Chapter 3
Implications of Global Climatic Change on Water and Food Security

P. K. Aggarwal and A. K. Singh

Abstract Water availability, access, and use has ensured food and livelihood security for millions. In the future, food and livelihood security may be challenged due to global environmental changes, particularly global climatic changes, that evidence has gradually shown to be appearing. The Intergovernmental Panel on Climate Change (IPCC) has projected that the global mean surface temperature will rise by 1.4–5.8°C by 2100 due to increases in atmospheric carbon dioxide concentration. Climate variability is also projected to increase, leading to uncertainty in the onset of monsoons and more frequent extreme weather events, such as more severe droughts and floods. These environmental changes are known to affect all aspects of the hydrological cycle, which in turn may alter the balance between food demand and supply in time and space in many parts of the world. Regions such as South Asia and Africa are expected to be particularly vulnerable to these environmental changes due to their large population, predominance of agriculture, and limited resource base. The potential impact of climatic changes on the quality of fruits, vegetables, cereals and medicinal plants can have a negative impact on emerging trade opportunities for these commodities in many countries. To ensure future water and food security, greater attention is now needed on adaptations to climatic change, which calls for increased diversification, improved land use and natural resource management policies, increased use of biofuels, improved risk management through early warning systems and crop insurance, and wastewater recycling in agriculture.

3.1 Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007a) has confirmed the increasingly strong evidence of humanity's influence on global climate. Global mean annual temperatures at the end of the twentieth century are 0.74°C above those recorded at the end of the nineteenth century. The 1990s was, on average, the warmest decade since the instrumental measurement of temperature started in the 1860s. The eleven warmest years occurred after 1995. All these changes have been ascribed primarily to the combustion of fossil fuel and land use change. Global warming has affected the hydrological cycle and,

C. Ringler et al. (eds), *Global Change: Impacts on Water and Food Security*,
DOI: 10.1007/978-3-642-04615-5_3,

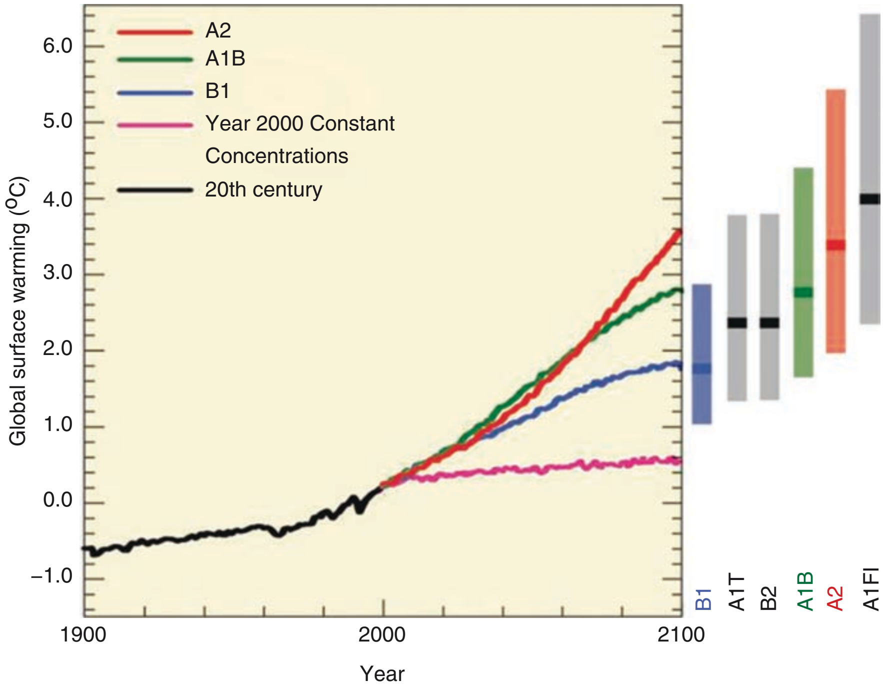

Fig. 3.1 Projected rise in surface temperature by different models. Each line is the result of a different scenario (IPCC 2007b)

as a result, precipitation patterns have changed and, in many regions, droughts, floods, and snowmelt have increased.

