

# 5 Determinants of Crop Growth and Yield in a Changing Climate

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## Introduction

The world population has crossed 6.7 billion; almost 20% of these people live in South Asia. The population of the world, especially of South Asia, continues to increase, even now, at a significant rate. This rapid and continuing increase in population implies a greater demand for food. Rice production in Asia alone must increase to more than 800 million t over the next 20 years (Hossain, 1995). Cereal requirements of India alone by 2020 will be between 257 and 374 million t (Rosegrant *et al.*, 1995; Kumar, 1998; Bhalla *et al.*, 1999). Demand for pulses, fruits, vegetables, milk, meat, eggs and marine products is also expected to increase very sharply. This additional food will have to be produced from the same, or even a shrinking, land resource base because there is no additional land available for cultivation.

Although the world as a whole has sufficient food for everyone and perhaps will continue to have in future as well, the widespread poverty in many countries prevents access to food. Today, even after several 'revolutions' in agriculture, almost 800 million people, who almost entirely live in the developing world, go hungry (FAO, 2006). About two-thirds of the undernourished in the world live in Asia. In the 21st century, one of the great challenges will be to ensure that food production is coupled with both poverty reduction and environmental protection.

The Intergovernmental Panel on Climate Change (IPCC), in its recently released report (IPCC, 2007a), has reconfirmed that the earth's temperature has increased by 0.74° C between 1906 and 2005. There is also a global trend for increased frequency of droughts, as well as heavy precipitation events over most land areas. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat-waves have become more frequent. The IPCC has projected that the temperature increase by the end of this century is likely to be in the range 1.5 to 4.0 °C. It is also likely that in future tropical cyclones will become more intense, with larger peak wind speeds and heavy precipitation. Himalayan glaciers and snow cover are projected to contract. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions.

Such global climatic changes will affect agriculture through their direct and indirect effects on crops, soils, livestock and pests. Global studies have indicated a loss of 5–40% cereal production by 2100 AD due to global warming, threatening the food security of several countries (Rosenzweig and Parry, 1994; Easterling *et al.*, 2007). Thus, there is a tremendous challenge facing agricultural scientists to develop technologies for increasing food production in the coming decades. There is an urgent need to secure the past yield gains and further increase the potential yield of major food crops.

High potential crop yields can be achieved/realized in future either by reducing yield gaps or by raising yield potential. For example, the potential yields of rice and wheat are calculated to be more than 6 t/ha in India whereas their average yields range between 2 and 3 t/ha (Aggarwal *et al.*, 2000). Such large yield gaps can be tapped in future for ensuring food security in the scenario of adverse climatic impacts. Institutional support in the form of improved extension services, markets and infrastructure needs to be provided in such regions to increase stability and bridge yield gaps. Raising yield potential is, however, important for regions where yields are already high and are stagnating, such as in Punjab, India.

Determination of the productivity potential of a crop requires a thorough understanding of crop growth and development. These, in turn, are dependent upon several climatic, edaphic, hydrological, physiological and management factors. The major factors affecting crop growth and development are radiation, temperature (yield determining), water, nutrition (yield limiting), and pests and diseases (yield reducing) (Van Ittersum and Rabbinge, 1997). In addition, productivity is also determined by many other factors, such as cultivar, its physiology and crop management, which interact with weather and soils to influence yield level. In irrigated and well-managed crops, productivity is primarily determined by radiation and temperature, whereas in rainfed areas, rainfall and soil moisture storage are of prime importance. In this chapter, our objective is to discuss the key determinants of crop growth and yield in a global scenario of changing climate.

## Key Determinants of Crop Growth and Yield

### Crop-climate interactions

Atmospheric carbon dioxide (CO<sub>2</sub>) concentration has reached 381 ppm today, from a low level of 280 ppm in 1750 AD. It is now rising at a rate of 1.8–2.0 ppm per year (IPCC, 2007a). Increase in atmospheric CO<sub>2</sub> has a fertilization effect on crops with a C<sub>3</sub> photosynthetic pathway and thus promotes their growth and productivity. The C<sub>4</sub> crops are not known to

significantly benefit from further CO<sub>2</sub> increase. Increased CO<sub>2</sub> also results in increased water use efficiency of all crops. Under field conditions, however, response to enhanced CO<sub>2</sub> is moderated by other environmental constraints. Long *et al.* (2006) have recently shown that the yield enhancement with high CO<sub>2</sub> is only to the extent of 10–15% in field-grown cereal crops, as against 20–30% response documented earlier (Kimball *et al.*, 2002). Using a crop model, Aggarwal (2003) showed that the benefit of enhanced CO<sub>2</sub> was moderated by nutrient and water constraints in wheat.

