissions are projected to increase further by 35%–60% by 2030 as a result of increased fertilizer use and increased livestock production (Forster et al. 2007).

Even though the quantity of methane and nitrous oxide emissions released into the atmosphere is far less than that of carbon dioxide, their potency or global warming potential is much greater than that of carbon dioxide. Methane is 23 times and nitrous oxide 310 times more potent than carbon dioxide (Bracmort 2010). This means that 1 t of methane is equivalent to 23 t of carbon dioxide (or 23 CO_2-eq) and 1 t of nitrous oxide is equivalent to 310 t of carbon dioxide (or 310 CO_2-eq).

SPECIAL REPORT ON EMISSION SCENARIOS AND CLIMATE MODELS

The Intergovermental Panel on Climate Change (IPCC), in a document called *Special Report on Emission Scenarios* (SRES), constructed four scenarios to explore the future dynamics of global growth and environment (Figure 1) (IPCC 2007). These scenarios were dubbed as A1, A2, B1, and B2 (IPCC 2007). The storylines for the four scenarios were defined as follows. A1: a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, and rapid introduction of new and more efficient technologies. A2: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and relatively slower. B1: a convergent world with the same global population as in A1 but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean, resource-efficient technologies. B2: a world with emphasis on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

Depending on the scenario and climate models considered, global mean surface temperature is projected to rise, by 2100, in the range of 1.8°C (with a range from 1.1°C to 2.9°C for B1) to 4.0°C (with a range from 2.4°C to 6.4°C for A1) (IPCC 2007). These figures translate into global annual mean temperatures that will be at least 2°C above preindustrial levels by 2050.

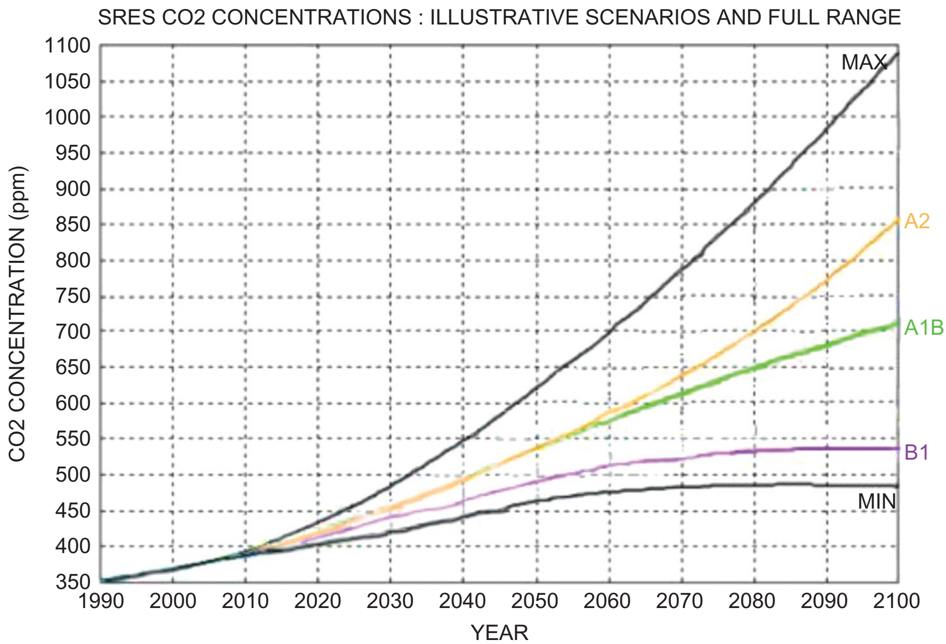

FIGURE 1 Projected atmospheric Co_2 concentrations under different case scenarios (color figure available online).

Data from IPCC. 2007. *Fourth assessment report*, edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. New York, NY: Cambridge University Press.

CONSEQUENCES OF CLIMATE CHANGE

Climate change poses many threats to agriculture, including the reduction of agricultural productivity, production stability, and incomes in areas of the world that already have high levels of food insecurity and limited means of coping with adverse weather (http://www.fao.org/climatechange/climatesmart/en/). Even a conservative projection of a 2°C warmer climate may cause heavy but erratic precipitation, frequent and intense droughts, floods, tornados, heat waves, and other weather extremes (IPCC 2011). The Arctic ice cap is continuing to decline, with planet-wide impacts on weather patterns. According to the United Nations Development Programme (UNDP 2007), nearly one-third of the glacial area of central Asia has disappeared since 1930. The devastating 2010 Pakistan floods (a 1-in-1,000-year event by historical standards) (Straatsma et al. 2010) and Russian heat wave (a 1-in-3,000-year event) might just be indicative of the kinds of extreme events that could hit the world (Stott et al. 2004; Min et al. 2011; Pall et al. 2011). The rainiest year on record was 2010, and it tied for the hottest year ever (NOAA 2011).

That global warming has potentially strong economic consequences is evident from the damages attributed to different weather-related phenomena. Coumou and Rahmstorf (2012) suggested that there was strong evidence linking specific events (e.g., heat waves and precipitation), or an increase in their numbers, to the human influence on climate. Some of the disastrous weather-related events and their economic and other consequences are listed in Table 1 (Coumou and Rahmstorf 2012).

Climate change plays a significant role in a nation's food security and economy, especially in a developing country like India (Chauhan et al. 2013). In 1989, while addressing the World Climate Conference in Geneva, Switzerland, on the theme "Climate Change and Agriculture," Prof. M.S. Swaminathan pointed out the implications of a 1°C–2°C rise in mean temperature for crop productivity in South Asia and sub-Saharan Africa (Swaminathan 2012, 144). In 2009, a team of experts of the United Nations Food and Agriculture Organization (FAO) concluded that for each 1°C rise in mean temperature, annual wheat yield losses in India were expected to be about 6 million tons (US$1.5 billion at current prices), and when losses of all other crops were taken into account, farmers were projected to lose US$20 billion each year (Swaminathan 2012, 144). Peng et al. (2004) reported

TABLE 1 Catastrophic weather-related events between 2005 and 2011 and their consequences (a partial list)

Extreme, Record-Breaking Event	Year	Area	Financial or Human Loss
Category 5 hurricane	2005	United States	Hurricane Katrina caused 1,836 deaths plus billions of dollars in damage
Wettest May–July since 1766	2007	England and Wales	Flooding caused US$4.7 billion in damage
Hottest summer since 1891	2007	Southern Europe (Greece)	Extensive wildfires
Heat wave	2009	Victoria, Australia	Devastating brush fires; nearly 200 human deaths
Highest December rainfall since 1900	2010	Eastern Australia	Flooding in Brisbane in early 2011; US$2.6 billion in damage
Record rainfall	2010	Pakistan	Flooding affected 20 million people; around 3000 human deaths
Record tornado activity since 1950	2011	United States (Joplin, Missouri)	116 Human deaths
Wettest January–October; Hurricane Irene	2011	Northeastern United States	Severe flooding
Extreme July heat wave	2011	United States (Texas, Oklahoma)	Wildfires burned 1.21 million hectares; ~US$7 billion in damage
Hottest and driest spring since 1880	2011	Western Europe (France)	12% Grain harvest lost

that between 1979 and 2003, annual mean maximum temperature at the International Rice Research Station in the Philippines increased by 0.35°C and minimum (night-time) temperature by 1.13°C. They found a close relationship between rice grain yield and minimum temperature during the dry cropping season (January–April). Peng et al. (2004) also showed that rice grain yield decreased by 10% for each 1°C increase in growing-season minimum temperature in the dry season. This will impact food security. The FAO defines food security as a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO 2002a). This definition entails four key dimensions of food security—availability, access, stability, and utilization—and climate change is set to impact all four dimensions.

