Research review article

Indian Journal of Agricultural Sciences **78** (10): 911–19, November 2008

Global climate change and Indian agriculture: impacts, adaptation and mitigation

P K AGGARWAL[1]

Indian Agricultural Research Institute, New Delhi 110 012

Received: 6 March 2008

ABSTRACT

Inter-Governmental Panel on Climate Change has shown that the earth temperature has increased by 0.74°C between 1906 and 2005 due to increase in anthropogenic emissions of greenhouse gases. By the end of this century, temperature increase is likely to be 1.8–4.0°C. This would lead to more frequent hot extremes, floods, droughts, cyclones and gradual recession of glaciers, which in turn would result in greater instability in food production. It is estimated that crop production loss in India by 2100 AD could be 10–40% despite the beneficial effects of higher CO_2 on crop growth. We could lose 4–5 million tonnes of wheat (*Triticum aestivum* L. emend. Fiori & Paol.) with every rise of 1°C temperature. Dynamics of pests and diseases will be significantly altered. Agriculture contributes 28% of the Indian greenhouse gases emissions, primarily due to methane emission from rice (*Oryza sativa* L.), enteric fermentation in ruminant animals, and nitrous oxides from application of manures and fertilizers to the soils. Potential approaches to reduce these emissions include mid-season drainage or alternate drying in rice, approaches to increase N-use efficiency and soil carbon, and improvement in livestock diet. Simple adaptation strategies, such as change in planting dates and varieties could help in reducing impacts of climate change to some extent. Additional strategies for increasing our adaptive capacity include development of adverse climate-tolerant genotypes and land-use systems, providing value-added climatic risk management services to farmers, and improved land-use policies and risk management though early warning system and crop-weather insurance.

Key words: Earth temperature, Greenhouse gases, Methane, Nitrous oxide

The Fourth Assessment Report of the Inter-Governmental Panel on Climate Change (IPCC) has reconfirmed that the global atmospheric concentrations of carbon dioxide (CO_2), methane and nitrous oxide, greenhouse gases (GHGs), have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The CO_2, methane and nitrous oxide concentrations in atmosphere were 280 ppm, 715 ppb and 270 ppb in 1750 AD and these values have increased to 379 ppm, 1774 ppb and 319 ppb, respectively in 2005. The increase in GHGs was 70% between 1970 and 2004. The global increases in CO_2 concentration are due primarily to fossil-fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.

Through a series of observations and modelling studies, the IPCC has shown that these increases in GHGs have resulted in warming of the climate system by 0.74°C between 1906 and 2005 (Fig 1). Of the last 12 years (1995–2006), 11 years rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The rate

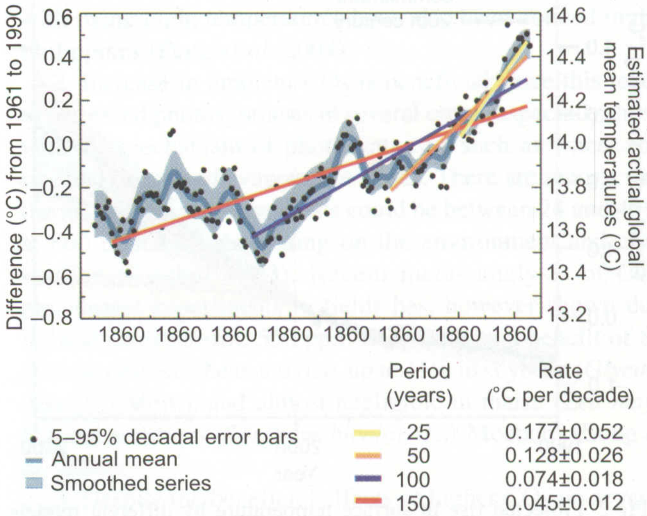

Fig 1 Change in average earth temperature during last 150 years
Source: (IPCC 2007a)

[1]ICAR National Professor and Network Co-ordinator (Climate Change), Division of Environmental Science

Table 1 Projected changes in surface air temperature and precipitation for South Asia under SRES A1FI (highest future emission trajectory) and B1 (lowest future emission trajectory) pathways for 3-time slices, viz 2020s, 2050s and 2080s

Season	Temperature (°C)		Precipitation (%)		Temperature (°C)		Precipitation (%)		Temperature (°C)		Precipitation (%)	
	A1F1	B1	A11	B1	A1F1	B1	A1F1	B1	A1F1	B1	A1F1	B1
Dec.-Feb.	1.17	1.11	–3	4	3.16	1.97	0	0	5.44	2.93	–16	–6
Mar.-May.	1.18	1.07	7	8	2.97	1.81	26	24	5.22	2.71	31	20
Jun.-Aug.	0.54	0.55	5	7	1.71	0.88	13	11	3.14	1.56	26	15
Sep.-Nov.	0.78	0.83	1	3	2.41	1.49	8	6	4.19	2.17	26	10

Source: IPCC (2007b)

of warming has been much higher in recent decades. This has, in turn, resulted in increased average temperature of the global ocean, sea level rise, decline in glaciers and snow cover (IPCC 2007a). There is also a global trend for increased frequency of droughts, as well as heavy precipitation events over the 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 temperature increase by the end of this century is expected to be in the range of 1.8–4.0°C (Fig 2). It is also likely that future tropical cyclones will become more intense with larger peak wind speeds and heavier precipitation. Himalayan glaciers and snow cover are projected to contract. It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent. Increase in the amount of precipitation are very likely in high-latitudes, while decreases are expected in most sub-tropical land regions, continuing observed patterns in recent trends. The projected sea level rise by the end of this century is likely to be 0.18–0.59 m.