Several approaches have been tried earlier by scientists to raise yield potential through manipulation of source and/or sink. The International Rice Research Institute (IRRI) has been trying to develop a new plant type of rice, with a yield potential 20–25% higher than that of existing semi-dwarf rice varieties, through ideotype breeding approaches (Khush, 1995) for tropical environments. The proposed plant type has a low tillering capacity (three to four tillers when direct-seeded), few unproductive tillers, 200–250 grains per panicle, a plant height of 90–100 cm, thick and sturdy stems, leaves that are thick, dark green and erect, a vigorous root system, 100–130 days growth duration and increased harvest index (Peng *et al.*, 1994). However, these did not yield well because of limited biomass production and poor grain filling (Peng and Khush, 2003).

Increase in temperature, depending upon the current ambient temperature, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distribution of pest populations thus developing a new equilibrium between crops and pests, hasten nutrient mineralization in soils, decrease fertilizer use efficiencies and increase evapotranspiration. The stages of growth at which weather extremes occur is important in determining yield losses. For example, a temperature increase for a short period around pollen formation, dispersal and germination can lead to partial/complete sterility in crops (Horie, 1993).

Depending upon the current temperatures and thresholds, increased temperature can sometimes result in yield increase. Easterling *et al.* (2007) have shown that an increase in temperature of up to 3 °C could result in increased yields of cereals in temperate environ-

ments, whereas in tropical countries yields could start decreasing with a small increase in temperature. This has implications on global food trade. It is expected that due to rising food demands and decreased production associated with global warming in tropical countries, trade flows of food would increase from temperate countries to tropics. Fischer *et al.* (2002b) estimate that by 2080 cereal imports by developing countries would rise by 10–40%.

Rainfall, and hence availability of water, is the major limiting factor in the growth and production of crops worldwide. Plants need adequate moisture, especially during critical stages of germination and fruit development. Irrigation systems have been developed around the world by many countries to ensure crop water supply. However, despite this, large areas still remain rainfed. In climate change scenarios, globally precipitation is likely to increase, with large spatial and temporal variation. These changes in precipitation, especially increased frequency of heavy rainfall events, would lead to increased probability of droughts and floods, in turn, affecting food production stability.

Frost causes significant damage to crops, especially to cruciferous and solanaceous crops such as mustard and potato in higher latitudes. Increasing trends in minimum temperatures in future can alleviate this stress in several regions and thus increase yields.

Changes in productivity due to climatic change can also result in geographical shifts of agriculture. This could be accelerated by shifts in the virulence of pathogens and insects. Newman (1980) showed that a 1 °C increase in mean annual temperature could shift the US corn (maize) belt by approximately 100 km. Carter and Saarikko (1996) showed a similar poleward shift in Finnish cereal cultivation by 100–150 km for each 1 °C increase in mean annual temperature. Aggarwal *et al.* (1995) also showed that wheat cultivation in India is likely to shift northwards with climate change.

Several adaptation strategies can alter crop–climate interactions and thus reduce the adverse impacts on agriculture. Farmers and societies have been increasing their adaptive capacities to changing environments, depending on technological and financial capabilities. For example, establishment of buffer food stocks and agricultural insurance schemes, and

development of irrigation infrastructure have been strengthened earlier by many countries to increase their adaptive capacity to climatic extremes such as droughts and floods. Many countries have the historical experience of dealing with climatic variability; climate change may, however, increase its dimensions to outside the range of previous experiences. Potential adaptation strategies for agriculture to mitigate climate change have been suggested which could be implemented by the farmers themselves (Aggarwal *et al.*, 2004; Easterling *et al.*, 2004). These include diversification to more-adapted crops and varieties, changing planting dates, and improving water and fertilizer management. Easterling *et al.* (2007) showed that the benefits of adaptation vary with crops, regions and temperature changes. In general, such adaptations lead to damage avoidance in grain yields of cereals crops caused by a temperature increase of up to 1.5–3 °C in tropical regions and 4.5–5 °C in temperate regions.

### Water availability

One of the significant impacts of global warming is on water resources. This is due to spatially variable changes in precipitation, increased rate of glacier melt and retreat affecting river water flows, greater evaporation due to increase in temperature and higher water demand. These changes are likely to affect all aspects of agricultural water management including irrigation availability, soil moisture, evapotranspiration and run-off.

The balance among precipitation, evaporation, run-off and soil drainage determines soil moisture. Climate variability, interseasonal 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). Increase in sea levels may also lead to salinity intrusion in coastal aquifers. In several regions such as South Asia, it is projected that the rainfall intensity may increase. Such changes may result in higher run-off and hence less groundwater recharge.