SUSTAINABLE GLOBAL AGRICULTURAL SYSTEM

Despite industrial and technological revolutions, agriculture continues to be the fulcrum of human civilization. It contributes 4% of the global gross domestic product (GDP) (World Bank 2003) and provides employment to 1.3 billion people (Dean 2000). It accounts for the bulk of human land use. Pasture and crops alone occupied 37% of Earth's land area in 1999. Around 2006, there were 276 million hectares (Mha) of irrigated cropland (FAO 2006), which represented a five-fold increase since the beginning of the twentieth century. Agriculture accounts for more than two-thirds of human water use; in Asia, agriculture's share is 80% (FAO 2002b). Because of the economic importance of agriculture, attention must be paid to developing a sustainable global agricultural system.

In the following section, we summarize broad predictions of future impacts of climate change on agricultural and economic systems and developmental pathways to a sustainable global agricultural system armed with improved adaptation and mitigation potential. The issues that follow have been discussed in light of direct or indirect impacts of climate change relative to global agriculture.

PROJECTED IMPACTS OF CLIMATE CHANGE ON AGRICULTURAL SYSTEMS

Changes in temperature and precipitation are projected to impact crop productivity, quality of produce, and land use in most countries of the world (Cline 2007). Higher temperatures could benefit agriculture in temperate latitudes, where area under cultivation would expand, the length of the growing period would increase, and crop productivity would see an upturn

(Schmidhuber and Tubiello 2007). A moderate incremental warming in some humid and temperate grasslands could increase pasture productivity and spread. These gains should be viewed in a scenario of increased occurrence of extreme events, such as heat waves and droughts in the Mediterranean region or increased heavy precipitation events and flooding (IPCC 2007). In drier areas, climate models have predicted increased evapotranspiration and lower soil moisture levels (Rosenzweig et al. 2001 2002; IPCC 2007). As a consequence, many cultivated areas might become unsuitable for farming and some tropical grasslands could become increasingly arid. The consensus of IPCC's Fourth Assessment Report (AR4) models (http://www.realclimate.org/index.php/data-sources) suggests an increase in annual precipitation in most of Asia during the century, the relative increase being largest in North and East Asia. The mean winter precipitation is also likely to increase in northern Asia and the Tibetan Plateau as well as in West, Central, Southeast, and East Asia. On the other hand, summer precipitation is likely to increase in South, Southeast, North, and East Asia but decline in West and Central Asia. Most of the AR4 models project reduced precipitation in December, January, and February. An increase in precipitation, however, may not necessarily mean an increased number of rainy days. An increase in the frequency of extreme weather events, including heat wave and intense precipitation events, is also projected for South, East, and Southeast Asia. An increase of 10%–20% in tropical cyclone intensities for a rise in sea surface temperature of 2°C–4°C above the current threshold temperature has also been projected (IPCC 2007).

Countries in the Southern Hemisphere are expected to suffer more than those in the Northern Hemisphere because of their narrow economic base and high population density, with a large proportion engaged in farming. In India, almost 58% of the labor force depends on farming (Groom and Tak 2013), a figure that goes up to 75% in many of the Asian rice-belt economies, such as Vietnam and Thailand. Vietnam, according to the International Food Policy Research Institute (IFPRI) reports, will be one of the most climate change–impacted countries. Because Vietnam is the second-largest rice exporter in the world and two-thirds of its rural labor force depends on rice production, rising sea levels and increased temperature would negatively impact the country's rice production and consequently its large population (Yu et al. 2010). Climate change could decrease Vietnam's annual rice production by 2.7 million tons by 2050 (Yu et al. 2010). A rise in mean temperature of 2°C above normal could mean that small islands, such as Tuvalu in the Pacific Ocean, and Maldives, Lakshadweep, and Andaman and Nicobar in the Indian Ocean, could face submergence (Swaminathan 2012, 143).

The Centre for Environmental Economics and Policy in Africa reported that droughts in Zambia had increased in both frequency and intensity during the past few decades; droughts in 1991–1992, 1994–1995, and 1997–1998 were especially harmful for subsistence farmers (http://blogs.worldwatch.orgnourishingtheplanet/fao-and-ecs-promotion-of-climate-smart-agriculture/). Because of increased drought and consequent fires, agricultural production is projected to decline throughout much of southern and eastern Australia, and throughout parts of eastern New Zealand by 2030 (ftp://ftp.fao.org/docrep/fao/meeting/013/ai782e.pdf). In contrast, there could be moderate yield increases in northeastern Australia and parts of New Zealand because of longer growing seasons, less frost, and increased rainfall (IPCC 2007). Agricultural productivity could become uncertain because of the effect of retreating glaciers on the quantum of water carried in snow-fed rivers on some of the most productive deltas of the world, including the Indo-Gangetic plains in India and the Mekong Delta in Southeast Asia, which are both thickly populated and intensively cultivated. Central Asia is expected to experience an increase in mean annual temperature of 2°C by 2020 and between 4°C and 5°C by 2100. A decrease in annual runoff of 12% is also projected by 2020, with a potential three-fold increase by 2050 (http://sdwebx.worldbank.org/climateportalb/doc/GFDRRCountryProfiles/wb_gfdrr_climate_change_country_profile_for_KGZ.pdf). Increased climate sensitivity is also expected in the southeastern United States and in the U.S. Corn Belt (Carbone et al. 2003). Crops that are currently near climate thresholds (e.g., wine grapes in California) are likely to suffer decreased yields or quality, or both, with even modest warming (medium confidence) (White et al. 2006). Yields of cotton, soybeans, and barley could change much more than those of maize, wheat, and some vegetable crops (Antle 2009). Reduced availability of water and elevated temperatures are expected to have negative effects on wheat, maize, and potentially soybean production in Brazil (de Siqueira et al. 1994). Rosenzweig et al. (1993) indicated northeastern Brazil to suffer yield impacts that would be among the most severe in the world.

Climate change is likely to shorten growing season and force large regions of marginal agriculture out of production in many African countries that already face semiarid conditions that make agricultural production challenging. Projected reductions in yield in some countries could be as much as 50% by 2020 (Radhouane 2013); crop net revenues could fall by as much as 90% by 2100, with small-scale farmers being the most affected (Kurukulasuriya et al. 2006; Benhin 2008). Although drought-induced food and water scarcity would become more acute in South Asia, sub-Saharan Africa, and small islands, northern latitudes would benefit from longer seasons and higher yields (Swaminathan 2012, 143).

Black carbon and tropospheric ozone also act as primary drivers of the tropical expansion being observed in the Northern Hemisphere; detailed observations have shown that the tropics have widened by 0.7° latitude per decade, with warming from GHGs contributing further to the expansion in both hemispheres (Allen et al. 2012). Such unabated tropical belt expansion would impact large-scale atmospheric circulation, especially in the subtropics and midlatitudes; and if a poleward displacement of midlatitude storm tracks also occurs, midlatitude precipitation will be shifted poleward, impacting regional agriculture, economy, and society, especially in the subtropics (Allen et al. 2012).

