RESEARCH ARTICLE

Climate Change and Agriculture: A Review Article with Special Reference to India

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Abstract: This paper provides an overview of climate change and agriculture, while paying some specific attention to the impact of climate change on Indian agriculture. This broad-brush account covers both the agronomic and economic aspects of the impact of climate change, as well as a critique of the methodologies used to estimate them. The paper ends with some comments on Indian agricultural policy in the era of climate change. An extended annotated bibliography provides a compendium of the likely impact of climate change on the yield and productivity of several major crops in India; on water-related parameters such as evaporation, water runoff and soil moisture; and on soil productivity, pests and crop diseases.

Keywords: climate change, Indian agriculture, yield gaps, semi-arid agriculture, adaptation, vulnerability, climate policy.

This paper undertakes a broad survey of the consequences of global warming of anthropogenic origin (or "climate change," as it is commonly called) and its impact on agriculture. It provides a broad-brush account of both the biophysical impact of climate change on agriculture, and its attendant economic and social consequences. Beginning with a discussion on climate change and agriculture at the global level, the paper goes on to focus on issues of specific relevance to India. It concludes with a brief discussion on the policy implications of climate change and its impact on Indian agriculture. Among the questions to which the paper pays particular attention is whether climate change, which is not a threshold phenomenon and is surely currently under way, has already had a discernible impact on agriculture. It summarises the main evidence on this question at the global level and for India.

The importance of understanding the ongoing impact of climate change on agriculture is often underestimated. Domestic policy considerations require that climate change be factored into development activities that are influenced by the weather and climate. At the same time, scientific evaluations of the immediacy of the impact of

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climate change and the extent of climate vulnerability are essential to the formulation of national negotiating positions at international climate-change negotiations. An early and equitable international agreement on climate change is beneficial to less-developed countries, but the question of how much delay by developed countries they can tolerate on this issue is of critical strategic interest to them.

Much of the concern about climate change stems from inferences based on established and ongoing science, rather than from direct evidence of its current impact. We therefore provide a brief account of methods of estimating the future impact of climate variability on agriculture. Additionally, in the case of India, we provide a summary of the scientific evidence for anticipated biophysical and other aspects of the impact of climate change on agriculture (see annotated bibliography).

The economic impact of climate change, particularly for less-developed countries and especially in sectors like agriculture, is of paramount importance. Existing estimates of such economic impact, however, are even more tenuous than those of physical impact. We briefly describe and evaluate some prevalent methods of estimating the economic impact of climate change on agriculture.

General Introduction

Explaining Climate Change

There is an overwhelming scientific consensus that the Earth's climate is changing as a consequence of human activity on the planet. The most important aspect of this change is that the average temperature of the Earth is rising, slowly but steadily, as a consequence of the emission of greenhouse gases (GHGs) and their increasing concentration in the atmosphere. Of the greenhouse gases that contribute to global warming, carbon dioxide (CO_2)[1] is by far the most significant, although there are other gases that also play this role, notably methane. CO_2 is emitted when fossil fuels are burnt in any form, ranging from traditional open coal fires to modern devices or processes like thermal power plants or the heating systems of buildings.

A critical factor in the rise in the Earth's temperature is the quantity of CO_2 emitted into the atmosphere. The Earth has a carbon cycle, arising from the partial absorption by oceans and other water bodies, and by vegetation on land, of the CO_2 in the atmosphere. Thus, apart from fossil fuel emissions, some of the CO_2 absorbed by water on the Earth's surface is re-emitted into the atmosphere, while the decay of vegetation also releases carbon in the form of methane. Further, there is slow circulation of CO_2 from the upper parts of oceans to their lower depths.

[1] Water vapour is also a significant greenhouse gas but the main contribution of water vapour comes from natural water bodies, particularly the oceans, and human activity contributes relatively little water vapour directly.

A consequence of the carbon cycle is that the net amount of CO_2 in the atmosphere is not equivalent to the total CO_2 that has been emitted. However, both the total stock of CO_2 emitted into the atmosphere and the net stock (after absorption by the carbon cycle) are relevant to study of the impact of climate change.

The total stock of CO_2 is the factor that determines the rise in temperature due to carbon dioxide emissions. Thus, even if all emissions were to cease immediately, the rise in temperature due to earlier emissions would continue for several decades.[2] The net stock of CO_2 is the measure relevant to the study of the consequences of global warming for the planet, especially for its impact on the biosphere. The net stock of CO_2 can be expressed in terms of million or billions of tonnes of CO_2, or, in relative terms, as the ratio of the volume of CO_2 to the total volume of all the gases in the atmosphere. This latter measure is a very small number. It is estimated, for instance, that the concentration of CO_2 at the beginning of the industrial era, *c.*1850, was of the order of 280 parts per million (ppm).[3]

The analogues of such processes vary across greenhouse gases. For instance, methane decays through chemical processes in the atmosphere into CO_2 and this CO_2 becomes a part of the carbon cycle. The global warming effect of gases such as methane is measured by comparing it to that of CO_2, and the concentration of these gases is expressed therefore in the equivalent amount of CO_2 they represent. Thus the total concentration of all greenhouse gases in the atmosphere is given in terms of parts per million of CO_2 equivalent (or CO_2e).[4]

The study of global warming is riddled with uncertainties. The best predictions that can be made about temperature rise due to greenhouse gas emissions are probabilistic in nature. Climate science estimates of temperature rise are made in terms of the probability of this rise, or the range of temperature increase that can occur for a

[2] This is one of the reasons why, in considering how to limit the effects of global warming, it is better to think of limiting the total quantity of greenhouse gases emitted into the atmosphere, rather than thinking of limiting the net amount of greenhouse gases in the atmosphere. It is interesting that this distinction has been made only recently in climate science literature; earlier literature has often phrased mitigation action in terms of limiting the net concentration of greenhouse gases in the atmosphere. The relevant scientific literature has been reviewed in the report from the Committee on Stabilisation Targets for Atmospheric Greenhouse Gas Concentrations, of the Board of Atmospheric Sciences and Climate, Division on Earth and Life Studies, National Research Council of the United States. See Committee on Stabilisation Targets for Atmospheric Greenhouse Gas Concentrations (2010).

[3] It must be emphasised that a certain level of CO_2 is essential to the maintenance of life on Earth. The issue in global warming is the rise of CO_2 concentrations to such an extent that the resulting temperature increase begins to affect the existing pattern of life on Earth. Continued temperature increase may go beyond the capacity of life on Earth to withstand such temperatures. It should also be remembered that over the long history of the Earth, which is well over four billion years old, the amount of CO_2 in the atmosphere has varied widely, but only in the pre-historic era.

[4] Another greenhouse gas that is significant in the context of agriculture is nitrous oxide, produced from the nitrogenous fertilizers commonly used in agriculture. In fact this should be a part of the study of the nitrogen cycle that is also being affected by anthropogenic causes. For a survey of the issue, see for instance, the Informal Report of the Task Force on Reactive Nitrogen (TFRN 2010).

given quantum of greenhouse gas emission. Some of these uncertainties are due to the lack of adequate scientific knowledge or insufficient accuracy in predictions, which may improve over time. There are others, however, that arise from the fact that the integrated system of the Earth's atmosphere, land (with its vegetation), and oceans is a highly complex one, and that full, deterministic certainty is unlikely to be achieved even with further scientific understanding. Typically, predicting the consequences of increased CO_2 concentration requires complex scientific models that are computer-based. Climate scientists often use approximate models that are simplified, but which nevertheless reflect some of the essential features of the more complex models.

Climatic Changes Due to Global Warming

The rise in temperature due to emission of greenhouse gases into the atmosphere has a profound effect on the Earth's climate system as a whole, and this in turn has important consequences for the geosphere and biosphere. The authoritative source for information regarding such effects remains the periodic assessment reports of the Intergovernmental Panel on Climate Change (IPCC), the latest being the Fourth Assessment Report (AR4) released in 2008.[5] The Fifth Assessment Report is currently under preparation and is due in 2012. According to AR4, the most significant climatic changes that could result from global warming are as follows:[6]

1. Daily and seasonal temperature patterns could change with increases in both maximum and minimum temperatures. Temperature increases will be the greatest over land in the northern latitudes, with fewer cold days and nights and an increasing number of hot days and nights.
2. Rainfall patterns could be subject to significant changes, with subtropical regions of the world likely to receive significantly lower rainfall and the northern latitudes experiencing increased rainfall. It is not only the total annual or seasonal rainfall that may change, but also the distribution of rainfall within a year or season. Consequently, the same total precipitation in a rainy season could be delivered over a fewer number of rainy days.
3. Rising temperatures will lead to increased frequency of extreme weather events like heat waves, extremely heavy rainfall, and intense storms and cyclones. Seasonal climate patterns, such as the monsoon, could also undergo changes.

[5] The reports of the IPCC are based on the worldwide published literature on climate science and climate-related issues. They provide the best scientific consensus available currently on most important aspects of climate change.

[6] The details are paraphrased from the IPCC's Summary for Policy Makers, AR4 Synthesis Report (Pachauri and Reisinger 2007). In the paraphrasing we have omitted, for ease of reading, the nuanced view in the Synthesis Report that attributes the terms, highly likely, very likely, likely, etc., for denoting the probability associated with various predictions. In all detailed considerations these nuanced statements must be taken as the correct view.

4. Following the increase in global temperatures, the melting of polar ice-caps will contribute to a rise in sea levels, although there are uncertainties regarding the extent of the rise. Rising sea levels will pose a threat of submergence to coastal communities and many island nations.
5. Global warming will lead to changes in the oceans. Due to increased CO_2 concentration the oceans will acidify, resulting in adverse consequences for marine flora and fauna. Ocean temperatures will also be affected, and disturbances in the current pattern of flow of ocean currents are possible. The flow pattern of ocean currents is an integral part of the mechanism by which the heat balance of the Earth is maintained. While disturbances in this pattern may be small in the present century, their impact on ocean circulation in later periods is less certain.

The magnitude of these effects depends on the actual extent of temperature increases, which in turn depends on the quantum of greenhouse gases that are released into the atmosphere. It is generally accepted that a temperature rise of 2°C would keep most of these effects within the reach of management by human intervention. A temperature rise of 2°C as the maximum acceptable level is now increasingly accepted in international climate negotiations, though some countries would prefer to limit this rise to 1.5°C, especially in order to minimise the threat from a rise in sea level to a number of island nations.