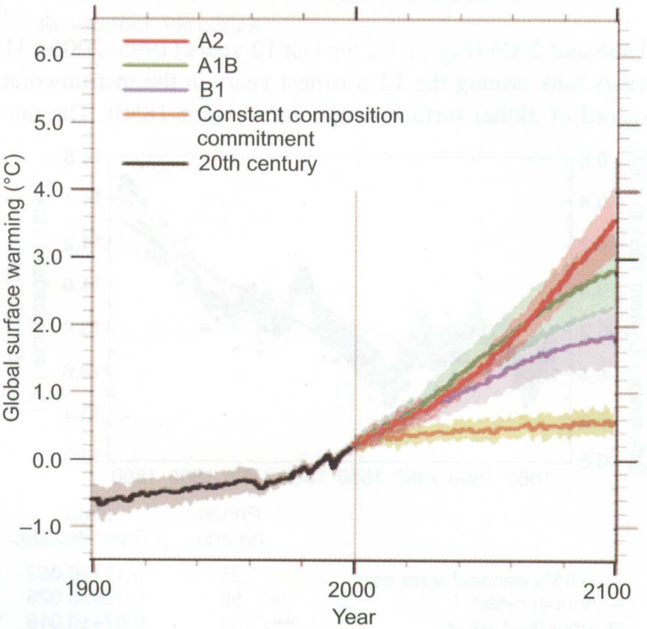

Fig 2 Projected rise in surface temperature by different models. Each line is the result of a different scenario
Source: (IPCC 2007a)

For Indian region (south Asia), the IPCC has projected 0.5–1.2°C rise in temperature by 2020, 0.88–3.16 °C by 2050 and 1.56–5.44°C by 2080 depending on the scenario of future development (Table 1, IPCC 2007b). Overall, the temperature increases are likely to be much higher in winter (*rabi*) season than in rainy (*kharif*) season. Precipitation is likely to increase in all time slices in all months except during December–February when it is likely to decrease.

Analysis done by the India Meteorology Department and the Indian Institute of Tropical Meteorology, Pune generally show the same trends for temperature, heat waves, glaciers, droughts and floods, and sea level rise as by the IPCC, although the magnitude of the change varies. It is projected that by the end of the 21st century rainfall over India will increase by 15 – 40%, and the mean annual temperature by 3 – 6°C (NATCOM 2004). Warming will be more pronounced over land areas with the maximum increase over northern India.

Such global climatic changes will affect agriculture through their direct and indirect effects on crops, soils, livestock and pests. Increase in atmospheric carbon dioxide promotes growth and productivity of plants with C 3 photosynthetic pathway. Increase in temperature, depending on the current ambient temperature, on the other hand, can reduce crop duration, increase crop respiration rates, affect the survival and distribution of pest populations, hasten nutrient mineralization in soils, decrease fertilizer-use efficiencies and increase evapotranspiration. Uncertainty in precipitation causes droughts and floods. These environmental changes and sea level rise could also affect fisheries directly and indirectly through the availability of feed. Similarly increased temperature and changes in fodder and water availability may also affect production of meat and milk.

Indirectly, there may be considerable impact on agricultural land-use due to snow melt, availability of irrigation, frequency and intensity of inter- and intra-seasonal droughts and floods, soil organic matter transformations, soil erosion, decline in arable areas (due to submergence of coastal lands), and availability of energy. Several important socio-economic determinants of food supply, such as government policies, capital availability, prices and returns, infrastructure, land reforms, and inter- and intra-national trade are also influenced by environmental change.

These environmental changes are likely to further increase the pressure on Indian agriculture, in addition to the on-going stresses of yield stagnation, land-use, competition for land, water and other resources, and globalization. It is estimated that by 2020, foodgrains requirement would be almost 30–50% more than the current demand (Paroda and Kumar 2000). This will have to be produced from same or even shrinking land resource due to increasing competition for land and other resources by non-agricultural sector. Alleviating poverty and attaining food security, thus, represent major challenges to India in the 21st century.

At the same time, agriculture is known to significantly contribute to global climate change, primarily through the production and release of greenhouse gases, such as methane and nitrous oxide. There is a great concern for the emission of methane and nitrous oxide because of their higher global warming potential (21 and 310 times than that of carbon dioxide respectively). Efforts are therefore needed to examine these emissions in detail and to explore options through which these emissions could be reduced.

To facilitate our preparedness for climatic change, it is important to identify the key information needs and research issues. The main objective of this paper is to provide a brief description of current understanding of the key impacts from global reports, such as those given by the IPCC and our own studies on specific impacts of climate change on agriculture, contribution of Indian agriculture to emission of greenhouse gases and some possible strategies to increase our adaptive capacity and mitigation potential.

IMPACT OF GLOBAL CLIMATE CHANGE

Systematic studies on climate change and Indian agriculture are relatively few and recent. These studies have focused on the quantification of impact on different

Fig 3 Free-Air - Carbon dioxide-Enrichment (FACE) setup at the Indian Agricultural Research Institute to study the impact of increased CO_2 on crops

commodities in various parts of the country, and assessment of impacts of recent climatic trends.