IPCC has projected that average global temperature will rise by between 1.1°C and 6.4°C over the next 100 years depending upon the scenario (Fig. 3.1). Although there is considerable uncertainty in precipitation projections for the future, it is likely that precipitation will increase in high latitudes and parts of the tropics and decrease in some sub-tropical and lower mid-latitude regions. More floods and droughts, decreases in the productivity of agriculture and aquaculture, displacement of millions of coastal dwellers due to sea-level rise and intense tropical cyclones, and the degradation of mangroves and coral reef ecosystems are considered to be some of the likely consequences of climate change (IPCC 2007c). Indeed, heavy precipitation and related floods, landslides, storm surges, and relatively higher temperatures have had devastating consequences in several parts of the world in recent years.

Such global climatic changes will affect agriculture through their direct and indirect effects on crops, soils, livestock, and pests. The increase in atmospheric carbon dioxide (CO_2) has a fertilization effect on crops with C_3 photosynthetic pathway and thus promotes their growth and productivity. The increase in temperature, on the other hand, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distribution of pest populations thus developing new equilibriums between crops and pests, hasten nutrient mineralization in soils, decrease fertilizer use efficiencies, and increase evapotranspiration. Indirectly, there may be considerable effects on land use due to snowmelt, availability of irrigation, frequency and intensity of inter- and intra-seasonal droughts and floods, and availability of energy. All of these effects can have a tremendous impact on agricultural production and hence food security. In this chapter, our objective is to present an overview of the effects of global climate change on key elements of the hydrological cycle and crop production. South Asia is considered to be particularly vulnerable to climate change due to its large population, reliance on agriculture, and limited resource base (Aggarwal et al. 2004). For this reason, as well as due to our greater familiarity with the region, many of the examples in this chapter are from India. These examples serve as an illustration of the probable vulnerability of agriculture in other developing countries to global climate change.

3.2 Impact of Global Climate Change on the Hydrological Cycle

3.2.1 Precipitation

The trends of change in precipitation vary for different parts of the world. IPCC (2007b) generally found an increasing trend over mid and high latitudes and a decrease in the tropics and subtropics during the last century, particularly during the last few decades. Negative trends in annual precipitation are largest over western Africa and the Sahel. In India an analysis of data on monsoon rainfall over the long term does not show any significant trend (Ministry of Environment and Forests 2004). Some areas such as along the western coast, north Andhra Pradesh, and northwest India, however, show an increasing trend during the last century (10–12% increase over the last 100 years). By contrast, a decreasing trend was observed in eastern Madhya Pradesh, northeast India, and parts of Gujarat and Kerala (6–8% decrease over the last 100 years). In China, there has been a slight decrease in annual precipitation over the last 50 years, accompanied by a significant decrease in the number of rainy days and an increase in the area affected by heavy precipitation (Folland et al. 2001). Globally, there has been an increase in the frequency of heavy precipitation events (IPCC 2007b).

In terms of future precipitation, most models predict that mean rainfall will increase in high latitudes, in South Asia during the monsoon period (Fig. 3.2), in Australia during the summer monsoon period, and over tropical oceans. Summer precipitation is likely to decrease over mid-latitude areas, especially Central America and the Mediterranean (Ruosteenoja et al. 2003; IPCC 2007b). There are also indications that the frequency of heavy rainfall events is likely to increase in many parts of the world, particularly in tropical and high-latitude areas. In many of these areas this translates into increased frequency of floods and droughts.

3.2.2 Evaporation

The increase in global warming generally is expected to result in increased evaporative demand. This response may, however, get modified by the change in other