The predictions made by climate science for specific regions are less accurate and more uncertain than predictions made on the basis of global averages.[7] Predictions at the regional scale require reliable meteorological and other time-series data in order to calibrate climate models, data that may not always be accurate or available, especially for less-developed countries.

Actual and Potential Effects of Climate Change on Developing Countries

Since the effects of climate change are evolving and cumulative, is there evidence that the five most significant climatic changes predicted by AR4 are already under way? Climate research provides a clear affirmative answer to this question.[8] Between 1906 and 2005, world average temperature increased by 0.7°C, with larger increases in the northern latitudes and larger increases over land than over the oceans. In accordance with predictions, sea levels have risen at the rate of 1.8 mm/yr from 1961 and at the (faster) rate of 3.1 mm/yr from 1993. These increases are consistent with the expansion effect of temperature on oceans, and the contribution from melting glaciers, ice caps and polar ice sheets. The incidence of cold days and nights has

[7] An example of the uncertainty associated with regional predictions is the continuing lack of dependable modelling of the effects of climate change on the Indian monsoon system. The current mismatches between data on the Indian monsoon and predictions of monsoon behaviour from many climate models are described in Rajeevan and Nanjundiah (2009).
[8] These details, and those in this entire section, are drawn from the Summary for Policymakers, AR4 Synthesis Report (Pachauri and Reisinger 2007).

decreased, while there has been an increase in the number of hot days and nights. Heat waves and extreme rainfall events have also become more frequent.

Climate change also has consequences for the biosphere. All flora and fauna are sensitive, to varying degrees, to climatic conditions. Flowering plants are sensitive to seasonal variations of temperature. Species of marine life, including fishes, are particularly sensitive to the temperature of ambient water. Total rainfall and its seasonal variation are critical for agricultural crops, particularly in areas of rainfed agriculture. Apart from direct sensitivity to geophysical conditions, plant and animal life are also sensitive to variations in different parts of the ecological system within which they are located. For instance, the susceptibility of crops to pests may be affected by climate variations.

One of the important factors that affect the climate-sensitivity of the biosphere is the pace at which climate change takes place. Global warming and consequent variations in climate may proceed at a faster rate than the rate at which ecological systems adapt to such changes. Forest ecosystems, for instance, may not adapt as rapidly as required by the rate of climatic change, and thus may be adversely affected.

Some of these effects have already been observed in different parts of the globe and have been documented in AR4. One such important effect is the earlier timing of spring events, and the poleward shift of animal and plant ranges as a consequence of increases in temperature. Similarly, changes in the behaviour of marine life offer further evidence. Shifts in the ranges and abundance of some algae, plankton and fish are clearly associated with rising water temperatures and other related changes, including in salinity and oxygen content.[9]

Overall, the Synthesis Report in AR4 records the conclusions of more than 29,000 observational data series from 75 studies that show significant changes in physical and biological systems. Of these data series, more than 89 per cent show changes along the lines predicted by studies on global warming. A weakness of this analysis, however, is that there is a wide variation in the number of data series available from different parts of the world.

It is clear from the scientific evidence that there is an urgent need to limit the total quantity of greenhouse gases, especially CO_2, that will be released into the atmosphere in the future. Given the past levels of emissions of CO_2, human society has to learn to live within a strict carbon budget, sharply reducing its dependence on fossil fuels in all forms. This transition will require many changes, including new technologies (both in terms of renewable energy sources and of preventing CO_2 in fossil fuel emissions from being released into the atmosphere) and a major restructuring of economic activity. For developing countries this constitutes a major challenge, since

[9] Further details of the observed changes are available in the AR4 Synthesis Report.

in the near future they will continue primarily to be dependent on the use of fossil fuels to meet their development needs, particularly for improved access to energy, further industrialisation and infrastructure building. In order to create this essential carbon space for developing countries, developed nations must reduce their CO_2 emissions sharply. Both in historical terms and in the recent past, developed nations have over-occupied the global atmospheric commons.

The current tendency is towards global warming beyond the acceptable limit of 2°C.[10] We must also remember that even if, eventually, the world succeeds in limiting maximum temperature increase to 2°C, such temperature rise itself will result in a number of serious consequences. Prominent among these is the impact of climate change on agriculture.

The Impact of Climate Change on Agriculture

We shall highlight three aspects of the relationship between climate change and agriculture. First, climate change has a direct bearing on the biology of plant growth. Secondly, any assessment of the impact of climate change on agriculture must consider the interaction between the direct biological effects of climate change on the one hand, and other (often dynamic) aspects of the biosphere and geosphere – such as, for example soil conditions, seed–water–fertiliser–pesticide technologies, plant entomology, and so on – on the other. Thirdly, we must consider the impact of climate change on society and economy, and the ability of existing social and economic institutions, particularly in rural areas, to deal with the challenges posed by global warming. Climate change is poised to have a sharply differentiated effect as between agro-ecological regions, farming systems, and social classes and groups.

Ongoing Climate Change and Agriculture

Has global warming due to human activity, particularly the use of fossil fuels, already had an impact on agriculture on a global scale in a significant way?

Data from Europe

As we have remarked earlier, one of the significant indicators of ongoing climate change is its impact on plant and animal life. With respect to agriculture, changes in crop phenology[11] provide important evidence for the effects of climate change. The IPCC's AR4 noted a number of such effects, reported mainly from Europe. Such

[10] Even if the so-called "Copenhagen Accord" accepts a 2°C limit as desirable, the limit is not backed by firm commitments for emissions reduction by developed countries. For global warming expected from current emissions reduction commitments, see Rogelj *et al.* (2010a), pp. 1126–128. See also Rogelj *et al.* (2010b).

[11] Phenology refers to the study of periodic phenomena relating to the initiation, differentiation and development of different parts of the plant.

effects are easier to observe for perennial crops than for annual crops (since they are less dependent on annual farm management decisions) and are often observed in conjunction with gradual shifts in farm management practices.

The bulk of the evidence on impact of climate change on agriculture presented in AR4 relates to the advance of the agricultural calendar. These include: (i) the advance of stem elongation in winter rye by 10 days in Germany over the period 1961–2000; (ii) the advance of the emergence of maize by 12 days in Germany, 1961–2000; (iii) the advance of seeding dates for maize and sugarbeet by 10 days in Germany, 1961–2000; (iv) the advance of sowing dates for maize by 20 days at experimental farms in France, 1974–2003; and (v) the advance of sowing dates for potato by 5 days in Finland, 1965–1999. Another similar indicator is an advance in the dates of the flowering of fruit trees by 2.3 days every 10 years in Germany, 1961–2000.[12]

In general, these conclusions are drawn from a careful statistical analysis of yearly observations on sowing dates or seeding dates over a few decades. Some of these studies have also demonstrated a close correlation between long-term temperature trends and long-term phenological changes, as well as between year-to-year variability in temperature and short-term phenological changes.[13]

Crop Production and Yields

The data on agriculture production at the global and national levels, across many countries and a variety of crops and eco-systems indicate that climate change has not so far seriously affected yield and gross production. In a study of maize, wheat and rice production across 188 nations over a period of 40 years, Hafner showed that, with respect to these data-sets, there has been an overall *rise* in agricultural production.[14] A decline in production occurred only in about one-sixth of the data-sets. Hafner concludes:

> National crop data sets that showed yield growth greater than 33.1 kg/ha/yr had much greater yields than those that showed slowing yield growth, demonstrating that yield growth is not being limited by general physiological constraints to crop productivity.

According to Hafner (2003), cereal yields must grow at a minimum rate of 33.1 kg/ha/yr in order to maintain current per-capita production levels in 2050. The number

[12] For further results and more detailed references, see Table 1.10 in the report of Working Group II of the IPCC's AR4 (Parry 2007).

[13] Regrettably, in the author's experience many civil society organisations, farmers' groups and movements do not realise the need for careful statistical analysis of observations (as in the studies referred to), and simply report perceptions collected over a few years as evidence of the impact of climate change. The long-term trends in crop phenology are also a fine example of the unconscious in human adaptation. Yearly sowing decisions are undoubtedly driven by conscious observation and intent, but the long-term trend can only be verified by statistical analysis and is not susceptible (except, perhaps, in very rare cases) to direct perception.

[14] Hafner (2003), pp. 275–83.

of data-sets that showed yield growth higher than this figure constituted 20 per cent of the total; they were also the most significant in contributing to the overall rise in agricultural production. They were, further, the most significant with respect to cropped area and increases in the global population.

With regard to yields, Lobell *et al.* (2009) show, from a meta-analysis of a wide range of case studies, that the gap between potential and actual average yields vary widely, ranging from 20 per cent to 80 per cent of yield potential. Licker *et al.* (2010) attempt to calculate global yield gaps by comparing the yields of 18 key crops in different locations with similar climatic conditions. They conclude that there is still substantial scope globally to close yield gaps under current climatic changes.

Some studies have also attempted to determine whether ongoing climate change is having an impact on agriculture, while accounting for the fact that such impact may be masked by the effects of other variables when considering gross production or yield. This is an important line of future research. See, for instance, Lobell and Field (2007).

The IPCC's AR4 notes, in its Working Group II volume, that so far little evidence has emerged of loss of yield or gross agricultural production due to climate change. It also notes some studies that report the influence of weather conditions on agricultural production, and, in the case of the Sahel (in Africa), the effect of warmer and drier conditions that have acted as a catalyst for other factors that have led to a decline in groundnut production. It is possible that AR5 of the IPCC, due in 2012, which will have more recent studies to draw upon, will modify this general assessment.

We may therefore summarise the impact of ongoing climate change on agriculture as follows.

There is some evidence of the impact of ongoing climate change on agriculture through its impact on crop phenology and associated farm management practices. The evidence for this comes largely from European data. Ongoing climate change, however, has had no significant impact across most nations on agricultural production and yields.