Several methods have been utilized by the Indian scientific community for assessing the possible impact of climatic variability and climatic change on agriculture. Historical data analyses by various statistical tools and analogue approach have traditionally been used to assess the impact of climatic variability. Controlled environment facilities, such as open top chambers, Free Air Carbon-dioxide Enrichment (FACE) facilities (Fig 3), phytotron and green houses are now increasingly being used to understand the impact of temperature, humidity and CO_2 on crop growth and productivity.

The interaction effects of CO_2, rainfall and temperature can be best studied through the use of crop growth simulation models. These models simulate the effect of daily changes on weather (including those caused by climatic change) for any location on growth and yield of a crop through understanding of crop physiological and soil processes. Several crop models, viz DSSAT series, ORYZA, and WTGROWS, have been the basis of a large number of studies. InfoCrop, an indigenous decision support system based on crop models is now increasingly being used to assess the vulnerability of agriculture to climate change and for optimizing crop management.

A brief summary of the key studies relevant for Indian agriculture is given here:

1. Analysis of the historical trends in yields of rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.emend Fiori & Paol.) crops in the Indo-Gangetic plains using regional statistics, long-term fertility experiments, other conventional field experiments and the crop simulation models has shown that rice yields during last 3 decades are showing a declining trend and this may be partly related to the gradual change in weather conditions during last 2 decades (Aggarwal *et al.* 2000). Similar decline in rice yields and their association with rising night temperatures have also been noticed in the Philippines (Peng *et al.* 2004).

2. Increase in ambient CO_2 is beneficial since this leads to increased photosynthesis in several crops, especially those with C3 mechanism of photosynthesis, such as wheat and rice and decreased evaporative losses. There are reports that the increase in photosynthesis could be between 24 and 43% at 660 ppm CO_2 depending on the environment and crop studied (Kimbal 1983). Recent meta- analysis of CO_2 enrichment experiments in fields has, however shown that in field environment, 550 ppm CO_2 leads to a benefit of 8–10% in yield in wheat and rice, up to 15% in soybean (*Glycine max* (L.) Merr.), and almost negligible in maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) (Long *et al.* 2005).

3. Despite the beneficial effects of higher CO_2 on several crops, associated increase in temperatures and increased variability of rainfall would considerably affect food

production. Recent report of the IPCC and a few other global studies indicate a probability of 10–40% loss in crop production in India with increase in temperature by 2080–2100 (Rosenzweig *et al.* 1994, Fischer *et al.* 2002, Parry *et al.* 2004, IPCC 2007b). These long-time horizon estimates generally assume business as usual scenario, no new technology development, and no or limited adaptation by all stakeholders.

4. There are a few Indian studies on this theme and they generally confirm similar trend of agricultural decline with climate change (Aggarwal and Sinha 1993, Rao and Sinha 1994, Lal *et al.* 1998, Saseendran *et al.* 2000, Mall and Aggarwal 2002, Aggarwal and Mall 2002, Aggarwal 2003). Recent studies carried out at the Indian Agricultural Research Institute indicate the possibility of loss of 4–5 million tonnes in wheat production with every rise of 1°C temperature[2] (1°C increase in temperature in India would approximately coincide with 2020–30 period) throughout the growing period even after considering carbon fertilization but no other adaptation benefits (Aggarwal *et al.* 2008 unpublished). It also assumes that irrigation would remain available in future at today's levels (an unlikely event due to receding of Himalayan glaciers and competition for water from other sectors). Losses for other crops are still uncertain but they are expected to be smaller especially for rainy season crops. These modeling-based estimates are in line with the field observations. For example, in March 2004, temperatures were higher in the Indo-Gangetic plains by 3–6 °C, which is equivalent to almost 1°C/day over the whole crop season. As a result, wheat crop matured earlier by 10–20 days and wheat production dropped by more than 4 million tonnes in the country (Samra and Singh 2004). Losses were also very significant in other crops, such as mustard (*Brassica juncea* (L.) Czernj. & Cosson), pea (*Pisum sativum* L.), tomato (*Lycopersicon esculentum* Mill.*nom.cons.*), onion (*Allium cepa* L.), garlic (*Allium sativum* L.), and other vegetable and fruit crops (Samra and Singh 2004).

5. It is, however, possible for farmers and other stakeholders to adapt to a limited extent and reduce the losses. Simple adaptations, such as change in planting dates and crop varieties could help in reducing impacts of climate change to some extent. For example, the Indian Agricultural Research Institute study quoted here indicates that losses in wheat production can be reduced from 4–5 to 1–2 million tonnes, if a large percentage of farmers could change to timely planting. This may, however, not be easy to implement due to constraints associated with wheat planting in rice-based cropping systems.

6. Droughts, floods, tropical cyclones, heavy precipitation events, hot extremes, and heat waves are known to negatively impact agricultural production, and farmers' livelihood. For example, recent drought of 2002 led to reduced area coverage of more than 15 million ha of the rainy season crops and resulted in a loss of more than 10% in food production (Samra and Singh 2002). The projected increase in these events could result in greater instability in food production and threaten livelihood security of farmers. Increased production variability could be perhaps the most significant effect of global change on India.