Erratic changes in rainfall amount, timing, and pattern or unpredictability of rainfall will affect nearly all land, and changes in temperature will shift the current distribution of crops, pests, parasites, disease vectors and organisms, pollinators, symbionts, and wild plants and animals (Van Noordwijk et al. 2011). Temperature rise will also expand the range of many agricultural pests and enhance the ability of pest populations to overwinter and attack spring crops. Another important change for agriculture is the increase in atmospheric CO_2 concentrations. The projected atmospheric CO_2 concentration depends on which SRES is invoked; it is projected to increase from 379 $mg \cdot kg^{-1}$ (or parts per million) today to 550 $mg \cdot kg^{-1}$ by 2100 in SRES B1 to 800 $mg \cdot kg^{-1}$ in A1FI, the latter being fossil fuel intensive (IPCC 2000, 2007). Higher CO_2 concentrations will benefit many crops, enhancing biomass accumulation and final yield. However, the magnitude of this effect is less clear, with significant variations depending on management type (e.g., irrigation and fertilization regimes) and crop type (IPCC 2001). Experimental yield response to elevated CO_2 shows that under optimal growth conditions, crop yield increase at 550 $mg \cdot kg^{-1}$ CO_2 in the range of 10%–20% could occur for C3 crops (e.g., wheat, rice, and soybean) and only 0%–10% for C4 crops, such as maize and sorghum (IPCC 2007). However, the nutritional quality of agricultural produce is unlikely to improve in line with higher yields. Many cereal and forage crops had lower protein concentrations under elevated CO_2 conditions (IPCC 2001). The same is true for protein- and oil-rich crops, as reduced seed accumulation of these components occurs under elevated temperature regimes. Studies have also estimated the likely changes in land suitability, potential yields, and agricultural production in the group of domesticated crops and cultivars available today (Fischer et al. 2007).

ACCESS TO FOOD AND LIVELIHOOD SECURITY

Climate-induced reductions in agricultural productivity, production stability, and, consequently, farm incomes are expected to further strain the capacity of developing countries to fight hunger and nutrition deprivation. During the past 30 years, falling food prices (World Bank 2001) in real terms and growing incomes have improved access to food in many developing countries. Increased purchasing power has allowed a growing number of people to purchase not only more food but also more nutritious food with more protein, micronutrients, and vitamins (Schmidhuber and Shetty 2005). Tilman et al. (2011) reported that increasing per capita demand for crops, measured as caloric or protein content of all crops combined, was related to increasing per capita real income since 1960. Accordingly, they forecast a 100%–110% increase in global crop demand from 2005 to 2050.

East Asia and, to a lesser extent, the Near East/North African region have particularly benefited from a combination of low food prices and rapid income growth from 1970 to 2001. The prevalence of hunger in these regions, as measured by FAO's indicator of undernourishment, declined from 24% to 10.1% in East Asia and from 44% to 10.2% in the Near East/North African region (Alexandratos, 1995). In the Near East/North African region, demand was spurred by revenues from oil and gas exports, and additional food supply came largely from imports. This resulted in reduced food and nutrition deprivation. The FAO's longer-term outlook to 2050 (FAO 2006) suggests that demand-side constraints will become even more important in the next 50 years than in the past. A double-digit inflation in food prices is already evident in many populous countries, such as India, which saw rapid economic growth during the first decade of this millennium. Several investigations have ventured to estimate the seeming impact of climate change on food prices (Darwin et al. 1995; Reilly et al. 1996; Fischer et al. 2002). On average, food prices are expected to rise moderately in line with moderate increases in temperature (until 2050). Some studies even expect a marginal decline in real prices until 2050. After that, and in a scenario of increasing temperatures, prices are expected to increase more substantially for some commodities (e.g., rice and sugar) by as much as 80% above their reference levels even without invoking climate change (Reilly et al. 1996). The effects of climate change notwithstanding, altered socioeconomic development paths would also imply an increase in real cereal prices by as much as 170%; additional price increase, caused by climate change (in the Hadley Centre Coupled Model, version 3, climate change case), in contrast, would only be 14.4%.

High international cereal prices have in the past sparked food riots in several countries. Shifts to energy crops at the cost of food crops and reductions in arable land and rangelands attributable to rapid urbanization may further fuel food prices. The increasing population and land-use equilibria, coupled with increasing climatic uncertainties, are responsible for increased agricultural vulnerabilities and consequently restricted access to affordable food. Evidence for changing climate trends in the Sahel and West Africa and their implications for food security and regional stability were released recently at the United Nations Climate Change Conference held in Durban, South Africa (http://www.unep.org/newscentre/default.aspx?DocumentID=2661&ArticleID=8971). The analysis revealed an overall rise in mean seasonal temperature from 1970 to 2006 of approximately 1°C, with a greater increase between 1.5°C and 2°C observed in far eastern Chad and northern Mali and Mauritania. The study showed that the frequency of floods and the flooded area had increased in parts of the region during the past 24 years. For example, large areas of southern Burkina Faso, western

Niger, and northern Nigeria experienced up to 10 floods during this period. The report *Livelihood Security: Climate Change, Migration and Conflict in the Sahel* used an innovative mapping process to delineate 19 "climate hot spots" where climatic changes had been the most severe. The study found that the impacts of such changing climatic conditions on the availability of natural resources, combined with factors such as population growth and weak governance, led to greater competition for scarce resources and to changing migration patterns in the region. The competition for freshwater, coastal resources, and land among fishermen, farmers, and pastoralists as well as new migrants has been increasing, and in some cases, it has led to heightened tensions and conflict, most notably in the area surrounding Lake Chad. The frequency and severity of flooding has increased in the Sahel and West Africa, allowing for less recovery time for farmland and pastures between floods, resulting in increased risk of deaths, massive population displacement, and crop and cattle losses. As the livelihoods and food security in the region are heavily dependent on natural resources, further impacts of climate change on ecosystems could be dramatic. This analysis highlights how competition between communities for scarce resources, especially land, water, and forests, is already a reality in West Africa.

Agriculture is a major source of livelihood in many Asian–Pacific countries, and there are many areas that are vulnerable to climate change. Livelihoods are more at risk in mountainous areas, such as the Himalayas; arid and semiarid areas, such as Pakistan and India; vast coastal areas in South and Southeast Asia and the Pacific Islands and forest areas in these regions. Small islands are extremely vulnerable because of high exposure of population and agricultural infrastructure to sea-level rise (e.g., Maldives) and storms of increased intensity and number (Dev 2011; http://www.igidr.ac.in/pdf/publication/WP-2011-014.pdf). In general, a clear linkage exists between poverty and vulnerability to climate change. Poorer households are dependent on the agricultural options that are most sensitive to climate hazards. On account of poverty, they also have fewer alternative food and income sources available in the event of crop failure. This, most often, results in food insecurity caused by a lack of stability in the availability of and access to food.