Yield gaps, measured both nationally and globally, suggest that agricultural production and yield still have considerable room for advance. Whether the corresponding intensification of various crop management and land-use practices, extrapolating along current trends, will be sustainable without having adverse consequences for ecosystems remains unclear. Such negative consequences could occur independently of climate change, though it is also possible that they are exacerbated by climate change or that they lead to greater vulnerability to climate change.

Some Projections

Biophysical Impact

In general, there are two major variables in climate change that have a direct bearing on crop physiology. One is the effect of carbon fertilisation. This means that increased concentrations of CO_2 in the atmosphere are beneficial to plant growth, both since CO_2 is essential to the production of carbohydrates and since increased CO_2 concentration reduces the rate of water loss due to respiration. The extent of this beneficial effect, however, varies across two broad classes of crops, referred to in scientific literature as C3 and C4 crops.[15] In C3, which includes rice, wheat and legumes, carbon fertilisation has a more beneficial effect, while in C4, which includes maize, millets, sorghum and sugarcane, the effect is much more limited. Early studies of carbon fertilisation were based on laboratory experiments, whereas more recent studies are based on "Free-Air Concentration Enrichment" (FACE) experiments conducted on field crops under agronomic conditions. Results from FACE experiments show that the effect of carbon fertilisation under realistic conditions is almost 50 per cent less than the effect as measured in laboratory studies for C3 crops, while the effect is virtually zero for C4 crops.

The second important variable in climate change is temperature. One of the major effects of increases in temperature is to speed up the period of growth of the crop, especially in the grain-filling stage, resulting in lower yields. This effect is especially pronounced in semi-tropical and tropical conditions, since in these areas many crops are already at the outer limits of the temperatures that they can tolerate. In higher latitudes as well, temperature increases beyond 1–3°C would result in lower yields. Other significant consequences of increased temperatures include increase in the transpiration rate and accelerated loss of soil moisture, both of which increase the water demand of a crop. All this is, of course, in addition to the possible overall decrease in total rainfall due to climate change.

While carbon fertilisation and temperature increase are the two main aspects of global warming that affect crop physiology, the precise consequences of these two factors on crop yields can be determined only by complicated modelling. Final crop yields are determined by a number of factors, including not only carbon fertilisation and temperature increase, but also changes in precipitation, water balance, energy balance, soil conditions, nutrient availability and so on. Of course, these factors may themselves vary due to climate change.

Crop growth simulation models provide detailed analyses of the biophysical impact of climate change on crops. These are computer models that attempt to simulate the entire range of physical and biological effects that affect crop growth and development. Such models, which have been developed for a number of crops, allow

[15] These two classes are distinguished precisely by the differences in the process of CO_2 absorption. There is also a third class, referred to as CAM, which is characteristic of plants specially adapted to arid conditions.

variation in a number of parameters as well as the incorporation of variations in the interconnections between them. In more advanced models, such analysis can incorporate even genetic variables under varying environmental conditions.

Simulating the effects of climate change also needs to include effects such as the interaction with other factors of pests and weeds. The impact of increased CO_2 and temperature and variation in rainfall will be modified by such interactions, while the behaviour of pests and weeds may itself vary with climate change. There is a significant literature on potential competition between C3 and C4 crops in the context of enhanced CO_2 levels. Such studies include the competition between C3 crops and C4 weeds. The IPCC's Third Assessment Report provides a useful summary introduction to these issues.[16] The studies cited there show that the interaction between pests and major food and cash crops could be complex, with elevated levels of CO_2 and temperature and increased or decreased precipitation, setting in motion secondary effects that affect crop–pest interactions. In rice, for instance, model studies show that leaf-blast epidemics are more likely with elevated temperatures in cool, sub-tropical zones than in warm, humid tropics, where such epidemics are inhibited by temperature rise. Another experimental study showed that higher concentrations of CO_2 lowered nitrogen uptake in plant tissues, leading to significantly enhanced damage by pests.

Crop Production: Specific Example

Apart from these general considerations, it is clear that detailed analysis is necessary to understand the impact of climate change on specific crops. There is a voluminous and growing literature on the impact of climate change on specific food and cash crops, including publications from specialised research institutions, individually and through collaborative networks.

Table 1 presents a summary of the expected impact of climate change on some major cereal crops, taken from a report by the International Food Policy Research Institute (IFPRI).[17]

Using the many studies that have been conducted, IPCC's AR4 notes[18] that it is possible to provide some indications at the global scale of the future impact of climate change on some specific crops. Such studies include not only the effects of temperature but also changes in other variables, such as climatic factors and land and farm management practices. The following graphs present some such global synthesis estimates for maize, wheat, and rice production, specifically the expected percentage change in yield as a function of temperature rise. These yield estimates

[16] See, for instance, Section 5.3. 3.2.3 of the report of Working Group II of the IPCC for the Third Assessment Report (McCarthy *et al.* [eds.] 2001).
[17] Nelson *et al.* (2009).
[18] See Section 5.4.2.2 of the report of Working Group II of the IPCC for AR4 (Parry *et al.* 2007).

include estimates of the possible adaptation to climate change, including changes in cultivars and planting and some shifts from rainfed to irrigated cultivation. These synthesis estimates include studies that take carbon fertilisation into specific account and studies that do not.

It is clear from even this limited view that less-developed countries, which are more numerous in low latitudes, will feel the impact of climate change more significantly than others, despite adaptation. On the other hand, for low levels of temperature rise, temperate agriculture may even register some gains, especially in high latitudes.

The key point to remember is that these effects of climate change on agriculture could proceed to dangerous levels, beyond the capacity of meaningful adaptation to such changes, if the emission of greenhouse gases continues unchecked. Beyond a 2℃ rise in temperature, there is increasing damage to agriculture. Unchecked temperature rise of 3–4℃ would lead to severe consequences. Such consequences cannot be considered in the sector of agriculture alone; we would need to consider a range of geophysical and biophysical effects, the combined effects of which would be very serious.

In the larger context of food security and climate change, it is also important to consider other sectors like animal husbandry and livestock, which are closely linked with agriculture. Another important sector is fisheries. It is generally expected that marine life will reflect the effects of climate change earlier as it is very sensitive to climatic conditions. A significant adverse impact of climate change, for instance, is on coral reefs. Other studies suggest that small fishes like sardines, mackerel and anchovies are good indicators of climatic change as they are sensitive to changes in their habitat conditions. Tropical fish are already exposed to near-lethal temperatures during the hottest part of the day. Further rise in temperatures would have a disastrous impact on such species. While food supplies for fish may increase due to rising temperatures, this may be more than offset by the acceleration of their metabolism, leading to a relative shortage of food supply. Warming would also lead to oxygen depletion in the water, which would have negative consequences for fish metabolism.

Economic Assessments

The general literature on the economics of climate change and agriculture may be divided into two broad categories. The first considers the general, macroeconomic impact of climate change variations on agriculture, i.e. how its impact on the yields and production of various crops would affect the prices of agricultural products and earnings from agriculture, and the consequent implications for national and global economies. The second category of studies focuses on the economic impact of climate change on developing countries, where agriculture is critical to the livelihood of a significant section of the population. These studies also consider associated issues of food security, poverty alleviation and overall human development, and the potential local economic impact of climate change on agriculture across many regions and locations in developing countries.

Table 1 *The effect of climate change on the production of rice, wheat, maize, millet and sorghum in 2050 (under scenarios projected separately by CSIRO and NCAR), expressed as a percentage gain or loss of production with respect to expected production in 2050 in the absence of climate*

Agricultural Product	South Asia	East Asia and the Pacific	Europe and Central Asia	Latin America and the Caribbean	Middle East and North Africa	Sub-Saharan Africa	Developed Countries	Developing Countries	World
Rice									
2000 (mmt)	119.8	221.7	1.1	14.8	5.5	7.4	20.4	370.3	390.7
2050 No CC (mmt)	168.8	217	2.6	17.8	10.3	18.3	20.3	434.9	455.2
2050 No CC (per cent change)	41	−2.1	144.4	19.8	87.4	146	−0.3	17.4	16.5
CSIRO (per cent change)	−14.3	−8.1	−0.2	−21.7	−32.9	−14.5	−11.8	−11.9	−11.9
NCAR (per cent change)	−14.5	−11.3	−0.8	−19.2	−39.7	−15.2	10.6	−13.6	−13.5
Wheat									
2000 (mmt)	96.7	102.1	127.5	23.5	23.6	4.5	205.2	377.9	583.1
2050 No CC (mmt)	191.3	104.3	252.6	42.1	62	11.4	253.7	663.6	917.4
2050 No CC (per cent change)	97.9	2.1	98.1	78.7	162.3	154.4	23.6	75.6	57.3
CSIRO (per cent change)	−43.7	1.8	−43.4	11.4	−5.1	−33.5	−7.6	−29.2	−23.2
NCAR (per cent change)	−48.8	1.8	−51	17.4	−8.7	−35.8	−11.2	−33.5	−27.4
Maize									
2000 (mmt)	16.2	141.8	38	80.1	8.2	37.1	297.9	321.3	619.2
2050 No CC (mmt)	18.7	264.7	62.7	143.11	13.1	53.9	505.1	556.2	1061.3
2050 No CC (per cent change)	15.7	86.6	65.1	78.8	59.4	45.3	69.6	73.1	71.4
CSIRO (per cent change)	−18.5	−12.7	−19	−0.3	−6.8	−9.6	11.5	−10	0.2
NCAR (per cent change)	−8.9	8.9	−38.3	−4	−9.8	−7.1	1.8	−2.3	−0.4

Millet									
2000 (mmt)	10.5	2.3	1.2	0	0	13.1	0.5	27.3	27.8
2050 No CC (mmt)	12.3	3.5	2.1	0.1	0.1	48.1	0.8	66.2	67
2050 No CC (per cent change)	16.5	50.1	77.2	113	128	267.2	60.5	142.5	141
CSIRO (per cent change)	−19	4.2	−4.3	8.8	−5.5	−6.9	−3	−8.5	−8.4
NCAR (per cent change)	−9.5	8.3	−5.2	7.2	−2.7	−7.6	−5.6	−7	−7
Sorghum									
2000 (mmt)	8.4	3.1	0.1	11.4	1	19	16.9	43	59.9
2050 No CC (mmt)	9.6	3.4	0.4	28	1.1	60.1	20.9	102.6	123.5
2050 No CC (per cent change)	13.9	11.6	180.9	145.3	12.2	216.9	23.6	138.7	106.2
CSIRO (per cent change)	−19.6	1.4	−2.7	2.3	0.3	−2.3	−3.1	−2.5	−2.6
NCAR (per cent change)	−12.2	6.7	−10.4	4.3	0.7	−3	−7.3	−1.5	−2.5

Notes: The figures in the table ignore the effects of carbon fertilization.
NCAR = National Center for Atmospheric Research, USA; CSIRO = Commonwealth Scientific and Industrial Research Organisation, Australia; mmt million metric tonnes.
Source: Reproduced from Table 3 of Nelson *et al.* (2009).