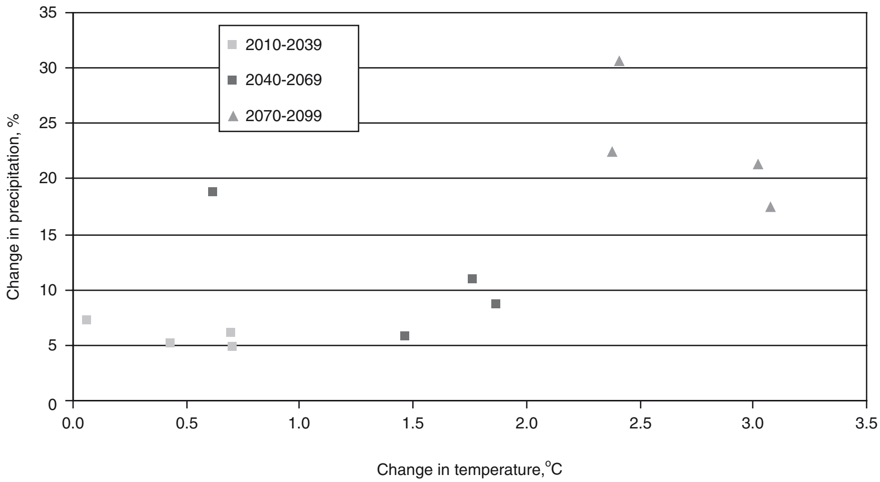

Fig. 3.2 Scatter plot of temperature and precipitation change during the monsoon season for different time periods for a given development (A2) scenario for South Asia. Note: Each point in a given time frame represents output from a different GCM model (Adapted from Rousteenoja et al. 2003)

meteorological parameters such as the water vapor content of the atmosphere and net radiation and vegetation. Increased CO_2 reduces stomata conductance in C_3 plants and hence transpiration (evaporation of water through plants) is reduced and water use efficiency increased. This may however, be counterbalanced by CO_2-mediated heavier plant growth, which may further influence transpiration. Kimball et al. (2002) reported a small decrease in evaporation in field experiments with CO_2-enriched wheat crops. Uncertainties in these effects get magnified at larger scales than those used in field experiments.

3.2.3 *Soil Moisture*

The balance between precipitation, evaporation, runoff, and soil drainage determines soil moisture. A change in precipitation, therefore, has a direct effect on soil moisture. Increased evaporation due to higher air temperatures may, however, confound the results. The historical observational records of soil moisture data are limited and, therefore, it is difficult to draw any conclusions about past trends. Soil moisture projections indicate a decrease in the sub-tropics and in the Mediterranean, and an increase in regions with high precipitation such as in East Africa and Central Asia (IPCC 2007b). There is, however, considerable uncertainty in climate change models regarding soil moisture changes due to climate change. For the same region, some models predict an increase in soil moisture while others indicate a declining trend. More studies are needed to clarify these points of discrepancy.

3.2.4 Groundwater and Water Quality

Climate variability, inter-seasonal as well as annual, is known to affect water levels in aquifers. Changes in temperature and precipitation associated with global warming will alter recharge to groundwater aquifers, causing shifts in water table levels (IPCC 2001). However, in most locations, deciphering climate-related changes in groundwater is difficult due to its frequent withdrawal. Increasing sea levels may also lead to salinity intrusion in coastal aquifers. In several regions, such as South Asia, it is projected that rainfall intensity may increase. Such changes may result in higher runoff and hence less groundwater recharge.

Climate change has the potential to alter water quality significantly by changing temperatures, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants. Global and regional increases in air temperature, and the associated increases in water temperature, are likely to lead to adverse changes in water quality, even in the absence of changes in precipitation. Changes in precipitation and stream flow can lead to both positive and negative impacts on water quality.

3.2.5 Runoff

Arnell (2004) and IPCC (2007b) simulated the change in runoff in various parts of the world under different scenarios of climate change. Their results showed a significant decrease in runoff in much of Europe, the Middle East, southern Africa, North America and most of South America. Areas with consistent increases in runoff included high-latitude North America and Siberia, eastern Africa, Australia, and South and East Asia. These increases, however, may not be very beneficial because the increase is largely during the wet season and the extra water may not be available during the dry season unless storage infrastructure could be vastly expanded. This 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 affect runoff. The gradual retreat of glaciers due to global warming would increase river flows in the short term, but in the long term the effect would become smaller. In recent decades, there has been widespread shrinkage of the world's glaciers largely due to global warming (Bates et al. 2008), which may have contributed to sea-level rise. Himalayan glaciers have receded between 2.6 and 28 m/year (Kulkarni and Bahuguna 2002). Mass balance studies indicate a significant increase in glacial degraded runoff volume in the last decade from 200 mm in 1992 to 455 mm in 1999 (Dobhal et al. 2004). Furthermore, glaciers are projected to lose 60% of their volume by 2050 due to climate change (Bradley et al. 2004). This will affect large populations living in glacier- and snowmelt-fed river basins (Kundzewicz et al. 2007).