SOIL AND SUBSOIL WATER RESOURCES

The potential of climate change—as expressed in changed precipitation regimes—to increase the risk of soil erosion, surface runoff, and related environmental consequences is obvious. The actual damage that would result from such a change is uncertain. Regional, seasonal, and temporal variability in precipitation is large both in simulated climate regimes and in the existing climate records. Different landscapes vary greatly in their vulnerability to soil erosion and runoff. A change in precipitation intensity also alters the level of risk to which agricultural land is exposed. The effect of a particular storm event also depends on the moisture content of the soil. Timing of agricultural production practices creates even greater vulnerabilities to soil erosion and runoff during certain seasons. These interactions among precipitation, landscape, and management actually translate into more uncertain and complex outcomes of any particular change in the precipitation regime. In general, a regime with greater annual precipitation—particularly, if intensity changes more than frequency—heightens the risk of soil erosion, water runoff, and related environmental and ecological damages. Risk increases at a rate greater than the rate at which precipitation amount or intensity increases. A more risky baseline condition might translate into greater soil degradation, pollution of surface water, pollution of groundwater, or a combination of all three outcomes. Increased global temperature accelerates carbon losses from soils, increasing the concentration of carbon dioxide in the atmosphere. The changes in rainfall patterns are most likely to contribute to an increase in erosion in vulnerable soils, especially the ones containing low organic matter. Climate change will thus put further pressure on soil quality and increase the risk of desertification and land degradation.

That agriculture uses more water than any other sector is an undisputed fact. In low-income countries, agriculture uses 87% of total extracted water, whereas this figure is 74% in middle-income countries and 30% in high-income countries (World Bank 2003). Overexploitation of groundwater resources, coupled with reduced groundwater recharge, has already created problem of receding water tables and increased salinization of groundwater (Hira 2010). Impacts of climate change on global water resources also include increased evaporation, a higher proportion of precipitation received as rain instead of snow in temperate regions, early and short runoff seasons, elevated water temperatures, and decreased water quality. Increased moisture deficits, especially in summers, may decrease soil moisture levels besides causing intense and more frequent droughts, severely damaging both managed and natural ecosystems. Even without climate change, Africa, particularly northern Africa, will exceed the limits of its economically usable land-based water resources before 2025. About 25% of Africa's population (about 200 million people) even now experiences high water stress (Jarvis et al. 2008). The population at risk of increased water stress in Africa is projected to be 75–250 million by the 2020s and 350–600 million by the 2050s. By the 2080s, the proportion of arid and semiarid lands in Africa is expected to increase by 5%–8% (Jarvis et al. 2008).

The chronic drought that hit western North America from 2000 to 2004 was said to be the strongest in 800 years, which left forests dying and river basins depleted in its wake. This drought affected precipitation, soil moisture, river levels, crops, forests, and grasslands. Global warming is said to be responsible for the increased frequency of such climatic extremes

(Schwalm et al. 2012). In addition to its impact on forests, crops, rivers, and water tables, drought cut carbon sequestration by an average of 51% in a massive region of the western United States, Canada, and Mexico, although some areas were hit much harder than others (Schwalm et al. 2012). There was a 5% decline in crop productivity in much of the West.

Climate change is also expected to affect water quality in both inland and coastal areas (http://www.choicesmagazine.org/2008-1/theme/2008-1-04.htm). Specifically, precipitation is expected to occur more frequently via high-intensity rainfall events, causing increased water runoffs. More sediments and chemical runoffs will reach streams and groundwater systems. This, coupled with reduced percolation in arid areas, would increase nutrient and contaminant load in subsoil water. Increased air and water temperatures would also accelerate organic matter decomposition and nutrient-cycling rates in lakes and streams, resulting in lower dissolved oxygen levels and impacting the already fragile water ecosystems. In drier areas of Latin America, climate change is likely to lead to salinization and desertification of agricultural lands. By the 2050s, 50% of agricultural land is highly likely to be subjected to desertification and salinization in some areas (Jarvis et al. 2008).

RISE IN SEA LEVELS AND SEAWATER ACIDIFICATION

Another most obvious way in which climate change will affect the economy, including agriculture, is by the predicted sea-level rises, varying from a mere 200 mm to several meters, depending on the effect of global warming on the Arctic and Antarctic ice sheets. A rise of just 1 m will be sufficient to flood most of New York City. South and Southeast Asia and the Pacific Islands are highly vulnerable to rising sea levels, with increased risk of floods. The global sea level gradually rose during the twentieth century and continues to rise at increasing rates (Cruz et al. 2007). In coastal areas of Asia, the current rate of sea-level rise is reported to be between 1 and 3 $mm \cdot yr^{-1}$, which is marginally higher than the global average sea-level rise (IPCC 2007).

Rising sea levels will no doubt affect all coastal land use and communities (Van Noordwijk et al. 2011). The sea level in Asia and the Pacific is expected to rise, in conjunction with regional sea-level variability, approximately 3–16 cm by 2030 and 7–50 cm by 2070. The population densities of China's 11 coastal provinces average more than 600 people per square kilometer of coastline, and more and more people are moving to coastal areas because of better employment opportunities there. Rising sea levels and population pressure have already eroded many of the world's extensive sandy beaches, increasing the risk from tidal waves and tsunamis. Increased sea levels may also impair water quality and availability in coastal areas directly by saltwater intrusion or indirectly by causing water tables in groundwater aquifers to rise. This may increase surface runoff at the expense of aquifer recharge. A worst-case scenario is the complete melting of the Greenland ice sheet or the West Antarctic ice sheet, which would trigger massive increases in the sea level and wipe out most of island nations and coastal metropolises in the world, setting off a colossal wave of human displacement.

In addition to causing global warming, high CO_2 emissions are known to alter the chemistry of the oceans and cause them to become more acidic. Such ocean acidification has already had significant consequences for marine ecosystems and can potentially disrupt marine food webs, coral-reef fishing, tourism, and other human activities. Ocean acidification is directly caused by greater atmospheric emissions of CO_2. These emissions have increased during the past 200 years, primarily because of rapid industrialization and agriculture, which increase the consumption of fossil fuels, and other land-use changes. The NOAA reports that the oceans have absorbed about 50% of the CO_2 released from the burning of fossil fuels. Many organisms depend on the relatively stable balance of carbonate chemistry, which had endured for millions of years until the onset of the Industrial Revolution. Since then, there has been a 30% decrease in pH and a 16% decrease in carbonate ion concentrations. As CO_2 emissions continue to rise, ocean acidification is rapidly becoming a critical issue, with the potential of affecting many species and their ecosystems, especially those associated with human food resources. Ocean acidification is happening now, is measurable, and will increase as more CO_2 is emitted. It is likely that if CO_2 emissions continued unabated, ocean acidification would have a considerable influence on marine-based diets of billions of people worldwide. Based on the current rates of CO_2 emissions, projections are that by the end of the 21st century, global ocean pH would decrease further by 0.3, which represents a total increase in acidity of 150%. A continuing decrease in ocean pH could lead to the loss of some shell- or skeleton-forming organisms. Eventually, the sediments in the oceans would buffer these chemical changes, but chemical recovery from such events might take tens of thousands of years, and a return to the biological status quo, even if possible, could take millions of years. One must also realize that a very large volume of human food and nutritional requirements is met from seafood. Thus, the well-being of sea ecosystems is a must; otherwise, millions of people who depend on stable seas for food and livelihoods would be adversely affected.