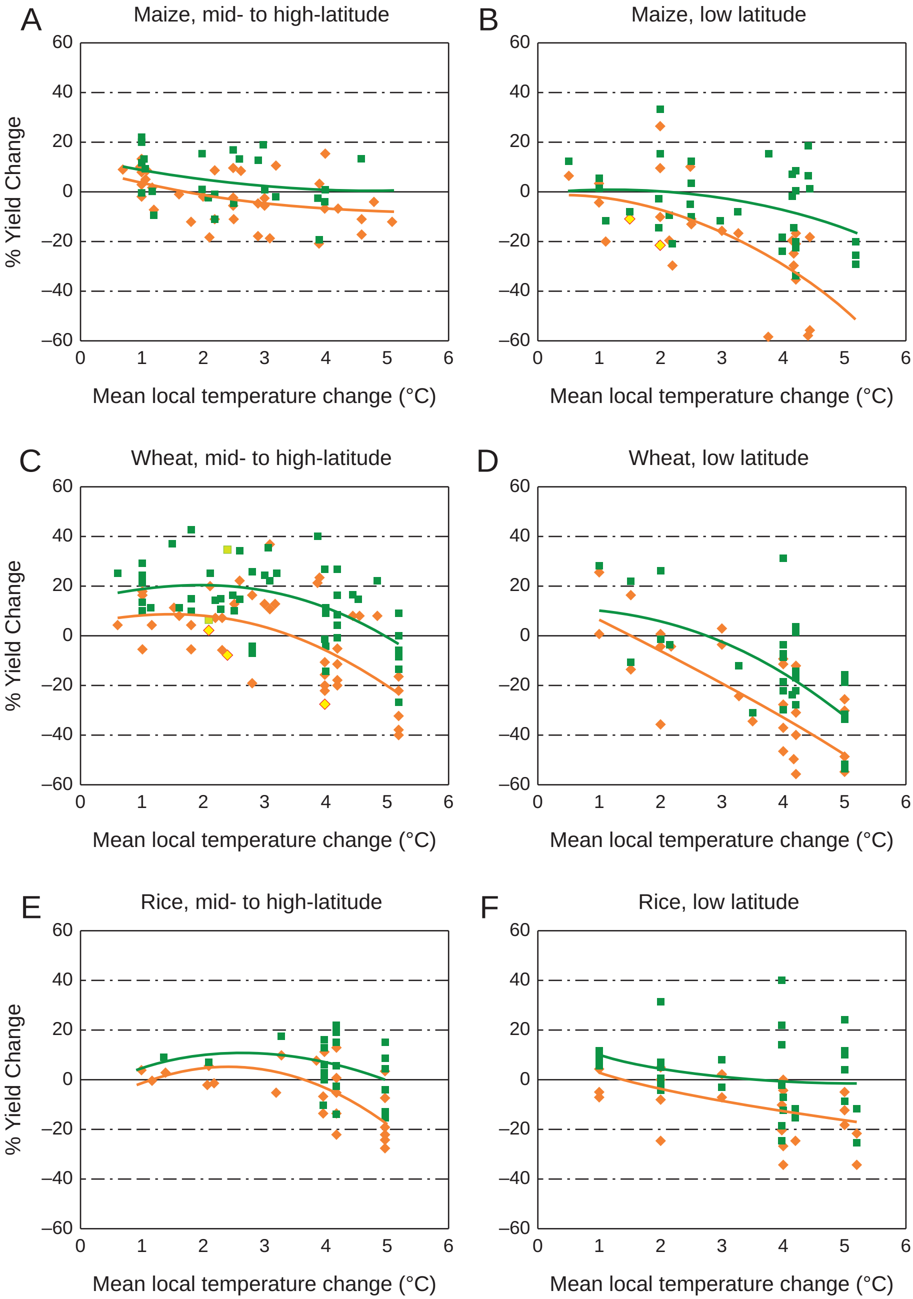

Figure 1 *cont'd*
For legend see opposite page

Many of the viewpoints and assumptions underlying the study of the impact of climate change on agriculture as an economic activity are open to debate. The bulk of the literature on these issues emerges from the academic and policy apparatus of the advanced capitalist world. The global South has a fairly weak presence in this literature, though not without important exceptions. To those who appreciate that the science of economics in the contemporary world is far more value-laden and ideologically driven than the natural sciences, it should be obvious that much of the contemporary literature on the impact of climate change on the economics of agriculture should be read with some caution.

In general, studies of losses or gains to the global economy or national economies are based on a combination of computable general equilibrium (or CGE) models. Such models may incorporate detailed data on one or more specific sectors, but are, in general, highly aggregative in their use of information. These models are coupled with climate models, which feed future climate data into the model as exogenous inputs. The output of such models is a quantification of the losses and gains to GDP relative to some reference model of economic growth. They also typically include predictions of future carbon prices. While early versions of such models were fairly simple, current versions, referred to as Integrated Assessment Models (IAMs), are rather complicated.[19]

Such models have become ubiquitous in the computation of the economic impact of climate change and the cost of mitigation policies. However, as models cover more and more sectors of the economy and become increasingly complex, it is obvious that there are cascading sets of uncertainties that derive from economic assumptions the uncertainties of agronomic considerations and the uncertainties of climate modelling. The CGE and IAM frameworks, therefore, are open to much criticism that is not easily dealt with simply by tinkering with the details of such models.[20]

[19] For an early but still valuable guide to IAMs, see Center for International Earth Science Information Network (CIESIN 1995), and all pages linked to it.
[20] For a general critique of the CGE framework, see DeCanio (2003). For a specific critique of IAMS in the CGE framework with special reference to the nature of discounting, etc., see Ackerman *et al.* (2009), pp. 297–315. With reference to the incorporation of details of trade, see the critique of trade in the CGE framework in Taylor and Arnim (2006).

Figure 1 *Sensitivity of cereal yield to climate change: maize, wheat and rice*
Notes: (i) The data-points are derived from the results of 69 published studies at multiple simulation sites, against mean local temperature change used as a proxy to indicate the magnitude of climate change in each study.
(ii) Responses include cases without adaptation (red dots) and with adaptation (dark green dots).
(iii) Adaptations+ represented in these studies include changes in planting, changes in cultivar, and shifts from rainfed to irrigated conditions.
(iv) Lines are best-fit polynomials and are used here as a way to summarise results across studies rather than as a predictive tool.
(v) The studies span a range of precipitation changes and CO_2 concentrations, and vary in how they represent future changes in climate variability. For instance, the lighter-coloured dots in (b) and (c) represent responses of rainfed crops under climate scenarios with decreased precipitation.
Sources: Reproduced from Fig. 5.2 in Parry *et al.* (2007). Data-points are based on studies referenced therein.

IAMs are also used for sectoral assessments of agriculture.[21] A feature of these studies relevant to this discussion is that IAMs use varying methods to determine the current climate sensitivity of agriculture. One of the key uncertainties in all these models is the construction of a reference scenario of agriculture in a future world without global warming. The impact of climate change on agriculture is measured with respect to this reference scenario.

Three major methods have been used in the current literature to study the climate sensitivity of agriculture.[22] The first method is based on studying net revenue per hectare across a number of regions with different climatic conditions.[23] Where time-series data are available, the climate variables are averaged out over the entire time period. In such studies, land value or net annual revenue is regressed against temperature and precipitation data from different seasons. Soil quality, other input variables and other variables accounting for a number of socio-economic factors are also introduced into the regression models. The claim is that such analysis includes the effects of climate adaptation in various forms, particularly the appropriate choice of crop for the relevant climatic conditions, based on current climatic variability. However, variations in net revenue per hectare across farms may also depend on other variables: biophysical ones like water supply (by means other than direct precipitation), and economic ones such as the impact of prices and other market effects. Such variables have not yet been incorporated into models based on the cross-sectional method.[24]

The second method, which has been termed the "agronomic–economic" approach, is based on detailed crop growth models.[25] These models are calibrated against several experiments, both in laboratory and field settings, and thus provide fairly dependable information on the relationship between climate and yields. These results are then fed into economic models that predict aggregate crop output and prices to determine the "final" economic impact of climate change on agriculture. This class of models does not typically incorporate climate adaptation and has no means of accounting for possible changes in technology.

The third method is the "agro-ecological zones method" developed by the Food and Agriculture Organization (FAO).[26] Here, detailed models are built of potential crop yields in different agro-ecological zones and include the effects of a number of

[21] Strictly speaking, these models are referred to as Applied General Equilibrium (AGE) models and originally were unrelated to CGE models. For more details on the relationship between AGE and CGE models, and a delightfully written critique of the two approaches, see Mitra-Kahn (2008).
[22] The summary description of these approaches draws heavily on the useful review in the Food and Agriculture Organization document, "Two essays on climate change and agriculture" (FAO 2000).
[23] This is often referred to as the "cross-sectional" method or, somewhat more inaccurately, the "Ricardian" method. For a recent review of the method, see Sanghi and Mendelsohn (2008), pp. 655–65.
[24] FAO (2000). For a critique of the cross-sectional method, see Reilly (1999).
[25] For an important discussion of the agronomic–economic approach, see Rosenzweig and Parry (1994), p. 133. These models can also be used at regional or national levels.
[26] Darwin, Tigras, Lewandrowski and Raneses (1995).