7. Cold waves cause significant impact on crop production in northern India. During December 2002–January 2003, there was a cold wave all over northern India and this caused considerable damage to crops, such as mustard, mango (*Mangifera indica* L.), guava (*Psidium guajava* L.), papaya (*Carica papaya* L.), brinjal (*Solanum melongena* L.), tomato (*Lycopersicon esculentum* L. Mill. non. cons.), potato (*Solanum tuberosum* L.) and Indian mustard (*Brassica juncea* L. Czernj. Coss.) (Samra and Singh 2003). There are indications that such cold waves and frost events could decrease in future due to global warming. Probability of yield losses in these crops associated with frost damage in northern India is, therefore, likely to decrease.

8. The IPCC (2007b) reported a significant increase in runoff in many parts of the world including India. This, however, may not be very beneficial, as the increase was largely in the wet season and the extra water may not be available in the dry season unless storage infrastructure could be vastly expanded. This extra water in the wet season, on the other hand may lead to increase in frequency and duration of floods. The increased melting and recession of glaciers associated with global climate change could further change the runoff scenario. Himalayan glaciers have shown an overall reduction in area from 2 077 km^2 in 1962 to 1 628 km^2 at present, an overall deglaciation of 21% (Kulkarni *et al.* 2007). Mass balance studies indicate 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). Such increase in glacier melt in the Himalayas could affect availability of irrigation especially in the Indo-Gangetic plains, which, in turn, would have consequences on food production.

9. Fertilizer-use efficiency in India is generally very low (30–50%). Increasing temperature in future is likely to further reduce fertilizer-use efficiency. This will lead to increased fertilizer requirement for meeting increased future food production demand. A large number of resource-poor farmers in tropics are not able to apply desired levels of fertilizers, irrigation and pest control. Simulation studies done at different levels of N management indicate that the crop response could vary depending on the N management and the climate change scenario (Aggarwal 2003). In the agro-ecosystems where inputs use remains low, as in today's rainfed systems, the direct impact of climatic change would be small. Indirectly, however, such farmers could become more vulnerable due to increased climatic variability and their limited capacity to adapt.

10. Easterling *et al.* (2007) found through an analysis of modelling results that in mid- to high latitude regions, a

moderate local increase in temperature (1–3°C), along with associated CO_2 increase and rainfall changes is likely to be beneficial for crop yields. As against this, in low-latitude regions, a temperature increase of 1–2°C is likely to have negative yield impacts for major cereals. It implies that food security of most developing countries including India, which happen to be in the low latitude regions, is likely to become vulnerable in the near future. At the same time, differential impacts of climate change on food production is likely to have consequences on international food prices and trade.

11. The quality of food is significantly affected by temperature in most crops. Increase in temperature may have significant effect on the quality of cotton (*Gossypium* sp.), fruits, vegetables, tea (*Camelia sinensis* (L.) O. kuntze), coffee (*Coffea* sp.), aromatic and medicinal plants. The nutritional quality of cereals and pulses may also be moderately affected which, in turn, will have consequences for nutritional security of several developing countries where cereals are the primary diet. Research has indeed shown that the decline in grain protein content in cereals could partly be related to increasing CO_2 concentrations and temperature (Hocking and Meyer 1991, Ziska *et al.* 1997). The quality of basmati rice is adversely impacted as temperatures increase above the optimal level (Nagarajan *et al.* 2008, unpublished).

12. Crop-pest interactions will change significantly with climate change leading to an impact on pest distribution and crop losses. Crop-weed competition will be affected depending on their photosynthetic pathway. Crops with C3 photosynthesis would be favoured over C4 weeds effecting the need for weed control. The accompanied temperature increase may further alter the competition depending on the threshold ambient temperatures. Diseases and insect populations are strongly dependent on the temperature and humidity. Any increase in them, depending on their base value, can significantly alter their population, which ultimately results in yield loss. 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 (Nagarajan and Joshi 1978). The appearance of black rust in north India in sixties and seventies was related to the temperature-dependent movement of spores from south to north India (Nagarajan and Joshi 1978). The swarms of locust (*Robinia pseudoacacia*) produced in the Middle East usually fly eastward into Pakistan and India during summer season and they lay eggs during monsoon period. Changes in rainfall, temperature and wind-speed pattern may influence the migratory behaviour of locust. More research is needed to understand the transboundary movement of pests in relation to climate change.

13. Global warming would increase water, shelter, and energy requirement of livestock for meeting projected milk demands. Climate change is likely to aggravate the heat stress in dairy animals, adversely affecting their reproductive performance. A preliminary estimate indicates that global warming is likely to result in a loss of 1.6 million tonnes in milk production in India by 2020 (Upadhyay R C, NDRI, 2008, personal communication).

14. Increasing sea and river water temperature is likely to affect fish breeding, migration, and harvests. A rise in temperature as small as 1°C could have important and rapid effects on the mortality of fish and their geographical distributions. Oil sardine (*Sardinella longiceps*) fishery did not exist before 1976 in the northern latitudes and along the east coast as the resource was not available/and sea surface temperature (SST) was not congenial. With warming of sea surface by 0.5–1.0 °C, the oil sardine is able to find temperature to its preference especially in the northern latitudes and eastern longitudes, thereby extending the distributional boundaries and establishing fisheries in larger coastal areas (Vivekanadan E, CMFRI, 2008, unpublished).

15. Corals in Indian Ocean are likely to be soon exposed to summer temperatures that will exceed the thermal thresholds observed over the last 20 years. Annual bleaching of corals will become almost a certainty from 2050. Given the implication that reefs will not be able to sustain catastrophic events more than 3 times a decade, reef building corals are likely to start disappear as dominant organisms on coral reefs between 2030 and 2040 (Vivekanadan E, CMFRI, 2008, unpublished).