3.2.6 Balance Between Water Demand and Supply: Irrigation Requirements for Agriculture

Accounting for 70% of global water withdrawals and 90% of global water consumption, the irrigation sector is the dominant water-use sector at the global scale. According to an FAO projection (Bruinsma 2003), developing countries would like to expand their irrigated area by 20% by 2030. Most of this expansion will occur in already water-stressed areas, such as South Asia, northern China, the Near East, and North Africa. This analysis does not consider increased irrigation requirements due to global warming and associated increases in evaporative demand. Döll (2002) found, for example, significant change in net irrigation requirements at the global scale due to global climatic changes. Depending on the emission scenario and climate model, global net irrigation requirements were found to increase by 1–3% per year until 2025 and by 2–7% per year until 2075.

The irrigation sector will be affected most by climate change, as well as by changes in the effectiveness of irrigation methods (Kundzewicz et al. 2007). The predicted increase in precipitation variability, which implies longer drought periods, would lead to an increase in irrigation requirements, even if total precipitation during the growing season remained the same (Eheart and Tornil 1999). However, where precipitation increases significantly during the growing period due to climate change, net irrigation requirements could decrease. Overall, irrigation demands could become even greater if rainfed areas are not able to meet projected food supply requirements.

Although irrigation requirements may increase in the future, we can expect reduced water supply for agriculture due to the effects of climate change on the hydrological cycle, increasing competition from industry and urban areas, and declining groundwater tables in many parts of the world. Therefore, production of an increased quantity of food with decreasing availability of quality irrigation water is a big challenge for the agricultural community.

3.3 Impacts of Global Climatic Change on Food Production

Global food demand has increased dramatically over the last 50 years due to the large increase in human population. Fortunately, the supply of food has kept pace with this increasing demand at an aggregated level in most areas of the world. The large expansion of irrigation systems, the use of synthetic nitrogen fertilizers, and the availability of dwarf wheat and rice varieties in the 1960s and 1970s were the main pillars of assured food supplies. The world population continues to grow rapidly with large increases in Asia, particularly in South Asia. Assuming a moderate population growth scenario, it is projected that about 700 million people, approximately equal to the current population of Europe, will be added in South Asia alone in the next 30 years. The rapid and continuing increase in population implies a greater demand for food. It is estimated that by 2020, food grain requirements in South Asia would be almost 50% more than current demand (Paroda and Kumar 2000). The additional quantities will have to be produced from the same or even shrinking land resources due to increasing competition for land from the non-agricultural sector. Alleviating poverty and attaining food security at the household and sub-national/regional level is thus a major challenge.

The net availability of food at any given time depends on a number of local, regional, national, and international factors. Climate-change associated variables, such as increasing CO_2 concentrations, and changes in rainfall and temperature can influence food availability through their direct effects on crop growth and yield. In addition, climate change may also affect crop production through indirect effects caused by changes in the hydrological balance discussed above, such as soil organic matter transformations, soil erosion, and changes in pest profiles. Equally important determinants of food supply are the socioeconomic environment, government policies, capital availability, prices and returns, infrastructure, land reforms, and inter- and intra-national trade, factors which may also be affected by climate change.

To study the effects of increased CO_2 concentrations, increased temperature, and decreased water availability-the key parameters of global climate change – sophisticated environmental control facilities are required. Such facilities are generally not available in developing countries. Research done in controlled environments in the developed world and field research in the tropics has enabled the development and validation of simulation models which are now greatly used to assess the impacts of climatic change on crop production in different parts of the world. In a recent report, the IPCC extensively reviewed the issues related to climate change impacts, adaptation, and the vulnerability of food systems in different regions of the world (Easterling et al. 2007). The following is a brief summary of the key impacts of climate change on food systems based on a review of the literature, including the IPCC report.

Several modeling-based studies have shown that in temperate regions, a 1–3°C increase in local mean temperature along with associated CO_2 increases and rainfall changes can have small beneficial impacts on crop yields. However, in tropical regions, even a small increase in temperature is likely to have negative yield impacts for major cereals. Further warming has increasingly negative impacts in all regions.

Climatic variability, including the frequency of droughts and floods, has been responsible for instability in food production in many parts of the world. In addition to projected mean changes in climate, projected changes in the frequency and severity of extreme climate events are likely to have significant consequences for food production and food security.

Smallholder and subsistence farmers are likely to suffer complex, localized impacts of climate change. These groups, which have limited adaptive capacity, are likely to experience the negative effects of climate change on yields of tropical crops and are highly vulnerable to extreme events.