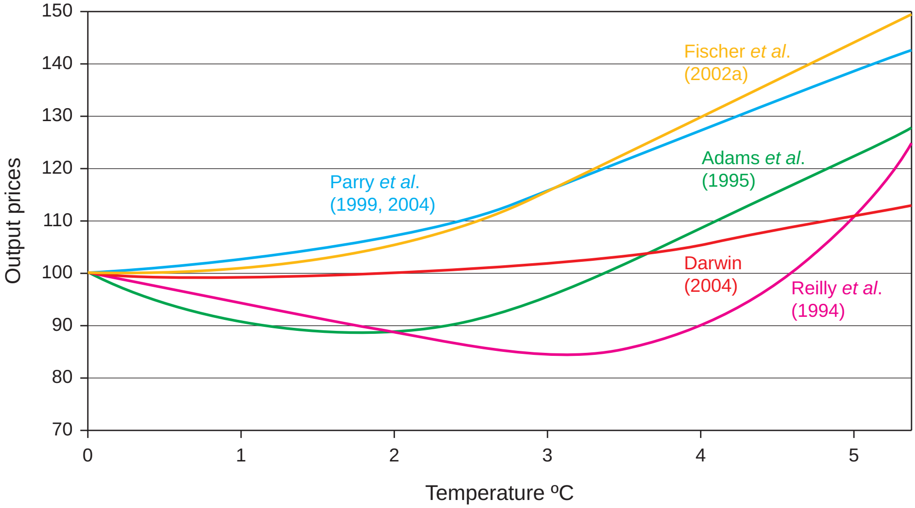

Figure 2 *Cereal prices (per cent of baseline) versus global mean temperature change for major modelling studies*

Note: Prices interpolated from point estimates of temperature effects.

Sources: Reproduced from Fig. 5.3 in Parry *et al.* (2007), and references cited therein.

eco-physiological variables. Originally a model built to simulate potential crop yields, FAO's agro-ecological zones model has been deployed for studying the economic impact of climate change on agriculture by coupling it with a revenue maximisation or cost minimisation module. The advantage in this case is its detailed modelling at the field level of a given range of production conditions in agriculture in less-developed countries. Technological advance cannot be directly simulated in it, but the impact of technology on specific eco-physiological features can be modelled. In the more advanced versions of this model, agro-ecological zoning is coupled with an applied general equilibrium model to derive more economically relevant estimates.

The IPCC's AR4 contains the most significant results on the estimated change in output prices as a consequence of climate change, reproduced in the figure below. The labels on various curves refer to different models. As we have already noted, such results are at best indicative and do not have much specific predictive value.

The report of the International Food Policy Research Institute (IFPRI) titled "Climate Change: Impact on Agriculture and Costs of Adaptation,"[27] provides interesting estimates of agricultural production and prices in 2050. The results are based on IFPRI's model of agricultural supply and demand projections and its model of biophysical impact for five crops: rice, wheat, maize, soybean and groundnut. Table 2 below has been reproduced from the report. The table makes it clear that over and above the price increases expected in the reference scenario, the additional effect of climate change is a further increase in prices.

[27] Nelson *et al.* (2009)

Table 2 *Projected world food prices in 2000 and 2050, with and without climate change*

Commodity	Price (in US$/metric tonne)				Change between 2000 and 2050				
	In 2000	In 2050			col. 3/col.2	col. 4/col.2	col. 5/col. 2	col. 4/ col. 3	col. 5/ col. 3
		With no climate change	With climate change, but no carbon fertilisation						
			according to NCAR	according to CSIRO					
1	2	3	4	5	6	7	8	9	10
Rice	190	307	421	406	1.6	2.2	2.1	1.4	1.3
Wheat	113	158	334	307	1.4	3.0	2.7	2.1	1.9
Maize	95	155	235	240	1.6	2.5	2.5	1.5	1.5
Soya bean	206	354	394	404	1.7	1.9	2.0	1.1	1.1
Beef	1925	2556	3078	3073	1.3	1.6	1.6	1.2	1.2
Pork	911	1240	1457	1458	1.4	1.6	1.6	1.2	1.2
Lamb	2713	3102	3462	3461	1.1	1.3	1.3	1.1	1.1
Poultry	1203	1621	1968	1969	1.3	1.6	1.6	1.2	1.2

Notes: NCAR = National Center for Atmospheric Research, USA; CF = Carbon Fertilisation; CSIRO = Commonwealth Scientific and Industrial Research Organisation, Australia; mt = million tonnes.
Source: Reproduced from Table 2 in Nelson (2009).

What conclusions can we draw from these results? Very few, it seems. It is useful in this context to recall the statement in IPCC's AR4 on the state of uncertainty that plagues all these models:

> Finally, the true strength of the effect of elevated CO_2 on crop yields at field to regional scales, its interactions with higher temperatures and modified precipitation regimes, as well as the CO_2 levels beyond which saturation may occur, remain largely unknown.
>
> In terms of modelling, calls by the Third Assessment Report (of the IPCC) to enhance crop model inter-comparison studies have remained unheeded; in fact, such activity has been performed with much less frequency after the Third Assessment Report than before. It is important that uncertainties related to crop-model simulations of key processes, including their spatial–temporal resolution, be better evaluated, as findings of integrated studies will remain dependent upon the particular crop model used. It is still unclear how the implementation of plot-level experimental data on CO_2 responses compares across models; especially when simulations of several key limiting factors, such as soil and water quality, pests, weeds, diseases and the like, remain either unresolved experimentally or untested in models (Tubiello and Ewert 2002). Finally, the Third Assessment Report concluded that the economic, trade and technological assumptions used in many of the integrated assessment models to project food security under climate change were poorly tested against observed data. This remains the situation today.

While it is clear that mere scepticism cannot be the correct attitude towards the effects of climate change on agriculture, a healthy caution appears warranted with reference to the quantification of these effects, especially in terms of future trends in prices of agricultural commodities and losses to national income. The strongest evidence pointing toward the potential impact of climate change emerges from basic agricultural science considerations and crop growth models that have been extensively tested and validated for purposes other than climate change studies. Estimates of changes in agricultural production and yield are next in line in respect of reliability, especially where they depend on validated agricultural growth models without further economic modelling added on.

Readers may object that we are too sceptical and unaccepting of current predictive economic models in the field. We note, however, that there is a difference between a critical view of current quantitative estimates of the effects of climate change on the economics of agriculture and a general, all-round climate scepticism. We also note that climate vulnerability is a serious problem for agriculture, especially in less developed countries, and that there is much to be learned for the future from the present.

Less-developed Countries: Areas of Concern

There is abundant evidence that climate change will disproportionately affect less-developed countries. One of the primary climatic reasons is that agricultural production in low latitudes, which account for a majority of less-developed countries, is more likely to be affected by rising temperatures, since ecosystems are already at their limits of thermal stress tolerance in many cases.[28] On the other hand, in temperate latitudes, even if the magnitude of temperature increases were to be higher, there is greater margin to cope with thermal stress.

Similarly, water stress arising from climate change is likely to be higher in many locations in lower latitudes. This also places greater stress on agriculture in less-developed countries. But given the great variations in socio-economic conditions across regions with similar climatic conditions, it is evident that climatic conditions alone do not determine or characterise the greater vulnerability of developing country agriculture to climate change.[29]

It is intuitively plausible that countries with low levels of human development, agricultural productivity, industrial capabilities and infrastructure would be at a greater disadvantage in dealing with the complex challenges posed by climate change. The gross social and economic inequalities that characterise rural society in many less-developed countries are likely to exacerbate such disadvantage.

All considerations of climate change vulnerability naturally begin with the proposition that while all societies are exposed to the risks of climate change, these risks are not uniform. Certain ecosystems face greater risk than others. Various occupational groups who are inhabitants of high-risk habitats or geographical regions, or whose livelihoods are dependent upon natural resources that are at higher risk, also face a greater degree of threat than others from climate change. Different socio-economic categories may suffer the effects of climate change in different ways even in the same agro-ecological setting. While the literature on climate vulnerability aims to capture this differential aspect in the assessment of the impact of climate change, there is considerable difference between studies in how the subject is developed.[30]

The United Nations Development Programme's (UNDP's) *Human Development Report* (HDR) of 2007–08, while taking account of theoretical advances in the field, provides a useful and policy-friendly perspective on climate vulnerability. In the first instance, it usefully distinguishes between risk and vulnerability. To put it simply, everyone is at risk from the impact of climate change, but the degree of vulnerability varies sharply across different levels of human development. Whereas risk captures the idea of the impact of natural shock in the context of climate change, "vulnerability is a measure of capacity to manage such hazards without suffering a

[28] See, for instance, Section 19.4.3 of the report of Working Group II in IPCC's Third Assessment Report and references therein (McCarthy *et al.* 2001), available at http://www.grida.no/publications/other/ipcc_tar/, viewed on August 20, 2010.
[29] While this may seem obvious, there is some literature that attributes global disparities in development to geographical and climatic differences. For a classic in this genre, see Sachs (2001). For a useful critique of this approach, see also Rodrik, Subramanian and Trebbi (2002).
[30] For a detailed list of references to the literature, see Cutter *et al.* (2009).

long-term, potentially irreversible, loss of well-being."[31] The processes by which risk is transformed into vulnerability in different countries depend on the state of the country's human development, including the "inequalities in income, opportunity and political power that marginalise the poor."[32] Poverty and low human development are the key sources of vulnerability, though poverty is not identical to climate-related vulnerability.

Poverty, human development and climate-related vulnerability are closely interlinked. Poverty exacerbates climate-related vulnerability since the poor lack a range of resources that could lower their vulnerability. From the perspective of human development, climate-related risks could lead to low human development traps, "a one-way downward descent" into further disadvantage. Climate change in general would act negatively on all existing manifestations of low human development and exacerbate the pre-existing vulnerability of different sections of the population of less-developed countries. Further, the strategies of the poor to cope with climate shocks may themselves lead to increased deprivation, thereby perpetuating low human development.

The *Human Development Report* notes the broad mechanism by which such low human development traps could come into operation. Poor cultivators are more risk-averse than the rich, since farming by the poor is more risky – even minor fluctuations of climate can expose them to adverse consequences. As a result, coping with climate risk may include staying away from commercial cropping, which provides higher returns only in exchange for accepting a higher degree of risk. Traditional coping strategies of the poor in response to climate or economic shocks may include the sale of productive assets such as land and livestock. Other coping strategies may have adverse effects such as losses with regard to nutrition, health, education and so on, which would further contribute to the inability of the poor to recover fully from any particular climate crisis.