AGRICULTURAL PERSPECTIVE OF MITIGATION AND ADAPTATION TO CLIMATE CHANGE

The IPCC defines mitigation (reducing emissions) as an anthropogenic intervention that reduces the sources or enhances the risks of greenhouse gases (IPCC 2001). Mitigation refers to any action taken to permanently eliminate or reduce the long-term risks and hazards of climate change to human life and/or property (http://www.global-greenhouse-warming.com/climate-mitigation-and-adaptation.html). Adaptation to climate change refers to the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damage, to take advantage of opportunities, or to cope with the consequences (http://www.global-greenhouse-warming.com/climate-mitigation-and-adaptation.html). Mitigation is a proactive approach, whereas adaptation (reducing vulnerabilities) is a reactive approach. In short, mitigation is "avoiding the manageable" (e.g., environmental and industrial measures) and adaptation is "managing the unavoidable" (e.g., genetic manipulation for crop adaptation). Fortunately, climate change adaptation and mitigation can go hand in hand in the agricultural sector as a critical component of the overall developmental goals. The potential role of agroecosystems in mitigation of climate change depends on a dual strategy of decreasing GHG emissions while increasing sinks, such that the net impact on climate change is less than it is at present (Lehmann et al. 2011).

There are many historical instances where civilizations that failed to adapt to changing climate fell and the ones that adapted prospered. Fribourg (2006) summed up the consequences of anthropogenic destruction or degradation of environment in a review of a book entitled *Collapse* by Jared Diamond. He points out that most civilizations collapse, and a primary cause of the demise of these societies is destruction of their environment. He cites the cases of the Maya in Mexico's Yucatán peninsula, whose population exceeded their crop-growing area, and the Anasazi in New Mexico, whose population exceeded their water supply. In the same context, he also refers to the Norse in Greenland, who settled during a warm period and then faced falling temperatures to extinction. Other examples included the statue builders of Easter Island, who cut every tree on which their civilization depended; the Mesopotamians (in an area formerly known as the Fertile Crescent), who exhausted their soils and brought up salt with their irrigation water; and many others who succumbed to various combinations of environmental degradation, climate change, aggression from enemies, and declining trade with neighbors. A highly scientific reconstruction of Holocene paleoclimate in the core monsoon zone (CMZ) of the Indian peninsula revealed that there seemed to be a gradual increase in aridity-adapted vegetation from approximately 4,000 until 1,700 years ago, and it was followed by the persistence of aridity-adapted plants (Pontan et al. 2012). The oxygen isotopic composition of planktonic foraminifera *Globigerinoidesruber* detected unprecedented high salinity events in the Bay of Bengal during the past 3,000 years, especially after 1,700 years ago. These suggest that the CMZ aridification intensified in the late Holocene through a series of submillennial dry episodes. Cultural changes occurred across the Indian subcontinent as the climate became more arid after approximately 4,000 years. Sedentary agriculture took hold in the arid Central and South India, with humidity-loving plants giving way to drought-tolerant millets and soil-restoring bean species. In contrast, a largely urban Harappan civilization collapsed in the already arid Indus basin. The establishment of a more variable hydroclimate during the last ca. 1,700 years may have led to the rapid proliferation of water-conservation technologies in southern peninsular India. Fribourg (2006) points out that the present society may be susceptible to thinking that they are different from those powerful societies of the past, and cautions us that the civilizations that collapsed, too, thought they were unique, right up to the moment of their collapse. Scientific studies have shown that, in recent history, climate change was responsible for the outbreak of war, dynastic transition, and population decline in China, Europe, and around the world because of climate-induced shrinkage of agricultural production (Zhang et al. 2007; Tol and Wagner 2010; Zhang et al. 2010). Recent research has concluded that climate change was the ultimate cause, and climate-driven economic downturn was the direct cause, of large-scale human crises in preindustrial Europe and the Northern Hemisphere (Zhang et al. 2011).

There may be lessons to learn here; for example, drought-tolerant agriculture has eroded across the world during the twentieth century, with a shift toward more water- and chemical-intensive forms of modern agriculture. Cultivation of rice in drier areas of the world is also unsustainable. Rice cultivation is known to accentuate environmental degradation as far as water requirements and methane emissions are concerned. Improved rice cultivation techniques are now necessary to reduce CH_4 emissions and improved nitrogen fertilizer application techniques to reduce N_2O emissions.

Transformation of agriculture to ensure food security in the face of changing climate with the least ecological cost will help mitigate the negative effects of climate change. More productive and climate-resilient agriculture requires better management of natural resources, such as land, water, soil, and germplasm, through practices such as conservation agriculture, precision agriculture, and integrated pest management. Cropping practices need to shift toward reduced-till or no-till technologies, which enhance water infiltration and conserve soil moisture, or toward irrigation technologies that are more efficient at the farm level (FAO 2009). Attempts to increase production by increasing mineral nitrogen use need to be harmonized with increased fertilizer-use efficiency and reduced N_2O emission potential. Fertilizer-evaluation experiments with crop plants may also include environmental costs relative to water contamination and N_2O emission, particularly in the most advanced countries. There is a strong case for reduced and targeted fertilizer use: promotion of legumes in crop rotations, increasing biodiversity, avoiding burning of crop residues, and promoting efficient energy use during agricultural operations. From the perspective of global agriculture, innovations, especially relative to the exploitation of variability in wild and weedy crop relatives and genetically engineered crops, will be needed to effectively prevent productivity losses and also increase crop productivity even in high-temperature, low-fertility regimes and other environmental extremities, such as drought and flooding. Water recycling and purification are necessary to ensure that communities in drought-prone regions and those impacted by rising sea levels or disappearing mountain glaciers would have access to drinking water, whereas engineering innovations are needed to safeguard those communities, buildings, and crops against rising water and other extreme weather. Writing on sustainable water systems for agriculture and 21st century challenges, Kanwar (2010) highlighted the impacts of climate change on glacier melting and sustainability of river water systems. He concluded that unless individual countries developed good land and water management policies and state-of-the-art irrigation and crop production technologies for water conservation, reduced carbon emissions, and environmental enhancement, food security and water sustainability would be very much at risk.

Integration of agricultural operations with accurate weather forecasting may help reduce weather-related losses. Producers may begin to supplement dwindling surface water supplies with overexploitation of groundwater resources, a response that has already been observed in many drought-stricken areas, including the plains of northwest India. There is a need to adjust water prices to encourage conservation. FAO and others are promoting this transformation of agriculture as "climate-smart agriculture"—an agriculture that sustainably increases productivity and resilience (adaptation) and reduces/removes GHGs (mitigation) while ensuring national food security and achievement of development goals (FAO 2010).

Tilman et al. (2011) considered two mitigation strategies or scenarios: first, if greater agricultural intensification in richer countries and greater land clearing or extensification in poorer countries were to occur, by 2050, globally nearly 1 billion hectares of land would be cleared and CO_2-eq GHG emissions would reach nearly 3 $Gt \cdot yr^{-1}$ and N-use would reach about 250 million tons per year. However, in a second scenario, resource use and GHG emissions would be substantially reduced if the 2050 demand were met by moderate intensification on croplands of under-yielding countries, adaptation and transfer of high-yielding technologies to these croplands, and global technological improvements. The authors forecast, in comparison with the first scenario, 80% less land clearing (about 0.2 billion ha) and 10% less global N-use (225 million tons per year) would be required, and 67% less CO_2-eq GHG emissions (about 1 $Gt \cdot yr^{-1}$) would occur.

Reductions in GHG emissions can be achieved by decreasing the heterotrophic conversion of organic carbon to CO_2 and by better management of agricultural waste streams to minimize the release of methane and nitrous oxide (Lehmann and Joseph 2009; Lehmann et al. 2011). The GHGs can be absorbed from the atmosphere through sinks. Carbon can be sequestered and stored in soils, resulting in increases in soil organic carbon (Lal et al.