Arnell (2004) and Nohara *et al.* (2006) simulated the change in run-off in various parts

of the world under different scenarios of climate change. Their results showed an increased run-off in high latitudes and the wet tropics, and decreased run-off in mid-latitudes and some parts of the dry tropics. Consequent declines in water availability are therefore projected to affect some of the areas currently suitable for rained crops (Easterling *et al.*, 2007).

The increased melting and recession of glaciers associated with global climate change could further change the run-off scenario. The IPCC in its recent report has shown that glaciers all over the world are receding at a rapid rate (IPCC, 2007a). In recent decades, Himalayan glaciers have receded between 2.6 and 28 m/year (Kulkarni and Bahuguna, 2002). Mass balance studies indicate significant increase in glacial degraded run-off volume in the last decade, from 200 mm in 1992 to 455 mm in 1999 (Dobhal *et al.*, 2004).

With 70% of the global water withdrawals and 90% of the global water consumption, the irrigation sector is the dominant water use sector at the global scale. According to an FAO (Food and Agriculture Organization of the United Nations) projection of agriculture in developing countries (Bruinsma, 2003), the 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 and North Africa. Such an analysis does not consider increased irrigation requirements due to global-warming-associated increase in evaporative demand. Doll (2002) projected significant change in the net irrigation requirements for the global scale due to climatic changes. Depending on emissions scenario and climate model, global net irrigation requirements were found to increase by 1–3% until 2025 and by 2–7% until 2075. Fischer *et al.* (2006) computed increases in global net irrigation requirements of 20% by 2080, with large spatial variations. Predicted increased variability of precipitation, which includes longer drought periods, would also lead to an increase in irrigation requirements, even if the total precipitation during the growing season remained the same (Eheart and Tornil, 1999).

The above results show that irrigation requirement may increase in future. In contrast, we can expect in future a scenario of reduced water

supply for agriculture due to the effects of global climatic changes on the hydrological cycle, increasing competition from industry/urban areas, and currently declining trends of groundwater tables. Production of an increased quantity of food with decreasing availability of quality irrigation water would, therefore, be a big challenge for the agricultural community.

### Soil suitability

Changes in precipitation patterns and amount, and temperature can influence soil water content, run-off and erosion, workability, temperature, salinization, biodiversity, and organic carbon and nitrogen content (Van Ittersum *et al.*, 2003; Nearing *et al.*, 2004). Changes in soil water induced by global climate change may affect all soil processes and ultimately crop growth. Increase in temperature would also lead to increased evapotranspiration, which may result in lowering of the groundwater table at some places. Increased temperature coupled with reduced rainfall enhances upward water movement, leading to accumulation of salts in upper soil layers. Similarly, rise in sea level associated with increased temperature may lead to saltwater ingress in the coastal lands, making them unsuitable for conventional agriculture.

The contribution of agriculture globally to greenhouse gas emissions is 13.5% (IPCC, 2007b), although there are large regional variations. Mitigating emission of greenhouse gases is today a global priority. Even though the contribution of agriculture is small, there are options available that can assist in reducing greenhouse gas emissions. Improved water and fertilizer management in rice fields, use of nitrification inhibitors such as neem-coated urea and efficient use of energy are some examples. Increasing the area under biofuels and agroforestry could also mitigate greenhouse gas emissions. However, this may have trade-offs with the goal of increasing food production.

Rapidly increasing demand for biofuels in North America and Europe is making fundamental changes to agricultural markets and is likely to keep the prices of agricultural commodities high over the next decade, according to a recent report by the Organization for Economic Cooperation and Development (OECD) and the

FAO (OECD-FAO, 2007). The study indicates that in the next 10 years (2009 onwards), substantial amounts of maize in the USA, wheat and rapeseed in the EU and sugar in Brazil will be used for ethanol and biodiesel production. It also indicates that high demand for biofuel feedstocks, such as cereals, sugar, oilseeds and vegetable oils, is likely to contribute to a 20–50% rise in international commodity prices over the next 10 years, in comparison with the 1997–2007 average. At the same time, the surging use of maize and other cereals for biofuel production decreases their availability for food, industry and poultry. There is considerable interest in growing more biofuels even in developing countries that are generally short of food.

Recent researches have shown that surface seeding or zero tillage establishment of upland crops after rice gives similar yields to those planted under normal conventional tillage over a diverse set of soil conditions. This reduces the cost 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 efficiency of water and fertilizers (RWC-CIMMYT, 2003). In addition, such resource-conserving technologies restrict release of soil carbon, thus mitigating increase of CO<sub>2</sub> in the atmosphere. It is estimated that zero tillage saves at least 30 l of diesel as compared with conventional tillage. This leads to 80 kg/ha/year reduction in CO<sub>2</sub> production (Grace *et al.*, 2003). If this saving could be translated even partially to large arable areas, substantial CO<sub>2</sub> emissions to the atmosphere could be reduced.