There are clearly wide variations in climate vulnerability among less-developed countries and regions within individual nations. Much of the global research on vulnerability to climate change in developing countries has correctly focused on the threat to agriculture in semi-arid regions or, more generally, on rainfed agriculture.[33] At the same time, the greater vulnerability of semi-arid or rainfed agriculture should not obscure the fact that even where agriculture is at present less vulnerable to climate variation than elsewhere, climate change may introduce greater vulnerability.

[31] See *Human Development Report 2007/2008* (UNDP 2007), p. 78.
[32] *Ibid.*
[33] A very useful early study of vulnerability, both in terms of theory and detailed regional studies, is available in Ribot *et al.* (1996).

Some General Results

What is the likely effect of global warming on the Indian subcontinent? Much of the work that projects possible climate scenarios of the future describes highly aggregated global situations. Though these global data and corresponding projections are undoubtedly important in providing the basis for common global action, nations and regions also need disaggregated information on the effects of climate change at national and regional scales. It has been clearly established that there are significant variations in climate change impact at the national and regional levels across the globe, variations that will be significant in terms of policy and societal action. The techniques for making predictions at the national and sub-national levels still need further development.

Following the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, India, as a non-Annex-I party to these international treaties, is committed to providing a periodic assessment or a National Communication (NATCOM) assessing the domestic emission scenario in detail, as well as an assessment of mitigation and adaptation measures. NATCOM I from India was submitted to the UNFCC in 2006, and it provides a preliminary basis for understanding the country-level impact of climate change on India.

The following is a broad-brush summary of the expected impact of climate change on India as provided by NATCOM I.[34]

1. Temperature increases have already been observed in the Indian subcontinent. Over the last 100 years, an increase of 0.4°C in annual average surface air temperature has been recorded. By the 2050s maximum temperatures are expected to rise by 2°C–4°C over south India (i.e. south of latitude 25°N) and by more than 4°C over northern India (north of latitude 25°N). Minimum temperatures are expected to rise by more than 4°C all over India over the same period.
2. So far there has been no significant change in the total rainfall delivered by the monsoon. Regional variations, however, are observed, and range from increases of 10–12 per cent over some regions to decreases of 6–8 per cent in some others. Total rainfall from the monsoon is expected to be relatively unchanged through to the 2050s. The spatial variability of rainfall, on the other hand, is likely to increase. A decrease in the number of rainy days is expected, with a corresponding increase in rainfall intensity in terms of rainfall per day ranging from 1 mm/day to 4 mm/day.
3. While the average frequency of cyclonic storms over the period 1887–1987 appears to have been unchanging, there appears to be a slight increase in the frequency of severe cyclonic storms in recent decades.

[34] Government of India, Ministry of Environment and Forests (2004), NATCOM I.

4. Surface water runoff patterns are likely to change, with reduction of runoff in many river basins, although calculating the final runoff requires detailed modelling.
5. Varying levels of water shortage are likely to appear across different basins. Perennial water shortages are expected in the Mahi, Pennar, Sabarmati and Tapti basins. Seasonal water shortages and regular water-stressed conditions are expected in the Ganga, Cauvery, Narmada and Krishna river basins. The Godavari, Mahanadi and Brahmani basins are likely to experience only moderate water shortage at a few locations.
6. Himalayan glaciers and snowfields are generally on the decline, though there is need for substantial further scientific work to accurately establish the changes that are taking place.
7. The severity of droughts and intensity of floods are likely to increase. Preliminary results suggest that peak discharge under climate change could be as high as twice the current peak discharge in some basins.
8. The rise in sea level along India's coastlines currently ranges between 0.4 and 2 mm per year, with the highest increases being registered along the coast of the Gulf of Kutch and West Bengal. Though substantial uncertainty is involved in estimating the rise in sea level in the future along specific stretches of the coastline, it is estimated that a general rise of up to 1 mm may be expected by the end of the century.
9. Groundwater supplies are likely to be affected by a number of factors, including higher runoff leading to lower recharge, increase in flooding (which will affect the quality of alluvial aquifers) and saline intrusion into coastal aquifers.

NATCOM I also provides an overview of the impact on the biosphere that may be expected as a result of the geophysical consequences of a rise in global temperatures.[35]

1. The impact of climate change on crops depends, at the biophysical level, on a complex interplay between the effects of rising temperature, increased CO_2 concentrations and variations in rainfall. Other more complex effects may arise due to changes in other variables, for instance, in the number of cloud-cover days. Focusing solely on the effect of rising temperature, it is known that, for both rice and wheat, a 2°C rise in temperature could lower yields by 15–17 per cent. Increasing temperatures would affect rabi production more seriously than kharif production. The effects of rising temperature, however, may be offset by the effects of increased atmospheric CO_2 concentrations. Simulation studies suggest that, in general, climate change in various scenarios of CO_2 concentration and temperature rise would result in a small increase in rice yields. They further suggest that the corresponding impact on wheat is more variable, ranging from negative to positive.

[35] *Ibid.*

2. The effect of predicted variation in rainfall is as yet unclear. In the case of rain-dependent small and marginal farms, the primary effect is likely to be increased vulnerability to lower yields because of increased uncertainties in rainfall. Similarly, yields from crops such as pulses, which are primarily rainfed, are likely to suffer due to increased rainfall uncertainties. Yields of C4 crops such as sorghum may be relatively unchanged. Rainfall pattern changes also affect the availability of irrigation water and soil erosion.
3. As temperatures increase, the response of crops to nitrogenous fertilizers is expected to decrease, forcing increased application of fertilizers to maintain a given level of food production. Increased temperatures and changing rainfall patterns may also adversely affect the current pattern of pest–crop interactions, leading to greater pressures on agricultural production.
4. NATCOM I further says that forests appear highly susceptible to the effects of climate change. Up to 70 per cent of the biomes in forests are unlikely to adapt to climate change in their existing location. Different species may suffer varying degrees of stress, leading to changes in the composition of forests. Apart from the stress on vegetation in their current location, the intrusion of species from other regions on account of climate change may pose a further source of stress. In the transition phase from one vegetation type to another, a delay may lead to loss of overall stock of vegetation. Biodiversity is also expected to decrease. Overall, the impact of climate change on forest ecosystems is likely to be long-term and irreversible.
5. Various natural ecosystems, such as inland wetlands, coastal mangrove systems and offshore coral reefs, are likely to be affected.
6. Climatic changes will affect the nature of various disease-carrying vectors, with serious consequences for health. NATCOM I presents a preliminary study of the malaria scenario under climate change.

Climate Variability

Over the last half a century or more, the overall trend in agricultural production has been one of increase for most crops, with pulses being the only case where the gains in overall production appear very small. This is evident from the charts below.

As in the global case, this clearly implies that, so far, agricultural production has managed to stay ahead of the curve with respect to climate change. Despite this growth, Indian agriculture is still susceptible to climate variability.[36] A recent study shows the clear correlation (Figure 4) between variation in food production and variation in the total summer monsoon rainfall.[37] It also shows (Table 3) that the loss

[36] While this has always been a subject of concern, recent heightened interest in climate change has re-emphasised studies to understand the impact of current climate variability.
[37] Rao (2008).