2011). Of the global technical potential estimated by Smith et al. (2007a,b), about 89% is from soil-carbon sequestration, about 8% from mitigation of methane, and about 2% from mitigation of soil N_2O emissions (WG III, IPCC 2007). Biochar—a carbon-rich material generated by heating biomass in the absence, or under a limited supply, of oxygen—is another sink for carbon and has the potential to reduce emissions by agriculture and to actively withdraw atmospheric CO_2 (Lehmann et al. 2011).

The IPCC has estimated that out of the global mitigation potential for agriculture (excluding forestry and fossil fuel offsets from biomass, including all gasses) to the tune of 5500 and 6000 Mt CO_2-eq per year by 2030, 89% is through soil-carbon sequestration. Mitigation efforts will require a focus on its five major sectors, namely, livestock, forestry, rangeland, agriculture, and fisheries. The classical mitigation options in the agricultural sector at large include reducing deforestation and forest degradation and enhancing afforestation and reforestation, along with forest-management interventions to maintain or increase forest-carbon density. Reduced-till or no-till agriculture, diversified cropping patterns, and increased soil cover also limit soil disturbance and increase soil carbon. Soil organic carbon can be increased through grazing land management, which improves the cover of high-productivity grasses and overall grazing intensity. In Asia, large potential exists in India, which has one of the world's largest grazing land areas (Rosegrant et al. 2010).

There is growing evidence that adaptation, mitigation, food security, and rural development can coexist. Field crops and forestry strategies can simultaneously increase adaptive capacity and mitigate climate change. For example, increasing soil organic matter in cropping systems, agroforestry, and mixed-species forestry can improve soil fertility and soil moisture-holding capacity, reduce the impact of droughts or floods, reduce vulnerability, and sequester carbon. Van Noordwijk et al. (2011) focused on the relationship between climate change adaptation, rural development, and the roles of trees and agroforestry. They suggested that both people and trees could adapt to change at various timescales, but the current rate of change implied that proactive planning as part of integrated rural development was needed. There is a need to explore and promote synergy between adaptation and mitigation in the agriculture and forestry sectors. People can take many actions to support both adaptation (ensuring that the land cover can deal with likely climate changes without major loss of function) and mitigation (reducing net emissions by enhancing terrestrial carbon storage). Institutional support for the combination (mitigadaptation) is needed (Van Noordwijk et al. 2011). More productive and resilient agriculture will need better management of natural resources, such as land, water, soil, and genetic resources, through practices such as conservation agriculture, integrated pest management, and agroforestry (http://www.fao.org/climatechange/climatesmart/en/). Because of the complexity of crop-environment interactions, a multidisciplinary approach to the problem is required, wherein plant breeders, crop physiologists, agrometerologists, and agronomists need to interact to find long-term solutions in sustaining agricultural production (Chauhan et al. 2013).

ECONOMICS OF CLIMATE CHANGE AND MITIGATION

In spite of the existence of a relatively broad understanding of issues related to climate change, global consensus is still elusive with regard to putting in place mitigation strategies and a set of policy interventions to control anthropogenic factors contributing to climate change. This is so partly because forecasting the economic consequences of climate change is a complex issue on account of the inherent element of uncertainty. It is practically impossible to correctly predict the cost of climate change, which includes expected losses and expenditure involved in mitigation efforts. The cost of reducing future emissions will depend on the existing prices of fossil fuels and renewable forms of energy, which, in turn, will depend on factors such as depletion of energy reserves, economic growth, demographics, national policies, and technological advances. Also, the cost of dealing with rising temperatures may vary with the location and severity of regional climate impacts, and ecosystems and the benefits we derive from them. This may also include human health and nutritional issues, such as response to new diseases and food utilization. From an agricultural point of view, it may also include development of climate-resilient crops and efficiency of land-use systems and avoidance of soil erosion and degradation. One can also extend the list to include the costs of weather management, pest forecasting systems, water management, land lost to sea-level rise, and saltwater intrusion. We can even add to this burgeoning expenditure basket, costs incurred on account of "climate refugees." It is, however, certain that climate change will infringe upon the ability of developing countries to manage their economies and may even adversely impact their quest for development.

Economists mostly agree on an equation that suggests that carbon emissions are a complex interplay of population, GDP, and carbon intensity of an economy (see the following equation). Carbon intensity is the amount of carbon by weight emitted per unit of energy consumed.

$$\begin{aligned} \textit{Carbon emissions} &= \textit{population} \times (\textit{GDP percapita}) \\ &\quad \times (\textit{carbon intensity of the economy}) \end{aligned}$$

or

$$C = P \times \frac{GDP}{P} \times \frac{C}{GDP}$$

where C/GDP is made up of two terms: E/GDP (energy intensity of the economy) and C/E (carbon intensity of energy supply). Apparently, one or more of these variables must change for a rapid reduction in global emissions.

Disastrous outcomes can be prevented if global emissions can be stabilized within 20 years and thereafter reduced by around 2% per year. There is a call for industrialized countries to reduce their emissions by 30% by 2020 and at least 60% by 2050. Environmentalists warn of a global recession that could hive off between 5% and 20% from the world's wealth later this century, unless there is a shift to a global low-carbon economy. Unfortunately, increasing trends of world GDP growth from 1958 to 2010 are associated with increasing CO_2 concentrations (Tapia Granados et al. 2012). For every US$10 trillion by which the world GDP deviates from the trend, CO_2 levels deviate by about 0.5 $mg{\cdot}kg^{-1}$. Preindustrial concentrations were estimated to be 200–300 $mg{\cdot}kg^{-1}$ (Tapia Granados et al. 2012). With global population expected to stabilize only around 2050, per capita GDP or carbon intensity of the economy must fall drastically to achieve reductions in carbon emissions. Sacrificing economic growth to reduce emissions may not be an acceptable proposition, given the poverty alleviation and growth needs of the bulk of the developing world. Further, even a voluntary economic contraction in the developed world cannot drive global carbon emissions toward zero. World economic growth has so far been fueled by massive industrial expansion, increased urbanization, and the large exploitation of low-cost fossil fuels. The latest edition of the low carbon economy index (LCEI) (Johnson 2011) indicates that the world economy is going backward rather than forward. To limit global warming to 2°C, as agreed during the 2010 climate change talks in Cancun, Mexico, a 4.8% annual reduction in carbon intensity is required, which is more than twice the rate required in 2000. The LCEI notes that against an improvement of 0.8% in carbon efficiency during 2010, the rate of decarbonization slowed to 0.7% during 2011 (Johnson 2011). According to the same report, absolute global emissions reached their highest level during 2010; the carbon intensity of the global economy also increased by 0.6%. Coming out of the 2009–2010 recession (5.8% vs. 5.1%), emissions grew faster than GDP. A wider acceptability of sacrificing growth through voluntary economic contraction in the name of climate mitigation will at best be extremely limited even in developed economies. Economic contraction is thus a nonsolution for significantly reducing emissions; it simply cannot result in substantial absolute decline in global carbon emissions in the short to medium term. This leaves us with just one key strategy to drive emissions toward zero; that is, we must accelerate the decarbonization of the global economy to significantly reduce the C/GDP term in the aforementioned equation. This can be achieved by acceleration of the global adoption of clean energy technologies and the decarbonization of the global energy supply through acceleration of the pace of energy innovation to make clean energy (e.g., solar or wind energy) cheaper.