16. Increase in temperatures associated with global climate change can affect yield formation of temperate crops, such as apple (*Malus domestica*). This is illustrated by a significant decrease observed in average productivity of apples in Kullu and Shimla (Himachal Pradesh) in recent times. A key reason for this could be a trend of inadequate chilling in recent decades, crucial for good apple yields. This seems to have resulted in a shift of apple belt to higher elevations. The new areas of apple cultivation have appeared in Lahaul and Spiti and upper reaches of Kinnaur district of Himachal Pradesh (Bhagat R M *et al.* HPKVV, 2008, unpublished).

ADAPTING INDIAN AGRICULTURE TO CLIMATE CHANGE

Any perturbation in agriculture can considerably affect the food systems and thus increase the vulnerability of large fraction of the resource-poor population. We need to understand the possible coping strategies by different sections and different categories of producers to global climatic change. Farmers and society have always attempted to adapt to climatic stresses by resorting to mixed cropping, changing varieties and planting times, and by diversifying their sources of income. Policy of maintaining buffer stocks of food helps in managing periods of scarcity. In future, such adaptation strategies would need to simultaneously consider the background of changing demand due to globalization and population increase and income growth, as well as the socio-economic and environmental consequences of possible adaptation options (Aggarwal *et al.* 2004, Easterling *et al.* 2007). Developing adaptation strategies exclusively for minimizing the negative impact of climatic changes may be risky in view of large uncertainties associated with its spatial and temporal magnitude. We need to identify 'no-regrets' adaptation strategies that may anyway be needed for sustainable development of agriculture. These adaptations can be at the level of individual farmer, society, farm, village, watershed, or at National level. Some of the possible adaptation options are discussed below.

Augmenting production

The climatic factors in India allow reasonably high yield potential of most crops. For rice and wheat these are estimated to be 10 and 8 tonnes/ha respectively (Aggarwal *et al.* 2000a). National demonstration plots also show considerably high yield potential of most crops than what is being achieved. The national average yields of rice and wheat crops are < 3 tonnes/ha today indicating large yield gaps in the country. In the eastern sector, gaps are especially large, and this region can be future source of food security for the whole of country. For meeting increased food demands of future and to overcome the constraints posed by climatic changes, there is a need to raise yield potential for regions, such as Punjab and parts of Tamil Nadu, where yield gaps are small, and increase use of available technologies to bridge yield gaps in the other regions. Fragile seed sector, poor technology dissemination mechanisms, lack of adequate capital and information are the key reasons for yield gaps.

Future breeding efforts would need to address multiple stresses-drought, floods, heat, pest load- imposed by changing global climate. There will be a need to stack several adaptive traits in a suitable agronomic background. This would require substantial breeding efforts, which will depend on the collection, conservation and distribution of appropriate crop genetic material among plant breeders and other researchers. There is a need for a better understanding of wild relatives, landraces, and their distributions, sensitivity of wild and cultivated species, and genetic material currently in the gene banks to climatic variables, creating trait-based collection strategies, and establishing pre-breeding as a public good for providing a suitable response to challenges of global climate change.

Changes in land-use and management

Small changes in climatic parameters can often be managed reasonably well by altering dates of planting, spacing and input management. Cultivating alternate crops or cultivars more adapted to changed environment can further ease the pressure. For example, in case of wheat, early planting or the use of long-duration cultivars may offset most of the loss associated with increased temperatures. Available germplasm of various crops needs to be evaluated for heat and drought tolerance.

Watershed management programme yield multiple benefits, such as sustainable production, resource conservation, groundwater recharge, drought moderation, employment generation and social equity as is evident from several studies already conducted in different agro-ecological regions of the country (Dhyani *et al.* 1997). Such strategies could be very useful in future climatic stress conditions.

Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yields planted under normal conventional tillage over a diverse set of soil conditions. This reduces 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. In a changed global climate scenario, such strategies for resource conservation would be very helpful.

Improved land-use and natural resource management policies and institutions

Adaptation to environmental change could be in the form of social aspects, such as crop insurance, subsidies, and pricing policies related to water and energy. Necessary provisions need to be included in the development plans to address these issues of attaining twin objectives of containing environmental changes 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 could create a situation of better utilization of groundwater in eastern India. Policies and incentives should be evolved that would encourage farmers to sequester carbon in the soil and thus improve soil health, and water use and energy more efficiently.

Increasing income from agricultural enterprises

Rising unit cost of production and stagnating yield levels are adversely affecting the income of the farmers. Global environmental changes including climatic variability may further increase the costs of production of crops due to its associated increases in nutrient losses, evapotranspiration and crop-weed interactions. Suitable actions, such as accelerated evolution of location-specific fertilizer practices, improvement in extension services, fertilizer supply and distribution, and development of physical and institutional infrastructure can improve efficiency of fertilizer-use.

Improved risk management through early warning system and crop insurance

The increasing probability of floods and droughts and other uncertainties in climate may seriously increase the vulnerability of eastern India and of resource-poor farmers to global climate change. Policies that encourage crop insurance can provide protection to the farmers, if their farm production is reduced due to natural calamities. Weather derivatives could greatly help in adapting to increased climatic risks. In view of these climatic changes and the uncertainties in future agricultural technologies and trade scenarios, it will be very useful to have an early warning system of environmental changes and their spatial and temporal magnitude. Such a system could help in determining potential food insecure areas and communities given the type of risk. Modern tools of information technology could greatly facilitate this.