At higher altitudes, low temperatures and shorter growing periods limit the productivity of crops. These restrictions become more conspicuous as altitude increases. Global warming is likely to prolong the growing season in these regions and this could result in potentially higher crop yields provided water remains available. However, the increased biomass production may not always ensure higher economic yields, since many temperate crops also need a minimum chilling period for flowering.

The quality of many crops is significantly affected by temperature. An increase in temperature may have a significant effect on the quality of cotton, fruits, vegetables, tea, coffee, and aromatic and medicinal plants. The nutritional quality of cereals and pulses may also be moderately affected which, in turn, will have consequences for the nutritional security of developing countries where cereals are staple foods. Indeed, research has shown that the decline in the grain protein content of cereals could partly be related to increasing CO_2 concentrations and temperature (Hocking and Meyer 1991; Ziska et al. 1997). The differential impact of global climatic changes on the quality of agricultural commodities in different parts of the world could have significant implications for agricultural trade in future.

Global environmental changes may aggravate current problems of sustainability and profitability of agriculture in many regions of the world. These changes may alter the interactions between biophysical and socioeconomic factors and the ways in which these are mediated by institutions. Some recent studies have examined the biophysical response of crops, the associated costs and benefits, and the expected response of farmers to understand the socioeconomic impact of global change. These studies indicate that the loss in farm-level net revenue may range between 9% and 25% for a temperature rise of 2–3.5°C. In the United States, maize production losses due to extreme climate events may double during the next 30 years, causing estimated additional damage of US$3 billion per year (Rosenzweig et al. 2002). Developing countries are thought to be more vulnerable to climate extremes due to their limited institutional and adaptive capacity.

It is estimated that insects, pathogens, and weeds are responsible for almost 30% of crop production losses at present. Avoidance of such loss constitutes one of the main sources of sustainability in crop production. The change in climate may bring about changes in population dynamics, growth, and distribution of insects and other pests. Besides having a significant direct influence on the pest population, the weather also affects the pest population indirectly through its effects on other factors like food availability, shelter, and natural enemies. Aphids, for example, are a major pest plaguing wheat and are highly influenced by weather conditions. Cloudy weather and enough relative humidity favor the occurrence of aphids in the field. Climate change may lead to aphid occurrence during the early and more susceptible stage of crop growth, potentially leading to tremendous loss. In addition, the swarms of locusts produced in the Middle East usually fly eastward into Pakistan and India during the summer season and lay eggs during the monsoon period. Changes in rainfall, temperature, and wind speed patterns may influence the migratory behavior of locusts.

Practically all soil processes important for agriculture are directly affected in one way or other by climate. Changes in precipitation patterns and amount, and temperature can influence soil water content, runoff, erosion, temperature, salinization, biodiversity, and organic carbon and nitrogen content. Changes in soil water induced by global climate change may affect all soil processes and ultimately crop growth. An increase in temperature would also lead to increased evapotranspiration, which may result in lowering of the groundwater table. Increased temperature coupled with reduced rainfall may lead to upward water movement leading to accumulation of salts in upper soil layers. Similarly, the rise in sea level associated with increased temperature may lead to salt-water ingression into coastal lands, making them unsuitable for conventional agriculture.

Changes in rainfall amount and frequency, and wind patterns may alter the severity, frequency, and extent of soil erosion. These changes may further confound the direct effects of increased temperature and CO_2 concentrations on crop growth and yields.

Fischer et al. (2002) have done an extensive global study on the impact of climate change scenarios on food production in different regions of the world. Their results show an increase in arid areas in all developing countries by 2080. For example, in Africa, the land area with a growing period length of less than 120 days would increase by 58–92 million hectares. Many other climate change scenarios predict global gains of potential agricultural land, especially in North America and the Russian Federation. By contrast, this study indicates a substantial loss in agricultural land in sub-Saharan Africa due to loss of potential double- and triple-cropping areas. The results further show an estimated 5%-loss in rainfed cereal production on currently cultivated land around the world. Most of the currently food-insecure regions, including large number of African countries, are projected to lose, on average, 10–20% of their cereal production potential due to climate change. Since most of these countries are poor, climate change may further aggravate the hunger situation.