According to Sir Nicholas Stern, former chief economist at the World Bank, the investment cost would be trivial in comparison with the possible damage. Stern (2007) has suggested a global investment of about 1% per year of global GDP during the next 50 years. He forecasts huge disruptions to African economies, in particular, as droughts hit food production; up to a billion people losing water supplies as mountain glaciers disappear; hundreds of millions losing their homes and land to sea-level rise; and potentially big increases in damage from hurricanes. The economic cost of failing to act could approach US$4 trillion by the end of the twenty-first century. Besides the efforts toward low-carbon economies, the role of innovation will be critical in achieving climate resilience. Shindell et al. (2012) considered 400 or so emission control measures to reduce ozone and black carbon by using current technology and experience. They identified 14 measures targeting methane and black carbon emissions that would reduce projected global warming to about 0.5°C by 2050. This strategy would avoid 0.7–4.7 million annual premature deaths from outdoor pollution and increase annual crop production by 30–135 million metric tons because of ozone reductions in 2030 and beyond. Methane emission reductions would benefit to the tune of US$700–US$5000 per metric ton of methane, which would be well above the marginal abatement costs of less than US$250 (Shindell et al. 2012). Thus, combating climate change (mitigation and adaptation) is vital for the global economy and survival of humankind.

REFERENCES

Alexandratos, N. (ed.). 1995. *World agriculture: Toward 2010, a food and agriculture organization study*. Chichester, UK: Wiley.

Allen, R. J., S. C. Sherwood, J. R. Norris, and C. S. Zender. 2012. Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature* 485:350–354.

Antle, J. M. 2009. *Agriculture and the food system: Adaptation*. Washington, DC: Resources for the Future (RFF).

Benhin, J. K. A. 2008. South African crop farming and climate change: An economic assessment of impacts. *Glob. Environ. Change* 18:666–678.

Bracmort, K. 2010. *Nitrous oxidefrom agricultural sources: Potential role in greenhouse gas emission reduction and ozone recovery*. CRS Report for Congress, Congressional Research Service. R40874. http://www.nationalaglawcenter.org/assets/crs/R40874.pdf. (Verified, November 27 2012)

Carbone, G., W. Kiechle, C. Locke, L. O. Mearns, and L. McDaniel. 2003. Response of soybeans and sorghum to varying spatial scales of climate change scenarios in the southeastern United States. *Clim. Change* 60:73–98.

Chauhan, B. S., P. Kaur, G. Mahajan, and M. S. Kang. 2013. Global warming and its possible impact on agriculture in India. *Advances in Agronomy* 123: In press.

Cline, W. R. 2007. *Global warming and agriculture: Impact estimates by country*. Washington, DC: Center for Global Development and Peterson Institute for International Economics.

Coumou, D., and S. Rahmstorf. 2012. A decade of weather extremes. *Nature climate change*. http://www.nature.com/natureclimatechange; accessed May 22 2012. doi:10.1038/NCLIMATE1452.

Cruz, R. V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, and N. H. Ninh. 2007. Asia. Climate change 2007: Impacts, adaptation and vulnerability. In *Contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (eds.), 469–506. New York, NY: Cambridge University Press.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses. 1995. *World agriculture and climate change: Economic adaptations. Agricultural economic report 703*. Washington, DC: U.S. Department of Agriculture.

deSiqueira, O. J. F., J. R. B. Farías, and L. M. A. Sans. 1994. Potential effects of global climate change for Brazilian agriculture: Applied simulation studies for wheat, maize and soybeans. In *Implications of climate change for international agriculture: Crop modeling study*, EPA 230-B-94–003, edited by C. Rosenzweig and A. Iglesias. Washington, DC: U.S. Environmental Protection Agency.

Dev, S. M. 2011. *Climate change, rural livelihoods and agriculture (focus on food security) in Asia-Pacific Region. Technical Background Paper*. Bangkok, Thailand: UNDP Regional Centre.

Food and Agriculture Organization (FAO). 2002a. *The state of food insecurity in the world 2001*. Rome, Italy: FAO.

Food and Agriculture Organization (FAO). 2002b. *Food agriculture towards 2015/2030*. Rome, Italy: FAO.

Food and Agriculture Organization (FAO). 2006. *Global forest resources assessment 2005: Progress towards sustainable forest management*. FAO forestry paper 147. Rome, Italy: FAO.

Food and Agriculture Organization (FAO). 2009. *FAO: Profile for climate change*. Rome, Italy: FAO.

Food and Agriculture Organization (FAO). 2010. *Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation*. Rome, Italy: FAO.

Fischer, G., M. Shah, and H. van Velthuizen. 2002. *Climate change and agricultural vulnerability. Preprints*. Johannesburg, South Africa: World Summit on Sustainable Development.

Fischer, G., F. N. Tubiello, H. van Velthuizen, and D. A. Wiberg. 2007. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technol. Forecasting Soc. Change* 74:1083–1107. doi:10.1016/j.techfore.2006.05.021.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, et al. 2007. Changes in atmospheric constituents and in radiative forcing. In *Climate change* 2007: *The physical science basis: Contribution of working group*

I to the fourth assessment report of the intergovernmental panel on climate change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). New York, NY: Cambridge University Press.

Fribourg, H. A. 2006. Collapse: An ethical book review. *J. Nat. Resour. Life Sci. Educ.* 35:24–25.

Groom, B., and M. Tak. 2013. *Welfare analysis of changing food prices: A non-parametric examination of export ban on rice in India. SOAS Department of Economics Working Paper Series No. 177*. London, UK: The School of Oriental and African Studies, Univ. of London.

Hira, G. S. 2010. Water management in northern states and the food security of India. In *Water and agricultural sustainability strategies*, edited by M. S. Kang, 136–157. Boca Raton, FL: CRC Press.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Land use, land-use change and forestry. Special Report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2001. Working Group II. Impacts, adaptation and vulnerability. In *Fourth assessment report*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. New York, NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2007. Working Group III. Mitigation of climate change. In *Fourth assessment report*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. New York, NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2011. Extreme weather and climate change: IPCC 2011 report. http://climate.uu-uno.org/articles/view/171595. (Verified November 28 2012)

Jarvis, A., H. Upadhyaya, C. L. L. Gowda, P. K. Aggarwal, S. Fujisaka, and B. Anderson. 2008. Climate change and its effect on conservation and use of plant genetic resources for food and agriculture and associated biodiversity for food security. Report to ICRISAT/FAO. November 2008. http://www.fao.org/docrep/013/i1500e/i1500e16.pdf.

Johnson, L. 2011. *Counting the cost of carbon: Low carbon economy index 2011*, 3rd ed. London, UK: PricewaterhouseCoopers LLP. http://www.pwc.com/en_GX/gx/sustainability/publications/low-carbon-economy-index/assets/low-carbon-economy-Index-2011.pdf

Kanwar, R. 2010. Sustainable water systems for agriculture and 21st century challenges. In *Water and agricultural sustainability strategies*, edited by M. S. Kang, 3–19. Boca Raton, FL: CRC Press.

Kurukulasuriya, P., J. K. A. Benhin, and T. Deressa. 2006. Will African agriculture survive climate change? *World Bank Econ. Rev.* 20(3): 367–388.

Lal, R., M. V. K. Sivakumar, S. M. A. Faiz, A. H. M. M. Rahman, and K. R. Islam (Eds.). 2011. *Climate change and food security in South Asia*. New York: Springer.