Recycling waste water and solid wastes in agriculture

Since freshwater supplies are limited and has competing uses, and would become even more constrained in changed global climate, we have to start vigorous evaluation of using industrial and sewage wastewater in agriculture. Such effluents, once properly treated can also be a source of nutrients for crops. Since water serves multiple uses and users, effective inter-departmental co-ordination in the Government is needed to develop the location-specific framework of sustainable water management and optimum recycling of water.

CONTRIBUTION OF INDIAN AGRICULTURE TO GLOBAL WARMING

Agriculture sector in India contributes 28% of the total GHG emissions (NATCOM 2004, Fig 4a). The global average from agriculture is only 13.5% (IPCC 2007a). In future, the percentage emissions from agriculture in India are likely to be smaller due to relatively much higher growth in emissions in energy-use in transport and industrial sectors.

The emissions from agriculture are primarily due to methane emission from rice fields, enteric fermentation in ruminant animals, and nitrous oxides from application of manures and fertilizers to agricultural soils (Fig 4b). Rice is generally grown in waterlogged condition, which creates an anoxic environment and is conducive for methane production by the anaerobic methanogenic bacteria. Methane is also produced as a result of microbial activity in anaerobic conditions in the rumen of cattle, buffalo, and other livestock for the degradation of cellulosic feeds and roughages eaten up by the animals. Anaerobic decomposition of dung also contributes to methane emissions. Agricultural soils, particularly those fertilized with inorganic or organic N, are major sources of nitrous oxide. Nitrification and denitrification are the processes that contribute towards nitrous oxide emission from soil.

The gross emissions from Indian agriculture are likely to increase significantly in future due to our need to increase food production. The latter would require greater emphasis on application of fertilizers and other inputs. This in a globally warm environment leads to increased emissions of nitrous oxides and other GHGs. Increased temperatures would lead to higher emissions even at the current level of fertilizer consumption.

Reducing greenhouse gases emissions (mitigation) from Indian agriculture

There are several potential approaches to reduce GHG emissions from agriculture that have been tested at experimental scale. These need large-scale testing from the mitigation perspective, and their cost : benefit assessed at a larger scale. The key approaches for mitigation are:

1. Controlling production, oxidation and transport of methane from paddies by the practice of mid-season drainage or alternate drying instead of continuous flooding. Research has shown that such a practice does not lead to any significant reduction in crop production. However, drainage can often lead to increase in emission of nitrous oxides. These water-management practices may be difficult to operationalize in lowland rainfed rice but has some potential in irrigated areas.

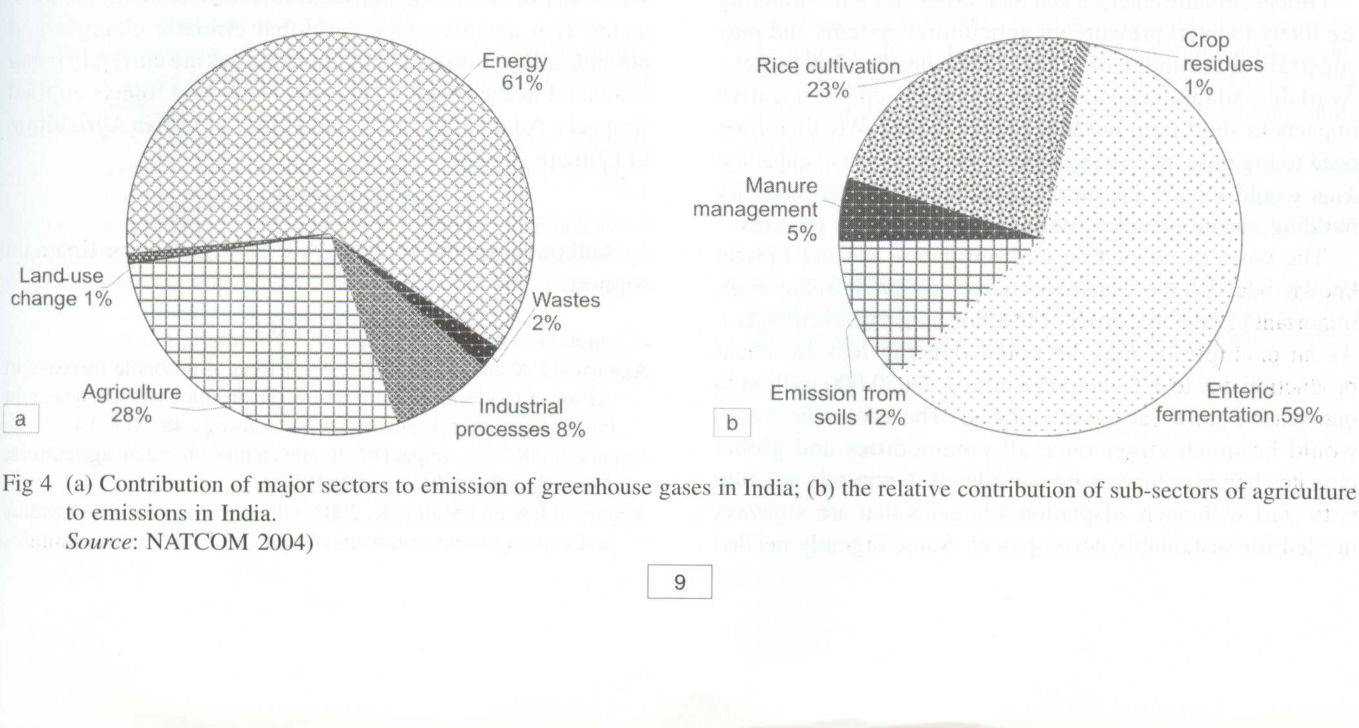

Fig 4 (a) Contribution of major sectors to emission of greenhouse gases in India; (b) the relative contribution of sub-sectors of agriculture to emissions in India.
Source: NATCOM 2004)