Recent studies by Parry et al. (2004) have shown that, in general, the world will be able to produce enough food to feed itself during this century. However, this is achieved through increased production in the developed world, which will compensate for decreased production in developing countries. The decrease in cereal production in developing countries will likely affect consumption in that region. Simulations indicate that despite increasing cereal production, many developing countries will be dependent on net cereal imports of between 170 and 430 million metric tons (mt). Climate change would further add to this dependence by 10–40% depending on the scenario. Climate change marginally increases the number of people at risk of hunger, with respect to overall large reductions in hunger due to socioeconomic development (Easterling et al. 2007). Compared to 820 million people undernourished today, SRES scenarios of socioeconomic development, without climate change, project there will be 100–240 million undernourished people by 2080. Scenarios with climate change, with or without positive effects of elevated CO_2 levels on crops, project that there will be 100–380 million undernourished people by 2080 (770–1,300 million under the SRES A2 scenario). Thus, the combined impact of climate change and socioeconomic trends will alter the regional distribution of hunger, with large negative impacts for sub-Saharan Africa.

3.4 Adaptation Strategies

Any perturbation in agriculture can considerably affect food systems and thus increase the vulnerability of a large portion of the resource-poor population. Therefore, it is important to understand the possible adaptation and coping strategies of producers in response to global climatic change. Adaptation strategies need to take a number of factors into consideration, including globalization, and population and income growth, and the resulting changes in food preferences and demand, as well as the socioeconomic and environmental consequences of alternative adaptation options (Aggarwal et al. 2004; Easterling et al. 2007; Aggarwal 2008). Developing adaptation strategies aimed at minimizing the negative impacts of climate change may be difficult due to large uncertainties associated with the spatial and temporal variations in impacts. Therefore, there is a need to identify "no-regrets" adaptation strategies that are beneficial for the sustainable development of agriculture under multiple alternative scenarios. These adaptations should occur at multiple scales, including the individual, society, farm, village, watershed, and national levels. Some of the possible adaptation options are discussed below.

3.4.1 Altered Agronomy of Crops

Small changes in climatic parameters can often be managed by altering planting dates, spacing, and input management. Use of alternate crops or cultivars more adapted to changing environmental conditions can further ease the pressure on food systems. For example, for the case of wheat, early planting or the use of longer-duration cultivars may offset most of the loss associated with increased temperatures in South Asia. Available germplasm of various crops needs to be evaluated for heat and drought tolerance.

3.4.2 Development of Resource-Conserving Technologies

Recent research has shown that surface seeding and/or zero-tillage establishment of upland crops after rice produces similar yields to when planted under conventional tillage over a diverse set of soil conditions. This reduces the costs of production, allows earlier planting and thus higher yields, results in less weed growth, reduces the use of natural resources, such as fuel and steel for tractor parts, and shows improvements in the efficiency of water and fertilizers. In addition, such resource-conserving technologies restrict the release of soil carbon thus mitigating the accumulation of CO_2 in the atmosphere. It is estimated that zero tillage saves at least 30 l of diesel as compared to conventional tillage. This leads to 80 kg/ha/year reduction in CO_2 production. If these savings could be translated even partially to large arable areas, substantial carbon dioxide emissions to the atmosphere could be reduced.

3.4.3 Augmenting Production and Its Sustainability

The yield potential of many crops is much higher given climate conditions than the amount that is currently harvested in many parts of the world. For example, the potential yields of rice and wheat are calculated to be more than 6 mt/ha while their actual yields range between 2 and 3 mt/ha, on average (Aggarwal et al. 2000). Yield gaps are very large in eastern India, for example, and, hence, this region could increase the food security of India while mitigating the adverse impacts of climate change, given efforts to close this yield gap. Institutional support in the form of improved extension services, markets, and infrastructure needs to be provided in such regions to increase the stability of agricultural production and bridge yield gaps.

3.4.4 Increasing Income from Agricultural Enterprises

Rising unit costs of production and stagnating yield levels are adversely affecting the income of farmers. Global environmental changes, including increasing climate variability, may further increase the costs of production of crops due to associated increases in nutrient losses, evapotranspiration, and crop-weed interactions. Suitable responses to reduce these losses and increase income from agriculture include development of location-specific fertilizer practices, improvement in extension services, increased fertilizer supply and distribution, and development of physical and institutional infrastructure. Such practices can also improve the efficiency of fertilizer use.