Lehmann, J., J. E. Amonette, and K. Roberts. 2011. Role of biochar in mitigation of climate change. In *Handbook of climate change and agroecosystems: Impacts, adaptation, and mitigation*, edited by D. Hillel and C. Rosenzweig, 343–363. London, UK: Imperial College Press.

Lehmann, J., and S. Joseph. 2009. Biochar for environmental management: An introduction. In *Biochar for environmental management: Science and technology*, edited by J. Lehmann and S. Joseph, 1–12. London, UK: Earthscan Publications.

Min, S.-K., X. Zhang, F. W. Zwiers, and G. C. Hegerl. 2011. Human contribution to more-intense precipitation extremes. *Nature* 470(7,334): 378–381.

National Oceanic and Atmospheric Association (N0AA). 2011. State of the climate annual 2010. http://www.ncdc.noaa.gov/sotc/2010/13.

Pall, P., T. Aina, D. A. Stone, P. A. Stott T. Nozawa, A. G. J. Hilberts, D. Lohmann and M. R. Allan. 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* 470(7,334): 382–385.

Peng, S., J. Huang, J. E. Sheehy, R. C. Laza, R. M. Visperas, X. Zhong, G. S. Centeno, G. S. Khush, and K.G. Cassman. 2004. Rice yields decline with higher night temperature from global warming. *Proc. Nat. Acad. Sci. (USA)* 101(27): 9,971–9,975.

Pontan, C., L. Giosan, T. I. Elington, D. Q. Fuller, P. Kumar, and T. S. Collett. 2012. Holocene aridification of India. *Geophysical Res. Lett*. doi:10.1029/2011gl050722.

Radhouane, L. 2013. Climate change impacts on North African countries and on some Tunisian economic sectors. *J. Agri. Environ. Intl. Develop.* (JAEID) 107(1): 101–113.

Reilly, J., W. Baethgen, F. E. Chege, S. C. van de Geijn, L. Erda, A. Iglesias, G. Kenny, et al. 1996. Agriculture in a changing climate: Impacts and adaptation. In *Climate change 1995: Impacts, adaptations and mitigation of climate change: Scientific-technical analyses, Contribution of working group ii to the second assessment report of the intergovernmental panel on climate change*, edited by R. T. Watson, M. C. Zinyowera, and R. H. Moss, 427–467. New York, NY: Cambridge University Press.

Rosegrant, M. W., G. Yohe, M. Ewing, R. Valmonte-Santos, T. Zhu, I. Burton, and S. Huq. 2010. Climate change and Asian agriculture. *Asian J Agricul. Dev.* 7(1): 1–42.

Rosenzweig, C., A. Iglesias, X. B. Yang, P. R. Epstein, and E. Chivian. 2001. Climate change and extreme weather events: implications for food production, plant diseases and pests. *Glob. Change Human Health* 2:90–104.

Rosenzweig, C., M. L. Parry, G. Fischer, and K. Frohberg. 1993. *Climate change and world food supply. Research Report No. 3.* Oxford, UK: Environmental Change Unit, Oxford University.

Rosenzweig, C., F. N. Tubiello, R. A. Goldberg, E. Mills, and J. Bloomfield. 2002. Increased crop damage in the U.S. from excess precipitation under climate change. *Glob Environ. Change* 12:197–202.

Schmidhuber, J., and P. Shetty. 2005. The nutritional transition to 2030. *Acta Agri. Scand*. 2/3– 4:150–166.

Schmidhuber, J., and F. N. Tubiello. 2007. Global food security under climate change. *Proc. Nat. Acad. Sci. (USA)* 104:19,703–19,708.

Schwalm, C. R., C. A. Williams, K. Schaefer, D. Baldocchi, T. A. Black, A. H. Goldstein, B. E. Law, W. C. Oechel, KThaPawU, and R. L. Scott. 2012. Reduction in carbon uptake during turn of the century drought in western North America. *Nature Geoscience*. doi:10.1038/ngeo1529.

Shindell, D., J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, et al. 2012. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335(13 January 2012): 183–189.

Smith, P., D. Martino, Z. Cai, D. Gwary, H.H. Janzen, P. Kumar, B. McCarl, et al. 2007a. Greenhouse gas mitigation in agriculture. *Philos Trans R Soc. B*. 363. doi:10.1098/rstb.2007.2184.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, et al. 2007b. Agriculture. In edited B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer (eds.) *Climate change 2007: Mitigation. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel On Climate Change*. New York, NY: Cambridge University Press.

Stern, N. 2007. *Stern review on the economics of climate change*. New York, NY: Cambridge University Press.

Stott, P. A., D. A. Stone, and M. R. Allen. 2004. Human contribution to the European heat wave of 2003. *Nature* 432(7017): 610–614.

Straatsma, M., J. Ettema, and B. Krol. 2010. Flooding and Pakistan: Causes, impact and risk assessment. ITC Faculty of Geo-Information Science and Earth Observation. Available at http://www.itc.nl/flooding-and-pakistan.

Swaminathan, M. S. 2012. *Remember your humanity: Pathway to sustainable food security*. New Delhi: New India Publishing Agency.

Tapia Granados, J. A., E. L. Ionides, and O. Carpintero. 2012. Climate change and the world economy: short-run determinants of atmospheric CO_2. *Env. Sci& Policy* 21:50–62.

Tilman, D., C. Balzer, J. Hill, and 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. (USA)* 108(50): 20,260–20,264.

Tol, R. S. J., and S. Wagner. 2010. Climate change and violent conflict in Europe over the last millennium. *Clim. Change* 99:65–79.

UNDP. 2007. *Fighting climate change: Human solidarity in a divided world*. Human Development Report 2007/08. New York: Palgrave Macmillan.

Van Noordwijk, M., M. H. Hoang, H. Neufeldt, I. Öborn, and T. Yatich (eds.). 2011. *How trees and people can co-adapt to climate change: Reducing vulnerability through multifunctional agroforestry landscapes*. Nairobi, Kenya: World Agroforestry Centre (ICRAF).

World Bank. 2001. World *development indicators*. Washington, DC: The World Bank.

World Bank. 2003. World *development indicators [CD-ROM]*. Washington, DC: The World Bank.

White, M. A., N. A. Diffenbaugh, G. V. Jones, J. S. Pal, and F. Giorgi. 2006. Extreme heat reduces and shifts United States premium wine production in the 21st century. *Proc. Natl. Acad. Sci. (USA)* 103(30): 11,217–11,222.

Yu, B., T. Zhu, C. Breisinger, and N. M. Hai. 2010. *Impacts of climate change on agriculture and policy options for adaptation: The case of Viet Nam*. Washington, DC: International Food Policy Research Institute (IFPRI).

Zhang, D.D., P. Brecke, H. F. Lee, Y. Q. He, and J. Zhang. 2007. Global climate change, war, and population decline in recent human history. *Proc. Natl*. Acad. Sci. (USA) 104:19,214–19,219.

Zhang, D. D., H. F. Lee, C. Wang, B. Li, Q. Pei, J. Zhang, and Y. An. 2011. The causality analysis of climate change and large-scale human crisis. *Proc. Natl. Acad. Sci. (USA)* 108(42): 17,296–17,301.

Zhang, Z., H. Tian, B. Cazelles, K. L. Kausrud, A. Bräuning, F. Guo, and N. C. Stenseth. 2010. Periodic climate cooling enhanced natural disasters and wars in China during AD 10-1900. *Proc. R. Soc. B* 277(1,701): 3,745–3,753.