2. Appropriate crop-management practices, which lead to increase in N-use efficiency and yield, hold the key to reduce nitrous oxide emission. Application of nitrate fertilizers in aerobic conditions and ammonium fertilizers in wetland crops help reducing the emission. Curtailing the nitrification process by the use of nitrification inhibitor, particularly the low-cost locally available plant-derived materials, such as neem cake is a good option to mitigate nitrous oxide emission from soil.

3. Improved management of livestock diet through use of improved feed additives, substitution of low digestibility feeds with high digestibility ones, concentrate feeding, substituting fibrous concentrate with starchy concentrate, supplementation with molasses and changing microflora of rumen could lead to reduced methane emission.

4. Approaches to increase soil carbon, such as organic manures, minimal tillage, and residue management should be encouraged. Resource-conserving technologies restrict release of soil carbon thus mitigating increase of CO_2 in the atmosphere (Grace *et al.* 2003). It is estimated that zero tillage saves at least 30 litres of diesel compared with the conventional tillage. This leads to 80 kg/ha/year reduction in CO_2 production. If savings could be translated even partially to large arable areas, substantial carbon dioxide emissions to the atmosphere could be reduced.

5. Improvement in the efficiency of energy-use in agriculture by using better designs of machinery, increasing fuel efficiency in agricultural machinery, commercialization of wind and solar power potential, and use of laser levellers could also lead to mitigation.

6. Changing land-use by increasing area under biofuels, agro-forestry could also mitigate GHG emissions. This, however, may have trade off with goal of increasing food production.

SUMMARY AND RECOMMENDATIONS

Global climatic changes and increasing climatic variability are likely to exert pressure on agricultural systems and may constrain attainment of future food production targets. Available adaptation strategies can help reduce negative impacts in short term but to a limited extent. We, therefore, need to urgently take steps to increase our adaptive capacity. This would require increased adaptation research, capacity building, development activities, and changes in policies.

The costs of adaptation and mitigation are not clearly known today but these are expected to be high. It is, however, important to note that costs of inaction could be even higher. As an example, it may be noted that the loss in wheat production due to 1°C would be almost Rs 50 000 million in one season alone (at today's prices). The economic losses would be much larger once all commodities and global climate change scenarios are considered. A win-win solution is to start with such adaptation strategies that are anyways needed for sustainable development. Some urgently needed key activities are:

1. Strengthen research on development of 'adverse climate tolerant' genotypes and land-use systems to ensure adequate food production. Biotechnology, and modern tools of information technology, space technology and communication have great role to play in this.

2. Provide value-added climatic risk management services to farmers in the form of reliable weather forecasts, and associated agro-advisories for the farmers in different agro-climatic regions. Establishment of early warning system for emerging climatic risks such as drought, floods, heat and cold waves, and for pests and disease outbreaks are desired.

3. Provide financial incentives to farmers for resource (carbon, water, energy)-conservation and efficient use. Costs of cultivation are continuously increasing and farm profits are decreasing. If agriculture has to provide environmental services, which may require farmers' additional time, energy and resources, society should provide financial incentives to farmers.

4. Enhance investment in water storage and efficient water-use technologies. In the future scenario of changing rainfall patterns and decreasing irrigation water availability associated with global warming, we should invest in technologies that allow aquifer recharge, and drip and sprinklers to increase efficient use of available water.

5. Mobilize national and international opinion to make food security and poverty alleviation central in climate negotiations. Global climate change affects food and livelihood security of millions of poor farmers and landless in the developing countries who have not contributed significantly to the emissions. International climate change negotiations revolve around mitigation of GHG emissions from industrial and other sources. Such discussions must also ensure that the vulnerability of farmers and poverty alleviation are also simultaneously addressed.

Some of these activities relating to assessment of the sensitivity of arable and horticultural crops, plantations, soils, water, fish and livestock to global climatic changes and possible adaptation and mitigation options are currently being evaluated in the ICAR's National Network Projects entitled 'Impacts, Adaptation and Vulnerability of Indian Agriculture to Climate Change'.

ACKNOWLEDGEMENTS

Author is grateful to the ICAR, New Delhi, for financial support.

REFERENCES

Aggarwal P K and Sinha S K. 1993. Effect of probable increase in carbon dioxide and temperature on productivity of wheat in India. *Journal of Agricultural Meteorology* **48**: 811–14.

Aggarwal P K 2003. Impact of climate change on Indian agriculture. *Journal of Plant Biology* **30**: 189–98.

Aggarwal P K and Mall R K. 2002. Climate change and rice yields in diverse agro-environments of India. II. Effect of uncertainties in scenarios and crop models on impact assessment. *Climate Change* **52**: 331–43.