3.4.5 Improved Land Use and Natural Resource Management Policies and Institutions

Strategies to adapt to climate change also involve natural resource management policies and institutions such as crop insurance, subsidies, and pricing policies related to water and energy. Necessary provisions need to be included in development plans in order to address the twin objectives of managing environmental change and improving resource-use productivity. Rational pricing of surface and groundwater, for example, can arrest its excessive and injudicious use. Availability of assured prices and infrastructure would promote better utilization of groundwater. Policies, such as financial incentives for green manuring, would encourage farmers to enrich organic matter in the soil and thus improve soil health.

3.4.6 Improved Risk Management Through Early Warning Systems and Crop Insurance

The increasing probability of floods and droughts, and other climate uncertainties may seriously increase the vulnerability of eastern India and of resource-poor farmers to global climate change. Crop insurance can provide protection to farmers in the event that their farm production is reduced due to natural calamities. In view of climate change and the uncertainty regarding future agricultural technologies and trade scenarios, it would be very useful to have an early warning system in place to alert the public to the spatial and temporal distribution of extreme events. Such a system would help identify potential food-insecure areas and communities and the type of risk. Modern information technologies would greatly facilitate the development of such early warning systems.

3.4.7 Recycling Wastewater and Solid Wastes in Agriculture

Since freshwater supplies are limited, the agriculture sector should evaluate the potential for using industrial wastewater and sewage. Such effluents, once properly treated, can be a source of nutrients for crops. Since water serves multiple uses and users, effective inter-departmental coordination in the government is needed to develop the location-specific framework of sustainable water management and optimum recycling of water.

3.4.8 Reducing Dependence on Agriculture

Although the share of agriculture in gross domestic product has declined in many countries, a large fraction of the population is still dependent on agriculture for their livelihood. For example, in India, the share of agriculture in the national gross domestic product has declined to less than 24%, but 58% of the population remains dependent on agriculture. Such trends have resulted in fragmentation and a decline in the size of land holdings, leading to inefficiency in agriculture, a rise in unemployment/underemployment, a low volume of marketable surplus, all of which increase vulnerability to global change. Institutional arrangements, such as cooperatives and contract farming, that can bring small and marginal farmers together in order to increase production and marketing efficiencies are needed.

3.5 Conclusions

To address the challenge of sustainable development, future agricultural planning in the developing world has to ensure sufficient food production, and employment and rural income generation while conserving natural resources. This has to be achieved in a context in which agriculture, especially in developing countries, is undergoing a transformation due to changing demands, markets, and agricultural technologies. The pace of these changes is expected to increase rapidly in the coming years and the whole system of agricultural production may become quite different in the next 10–20 years.

Global climatic change, including increasing climatic variability, could have severe adverse implications for achieving these production- and environment-related goals. The physical changes in CO_2 concentrations, rainfall, and temperature will alter the biological responses and, in turn, the socioeconomic conditions of millions of people. There is a consensus in the literature that poor people and regions are relatively more vulnerable to climate variability and change at all scales. The differential impacts of climate change, the projected shortages of water, and climatic extremes such as droughts, floods, and heat waves could increase migration and regional inequities.

Globalization is another important ongoing driver of change in agriculture. It affects the production of food, promotes the movement and trade of food, expands the role of large corporations, and decreases support currently available as subsidies to millions of poor farmers. Climate change and globalization together, therefore, create additional challenges for the world's poor farmers.

Addressing climate change is, therefore, critical for future food security and the attainment of the Millennium Development Goals, especially the goal of poverty alleviation. Developing nations and regions will need to implement strategies, linked with their development plans, to enhance their adaptive capacity. Several options are available today that can reduce vulnerability. "No-regrets" adaptation strategies that promote sustainable development and are also effective in reducing the negative impacts of climate change need to be identified and implemented. The Bali Action Plan (COP 13 2007) calls for cooperative action by all countries in order to meet the challenges of mitigation and adaptation through nationally appropriate commitments and actions, technology development and transfer, and the provision of financial investments and resources. More recently, world leaders have again urged governments to explore how farmers and smallholders in particular, could adapt and contribute to mitigation through global financial mechanisms and investment flows, and technology development and transfer (FAO 2008). Consensus among the global community will be essential to ensure food security for all.