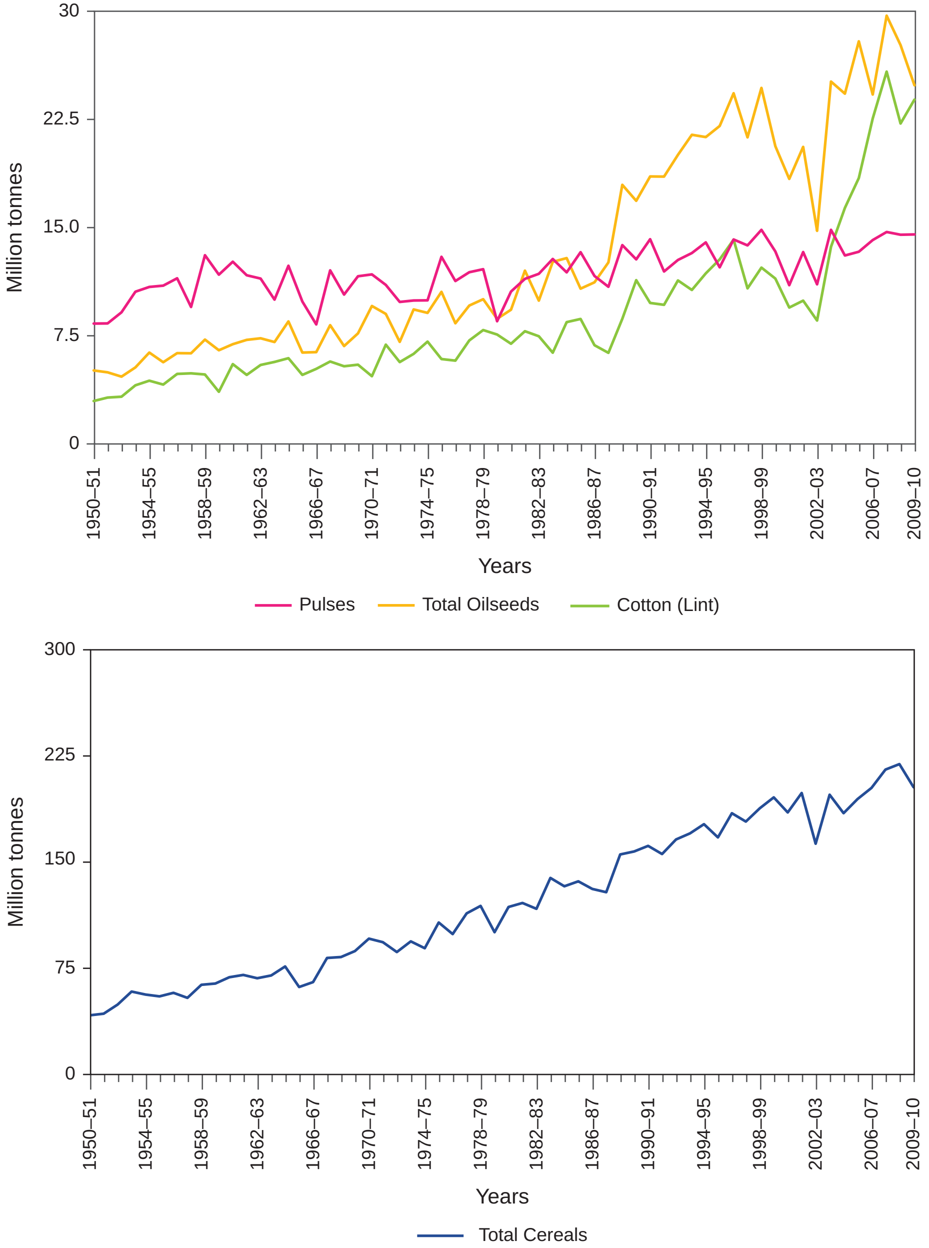

Figure 3 *(cont'd on next page)*

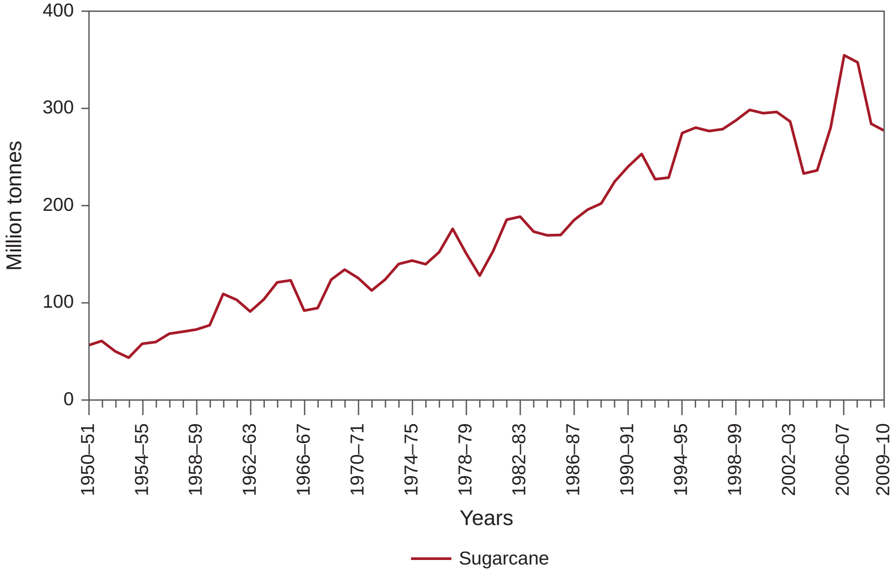

Figure 3 *Production of cereals, pulses, oilseeds, cotton and sugarcane, India, 1950–51 to 2009–10*
Source: Agricultural production data from Reserve Bank of India (2010).

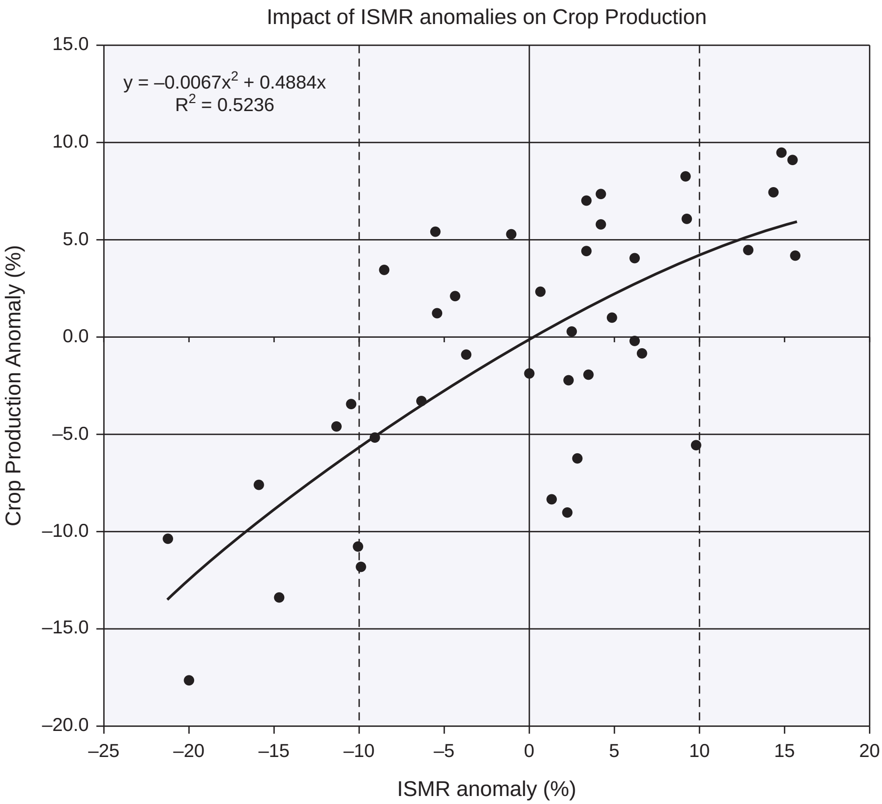

Figure 4 *Impact of Indian summer monsoon rainfall (ISMR) anomalies on crop production*
Source: Adapted from Rao (2008).

Table 3 *Monsoon anomalies (or deviations from the normal) and their impact on crop production*

ISMR Anomaly	Impact on crop production (% change)
−20	−12.44
−15	−8.83
−10	−5.55
−5	−2.61
0	0.00
5	2.28
10	4.22
15	5.83
20	7.10

Source: Adapted from Rao (2008).

in production in a rainfall-deficient year is greater than the gain in production in a year of above-average rainfall.

Another study shows that the aspect of weather fluctuation that has the most impact on agricultural production is variation in growing season temperature.[38] A third study used current climate data from seven locations in the Indo-Gangetic plain.[39] The study found that, for the given climate data, crop models showed a negative trend for potential yields in both rice and wheat. The main climatic effects accounting for these changes were decrease in solar radiation and increase in the minimum temperature.

More recently, a detailed study of crop production based on remote sensing data provides an interesting direction of study into the possible ongoing impact of climate change on Indian agriculture.[40] Remote sensing data for India show a marked slowdown in the growth rates of total production from the 1990s. Milesi *et al.* (2010) calculated that foodgrain production in the kharif season grew at a rate of 1.61 million tonnes per year from 1966–67 to 1991, and that this rate fell to 0.7 million tonnes per year in the period 1990–91 to 2005–06. The corresponding figures for the rabi season were 1.91 million tonnes per year from 1966–67 to 1995–96, and 0.41 million tonnes a year from 1995–96 to 2005–06 (the specific time-periods they used were determined by trend breaks in the time-series). These data need, of course, to be studied in conjunction with agronomic and other evidence to determine the extent to which environmental factors and climatic change are contributing to the observed decrease in growth rates of agricultural production.

One of the critical issues in Indian agriculture is the high proportion of rainfed agriculture in the part of the country climatically classified as semi-arid tropics

[38] Mall and Singh (2000), pp. 35–41.
[39] Pathak *et al.* (2003), pp. 223–34.
[40] Milesi *et al.* (2010), pp. 758–76.

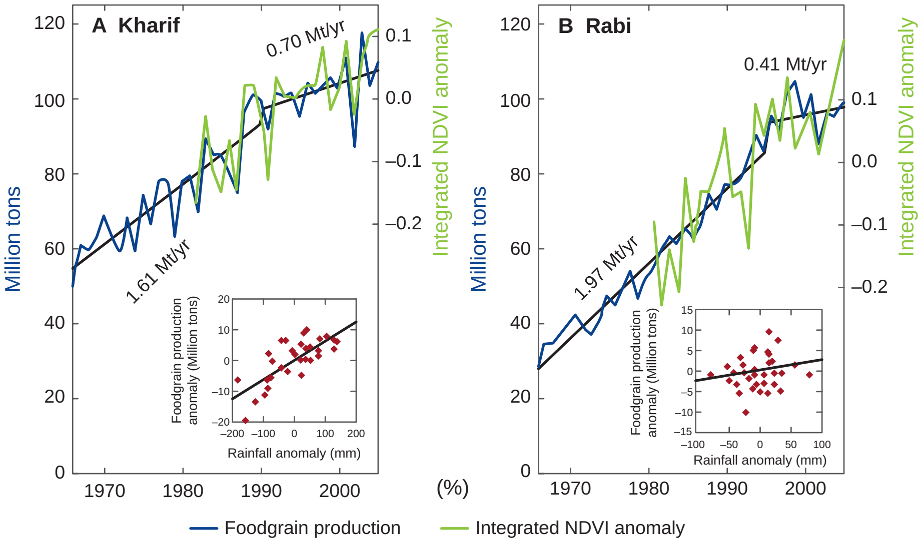

Figure 5 *Slowdown in growth rate of foodgrain production based on the integrated NDVI anomaly from remote sensing data*

Notes: Integrated NDVI = Integrated Normalised Differential Vegetation Index. In non-technical terms, NDVI measures the presence of greenness of vegetation. In this particular instance, the data are for Indian croplands.

Source: Milesi *et al.* (2010).

(SAT).[41] Rainfed agriculture[42] in the semi-arid tropics is particularly vulnerable to climate change. In 1999–2000, rainfed agriculture as a whole accounted for roughly 60 per cent of net sown area, amounting to nearly 87.5 million hectares out of a total of 142 million hectares. In the semi-arid tropic States of Andhra Pradesh, Gujarat, Maharashtra, Karnataka, Rajasthan, Tamil Nadu and Madhya Pradesh, rainfed agriculture accounted for 72.8 per cent of net sown area, whereas in the non-semi-arid tropics it accounted for 42.2 per cent of net sown area.[43] Rainfed agriculture in the semi-arid tropics carries a much higher degree of risk, and is characterised by high variability in production, low yields and low returns, often not even covering the cost of cultivation for several crops in many regions. The semi-arid tropics are important to total agricultural production, gross cropped area and farmers' livelihoods in India, particularly with respect to the cultivation of minor millets, oilseeds and pulses.[44] Climate change theorists may want to note that relative water-abundance is not a sufficient condition for the removal of income-poverty. The incidence of

[41] For reviews of rainfed agriculture in the semi-arid tropics in India, see Bhatia (2005) and Rao *et al.* (2005), p. 96. For an earlier review, see Kerr (1996). Following the FAO, Rao *et al.* (2005) define semi-arid tropics as those tropical regions where rainfall exceeds evapotranspiration for two to seven months in the year.