### Crop-pest interactions

It is estimated that insect pests, pathogens and weeds result in almost 30% loss in crop production at present. Avoidance of such loss constitutes one of the main sources of sustainability in crop production. Change in climate may bring about changes in population dynamics, growth and distribution of insects and pests. Besides having a significant direct influence on the pest population build-up, the weather also affects the pest population indirectly through its effects on other factors like food availability, shelter and natural enemies (Chakraborty and

Datta, 2003; Cocu *et al.*, 2005; Salinari *et al.*, 2006).

Aphid is a major pest of wheat and its occurrence is highly influenced by weather conditions. Cloudy weather with high relative humidity favours the occurrence of aphids in the field. Under most favourable conditions, a population density of 1000 million/ha in a wheat field has been reported. Weather changes may lead to aphid occurrence at the very juvenile and more susceptible stage of the crop, leading to tremendous loss. In nature, aphids are checked by *Coccinella septempunctata*, and in the case where the weather limits *Coccinella*'s growth, the production losses could be further magnified. With small changes, the virulence of different pests changes. For example, at 16 °C, the length of latent period is small for yellow rust. Once the temperature goes beyond 18 °C, this latent period increases but that of yellow and stem rusts decreases. Appearance of black rust in north India in the 1960s and 1970s was related to the temperature-dependent movement of spores from south to north India. Thus, any small change in temperature can result in changed virulence as well as appearance of new pests in a region.

Several pathogens such as *Phytophthora* and *Puccinia* group produce abundant propagules from the infected lesion or spot. Invariably they also possess a very short incubation cycle or life cycle period. Such pathogens and pests are highly sensitive to even minor changes in temperature, humidity and sunlight. Any change in the weather conditions that further reduce the incubation period will result in the completion of more cycles, greater terminal severity and much more severe yield losses. Changes in maximum or minimum temperature, even to the extent of 1 °C, will make all the difference between moderate and severe terminal disease development. Swarms of locusts produced in the Middle East usually fly eastward into Pakistan and India during the summer season and they lay eggs during the monsoon period. Changes in rainfall, temperature and wind speed pattern may influence the migratory behaviour of locusts.

Most crops have C<sub>3</sub> photosynthesis (responsive to CO<sub>2</sub>) and many weeds are C<sub>4</sub> plants (non-responsive to CO<sub>2</sub>). Climate change characterized by higher CO<sub>2</sub> concentration will

favour crop growth over weeds, although temperature increase may further accelerate crop–weed competition, depending upon the threshold temperatures in different locations.

### Socio-economic constraints

In addition to the biophysical determinants discussed above, the socio-economic environment, including government policies, capital availability, prices and returns, infrastructure, land reforms and inter- and intranational trade, is also an equally important determinant of crop production and hence food supply. Global environmental changes may alter the interactions between biophysical and socio-economic factors and the ways in which these are mediated by the institutions. Some recent studies have linked the biophysical response of crops, costs–benefits and the expected response of farmers to understand the socio-economic impact of global change. In the USA, maize production losses due to extremes of climate may double during the next 30 years, causing estimated additional damages of US\$3 billion per year (Rosenzweig *et al.*, 2002). Developing countries are thought to be more vulnerable to extremes of climatic variability owing to their limited institutional and adaptation capacity.

Simulation studies involving biophysical and socio-economic modelling indicate that climate

change is likely to increase the number of people at risk of hunger, depending on projected socio-economic developments. Fischer *et al.* (2002a) estimate that climate change will increase the number of undernourished people in 2080 by 5–26%. Parry *et al.* (2004, 2005), however, project small reductions by 2080, depending upon the climate change scenario. These studies also indicate that in future sub-Saharan Africa is likely to become the most food-insecure region of the world, and by 2080 may account for 40–50% of all undernourished people (Fischer *et al.*, 2002a; Parry *et al.*, 2004).

### Conclusions

Changes in food demands, markets and agricultural technologies have led to major changes in the structure and function of agricultural ecosystems around the world. The pace of these changes is expected to increase rapidly in the coming years, and the whole agricultural scenario may become quite different in the next 10 to 20 years. Global climatic changes and increasing climatic variability are likely to further exert pressure on agricultural systems and change the balance among the key determinants of crop growth and yield. Efforts to assess the impacts, adaptation measures and vulnerability to climate change in this changing world scenario need to be strengthened.

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