Aggarwal P K, Joshi P K, Ingram J.S and Gupta R K. 2004. Adapting food systems of the Indo-Gangetic plains to global environmental change: Key information needs to improve policy formulation. *Environmental Science and Policy* **7**: 487–98.

Aggarwal P K, Bandyopadhyay S K, Pathak H, Kalra N, Chander S and Sujith Kumar S. 2000. Analysis of the yield trends of rice-wheat system in north-western India. *Outlook on Agriculture* **29** (4): 259–68.

Aggarwal P K, Talukdar K K and Mall R K. 2000a. Potential yields of rice-wheat system in the Indo-Gangetic plains of India. 16pp. *Rice-Wheat Consortium Paper Series 10*. New Delhi, India.

Dhyani B L, Samra J S, Juyal G P, Babu Ram and Katiyar V S. 1997. *Socio-Economic Analysis of a Participatory Integrated Watershed Management in Garhwal Himalaya* (Fakot Watershed). Central Soil and Water Conservation Research and Training Institute, Dehradun.

Dobhal D P, Gergan J T and Thayyen R J. 2004. Recession and morphogeometrical changes of Dokriani glacier (1962–1995), Garhwal Himalaya, India, *Current Science* **86**: 692–6.

Easterling W E, Aggarwal P K, Batima P, Brander K M, Erda L, Howden S M, Kirilenko A, Morton J, Soussana J F, Schmidhuber J and Tubiello F N 2007: *Food, Fibre and Forest Products Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Inter-Governmental Panel on Climate Change, pp 273–13. Parry M L, Canziani O F, Palutikof J P, van der Linden P J and Hanson C E (Eds), Cambridge University Press, Cambridge.

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

Grace P R, Jain M C, Harrington L and Philip Robertson G. 2003. The long-term sustainability of tropical and sub-tropical rice and wheat systems: An environmental perspective. (*in*) *Improving the productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts*. ASA Special publication 65 Madison, USA.

Hocking, P J and Meyer C P. 1991. Carbon dioxide enrichment decreases critical nitrate and nitrogen concentrations in wheat. *Journal of Plant Nutrition* **14**: 571–84.

IPCC. 2007a. *Climate Change 2007: The Physical Science Basis*. Summary for Policymakers. Inter-Governmental Panel on Climate Change.

IPCC. 2007b. *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability*. Summary for Policymakers. Inter-Governmental Panel on Climate Change.

Kulkarni A V, Bahuguna I M, Rathore B P, Singh S K, Randhawa S S, Sood R K, and Dhar V. 2002. Glacial retreat in Himalaya using Indian remote sensing satellite data. *Current Science* **92**: 69–74.

Lal M, Singh K K, Rathore L S, Srinivasan G and Saseendran S A. 1998:Vulnerability of rice and wheat yields in NW - India to future changes in climate. *Agriculture & Forest Meteorology* **89**: 101–14.

Long S P, Ainsworth E A, Leakey A D B and Morgan P B. 2005. Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Philosophical Transactions of the Royal Society* B, **360**: 2011–20.

Mall R K and Aggarwal P K. 2002. Climate change and rice yields in diverse agro-environments of India. I. Evaluation of impact assessment models. *Climate Change* **52**: 315–30.

Nagarajan S and Joshi L M. 1978. Epidemiology of brown and yellow rusts of wheat over northern India. II. Associated meteorological conditions. *Plant Disease Reporter* **62**: 186–8.

NATCOM. 2004. *India's Initial National Communication to the United Nations Framework Convention on Climate Change*. 268 pp. Ministry of Environment and Forests.

Paroda R S and Kumar P. 2000. Food production and demand in South Asia. *Agricultural Economics Research Review* **13** (1): 1–24.

Parry M L, Rosenzweig C, Iglesias, Livermore A M and Fischer G. 2004: Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* **14**: 53–67.

Peng, S, Huang J, Sheehy J E, Laza R C, Visperas R M, Zhong X, Centeno C S, Khush G S and Cassman K G. 2004. Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Science* 101 (27): 9971–75.

Rao G D and Sinha S K. 1994. Impact of climatic change on simulated wheat production in India. pp 1–10. (*in*) *Implications of Climate Change for International Agriculture: Crop Modelling Study*. Rosenzweig C and Iglesias I (Eds). EPA, USA.

Rosenzweig C and Parry M L. 1994. Potential impact of climate change on world food supply. *Nature* **367**: 133–8.

Rosenzweig C, Tubiello F N, Goldberg R and *et al.* 2002. Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change* **12**: 197–202.

Samra J S and Singh G. 2002. *Drought Management Strategies*, 68 pp. Indian Council of Agricultural Research, New Delhi.

Samra J S and Singh G. 2003. *Cold Wave of 2002–2003: Impact on Agriculture,* 49 pp. Indian Council of Agricultural Research.

Samra J S and Singh G. 2004. *Heat Wave of March 2004: Impact on Agriculture*, 32 pp. Indian Council of Agricultural Research.

Saseendran S A, Singh K K, Rathore L S, Singh S V and Sinha S K. 2000. Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climatic Change* **44**: 495–14.

Ziska L H, Namuco O, Moya T and Quiland J. 1997. Growth and yield response of field grown tropical rice to increasing carbon dioxide and air temperature. *Agronomy Journal* **89**: 45–53.