References

Aggarwal PK (2008) Global climate change and Indian agriculture: impacts, adaptation and mitigation. Indian J Agric Sci 78:911–919

Aggarwal PK, Talukdar KK, Mall RK (2000) Potential yields of rice-wheat system in the Indo-Gangetic plains of India. Rice-Wheat Consortium Paper Series 10. New Delhi, India. RWCIGP, CIMMYT, 16pp

Aggarwal PK, Joshi PK, Ingram JS, Gupta RK (2004) Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. Environ Sci Policy 7:487–498

Arnell NW (2004) Climate change and global water resources: SRES emissions and socioeconomic scenarios. Glob Environ Change 14:31–52

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (Eds.) (2008) Climate change and water. Technical paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp

Bradley RS, Keimig FT, and Diaz HF (2004) Projected temperature changes along the American cordillera and the planned GCOS network. Geophys. Res. Lett., 31, L16210, doi:10.1029/2004GL020229

Bruinsma J (ed) (2003) World agriculture: towards 2015/2030. An FAO Perspective. Earthscan, UK, 444pp

COP 13 (Convention of Parties No. 13) (2007) Accessed at http://unfcccbali.org/unfccc/

Dobhal DP, Gergan JT, Thayyen RJ (2004) Recession and morphogeometrical changes of Dokriani glacier (1962–1995), Garhwal Himalaya, India. Curr Sci 86:692–696

Döll P (2002) Impact of climatic change and variability on irrigation water requirements: A global perspective. Clim Change 54:269–293

Easterling, WE, Aggarwal PK, Batima P, Brander KM, Erda L, Howden SM, Kirilenko A, Morton J, Soussana JF, Schmidhuber J, Tubiello FN (2007) Food, fibre and forest products. In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, (eds) Cambridge University Press, Cambridge, UK, pp 273–313

Eheart JW, Tornil DW (1999) Low-flow frequency exacerbation by irrigation withdrawals in the agricultural Midwest under various climate change scenarios. Water Resour Res 35: 2237–2246

FAO (2008) High-Level Conference on World Food Security: The Challenges of Climate Change and Bioenergy. Food and Agriculture Organization, Rome 51 pp

Fischer G, Shah M, van Velthuizen H (2002) Climate Change and Agricultural Vulnerability. International Institute for Applied Systems Analysis, Laxenburg, Austria

Folland CK, Karl TR, Christy JR, Clarke RA, Gruza GV, Jouzel J, Mann ME, Oerlmans J, Salinger MJ, Wang SW (2001) Observed climate variability and change. In: Houghton JT et al (eds) Climate change 2001: the scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 98–181

Hocking PJ, Meyer CP (1991) Carbon dioxide enrichment decreases critical nitrate and nitrogen concentrations in wheat. J Plant Nutr 14:571–584

IPCC (2001) Climate change 2001: Impacts, adaptation and vulnerability. Inter-Governmental Panel on climate change. Report of the Working Group II, Cambridge, UK 967

IPCC (2007a) Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri RK, Reisinger A (eds). IPCC, Geneva, Switzerland, 104 pp

IPCC (2007b) Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds), Cambridge University Press, Cambridge/New York/, 996 pp

IPCC (2007c) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds), Cambridge University Press, Cambridge, 976pp

Kimball BA, Kobayashi K, Bindi M (2002) Responses of agricultural crops to free-air CO_2 enrichment. Adv Agron 77:293–368

Kulkarni AV, Bahuguna IM (2002) Glacial retreat in the Baspa basin, Himalaya, monitored with 17 satellite stereo data (Correspondence). J Glacioll 48(160):171–172

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen Z, Shiklomanov IA (2007) Freshwater resources and their management. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds), Cambridge University Press, Cambridge, 173-210pp

Ministry of Environment and Forests (2004) India's initial national communication to the United Nations Framework Convention on Climate Change, 268pp

Paroda RS, Kumar P (2000) Food production and demand in South Asia. Agric Econ Res Rev 13:1–24

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socioeconomic scenarios. Glob Environ Chang 14:53–67

Rosenzweig C, Tubiello FN, Goldberg R, Mills E, Bloomfield J (2002) Increased crop damage in the US from excess precipitation under climate change. Glob Environ Change 12:197–202

Ruosteenoja K, Carter TR, Jylhä K, Tuomenvirta H (2003) Future climate in world regions: an intercomparison of model-based projections for the new IPCC emissions scenarios. The Finnish Environment 644, Finnish Environment Institute, 83pp

Ziska LH, Namuco O, Moya T, Quiland J (1997) Growth and yield response of field grown tropical rice to increasing carbon dioxide and air temperature. Agron J 89:45–53