[42] Rainfed agriculture is a crop system that is entirely dependent on rainfall, supplemented perhaps by small dams, tanks and associated runoff for individual holdings.

[43] The ratio of rainfed to irrigated area based on remote sensing data shows major discrepancies with such figures. However we will not enter into such issues here though they are potentially important.

[44] Bhatia (2005).

Table 4 *Yield gaps in India, by crops and States in per cent*

State	Irrigated			Rainfed			
	Paddy	Wheat	Mustard	Maize	Bajra	Jowar	Groundnut
Andhra Pradesh	123	23			191	231	83
Assam	175	46	114				
Bihar	162	74	174	195			25
Gujarat	60	43	124	99	191	541	1
Haryana	55	25	1	3	86		
HP	49	163	420	11			
Karnataka	132	28			258	292	49
Kerala	116						
Madhya Pradesh	135	73	89	105	165	231	55
Maharashtra	140	102					
Orissa	115	66	63	153			60
Punjab	87	40	25	6			
Rajasthan	27	82	130	114	309		106
Tamil Nadu	62				163	479	62
Uttar Pradesh	101	93	164	106	92		106
West Bengal	90	19	131	11			

Note: Yield gap = the ratio of the difference between attainable and actual yield to the actual yield, expressed as a percentage
Source: Reproduced from Chand (2005).

income-poverty does not appear necessarily very different between the semi-arid and humid zones of India, nor does the Human Development Index show any clear trend or pattern that correlates with agro-climatic zones or levels of irrigation.[45]

For detailed studies of climate variability in the context of climate change, it is also necessary to have village-level data available for the same locations over a number of years.[46]

Dryland agriculture did not receive the policy attention that irrigated agriculture did in the era of the Green Revolution. This relative neglect has characterised the more recent period as well. Today, awareness of climate vulnerability has helped to focus attention on the issue of dryland agriculture, and an all-round improvement in the performance of rainfed agriculture in India is clearly a crucial requirement in the era of climate change.

[45] Rao *et al.* (2005).
[46] The International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) has gathered village-level information on the nature and impact of climate variability. See their Research Briefs at http://www.icrisat.org/impi-research-briefs.htm, viewed on October 17, 2010.

As noted earlier, agriculture in less-developed countries is characterised by yield gaps. The same is true for India and overcoming these yield gaps remains a key issue on the agenda of Indian agricultural development. Table 4 shows the extent of yield gaps for irrigated and unirrigated land for select crops in different States.[47] We may also re-emphasise that bridging the yield gap fully may not be possible, both because of limitations imposed by local conditions of production and, in the longer term, because climate change could lower potential yields.

Current Evidence

There is little evidence of any direct impact of ongoing climate change on current agricultural production, especially with respect to major food and horticultural crops, and related activities such as livestock rearing and fisheries. Two observations, however, are noteworthy.

The first concerns the impact of climate change on apple production in Himachal Pradesh.[48] Apple production is sensitive to the extent of cold weather in a specified range during the winter months. This is calculated in terms of "chilling units" (the cumulative number of hours over which winter temperatures are in the correct range of coldness). The number of hours above the specified maximum during the winter months has a negative effect on apple yields. The data show that, below a height of approximately 2,400 metres above sea level, the number of chilling units has been decreasing, whereas above this height the number of days of suitable temperature has been increasing. This change is reflected in the pattern of apple production: the extent of apple cultivation is increasing at higher altitudes and declining at lower altitudes. Thus the extent of apple cultivation has increased sharply in Lahul-Spiti and the upper reaches of Kinnaur district, whereas it has reduced in the State as a whole, particularly in Kullu and Shimla. Apple yields per hectare have also declined overall in the State, from 10.8 to 5.8 tonnes/hectare. According to some studies (cited in Rana *et al.* 2009), these observations appear to match farmers' perceptions.

The second case of known impact of climate change comes from a study of Indian major carp, both in the Ganges river and in inland tank fisheries, especially in West Bengal. The Central Inland Fisheries Research Institute has undertaken a valuable study of the impact of climate change on the cultivation of Indian major carp in tank fisheries in West Bengal, covering 50 hatcheries in 4 districts.[49] Breeding in the hatcheries was based on techniques centred on the maturity period occurring, in the 1980s, around 24–31 May. It has, however, been observed that the maturity and spawning now occur as early as mid-April in the fish hatcheries of West Bengal and Orissa. The breeding period has extended from 110–120 days in the pre-1980–85

[47] Chand (2005).
[48] The material here is drawn from Rana *et al.* (2009).
[49] Vass *et al.* (2009), pp. 138–51, and references therein.

period to 160–170 days in 2000–05. The study attributes this to the change in water temperature, 1.7°C and 0.3°C respectively for the mean maximum and mean minimum in this region, corresponding to a 0.37–0.67°C change in air temperature. Changing patterns of precipitation also appear to influence the observed outcome. At present, the level of production shows that the fisheries industry appears to have adapted to this impact without any significant negative implications for fish production. The shift to earlier breeding may have had initially to do with higher prices for Indian major carp earlier in the year, prior to the breeding season in May. The increasing heat stress likely in the peak summer months, however, may undo the adaptation that has occurred so far.

Changes in the distribution of sardines and mackerel have already been observed along the Indian coast since 1989.[50] False trevally, which is an economically and culturally important fish in India, and ranks as a preferred and high-quality fish in the Gulf of Mannar region, has also suffered the effects of climate change. There has been a distinct decline of the fishery over the last few years because of increased water temperatures and decreased rain (which flushes critical nutrients from the land into the Gulf of Mannar). Overall, however, the impact of climate change on Indian fisheries appears uncertain, as research seems to be as yet at the preliminary level.[51]

Future Impact

Before we briefly review the highlights of the possible future impact of climate change on Indian agriculture, it is useful to note once again that these predictions are based on climate models, and that their application to specific regions of the Indian subcontinent needs substantial improvement. The study by Rajendran and Kitoh (2008) provides the most reliable description of future rainfall patterns, as it appears to be the most successful in reproducing past rainfall patterns.[52] Most predictions that have been made for agriculture have not, however, used the kind of climate models that this latest study has. The results we present below must be read with this limitation in mind. (These results have to do with more general features of crop behaviour under various regimes of temperature and rainfall change than with any specific scenario of future climate change.)

To illustrate some of the issues involved, we briefly note some results that project the impact of climate change on two specific crops, rice and wheat.

The pioneering study of Sinha and Swaminathan (1991) reported that for a 2°C rise in temperature, rice yields would decrease by 0.75 tonne/hectare in high-yielding regions and by about 0.06 tonne/hectare in low-yield coastal regions.[53] For a complete

[50] See the website of CMFRI, http://www.cmfri.org.in/html/cmfriEnviorn.html, viewed on October 25, 2010.
[51] See Krishnan and Ayyappan (2005), and Sugunan and Maurye (2003) cited therein.
[52] Rajendran and Kitoh (2008), pp. 1560–569.
[53] Sinha and Swaminathan (1991), pp. 33–45.

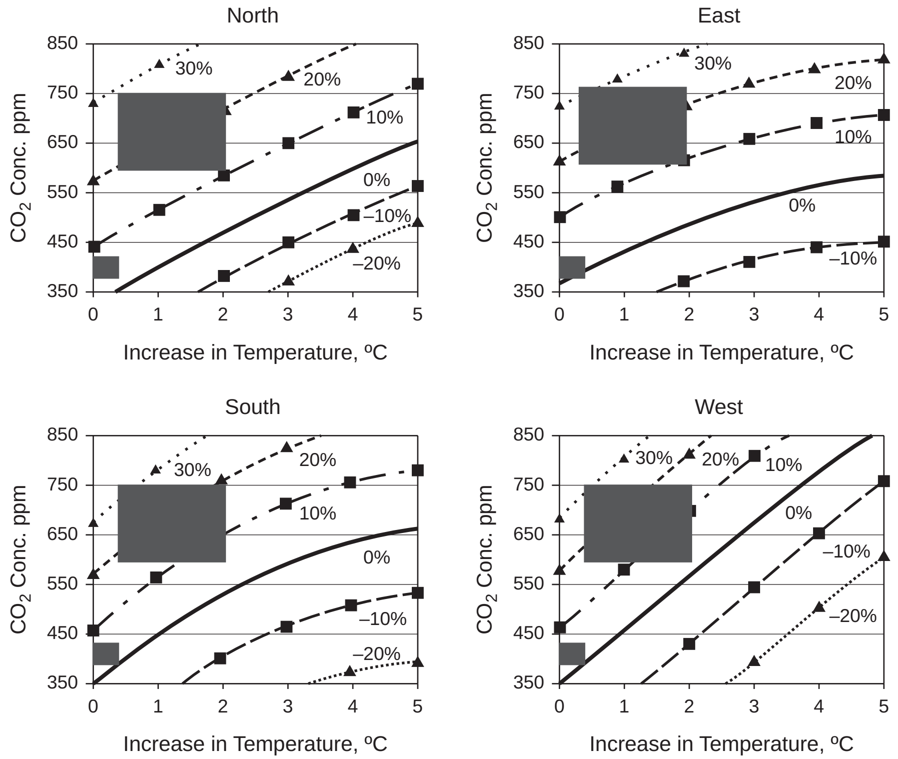

Figure 6 *Effect of increase in temperature and CO_2 concentrations on simulated grain yields of irrigated rice, with improved nitrogen management (allowing no nitrogen stress), in different regions of India by the year 2070*

Notes: (i) Lines refer to the equal change in grain yield (per cent change, labelled) at different values of CO_2 and increase in temperature. (ii) Large shaded boxes refer to the uncertainties in impact assessment due to the uncertainties in the IPCC scenarios for 2070. (iii) Small shaded boxes refer to the uncertainties in impact assessment due to the uncertainties in the scenario for 2010.

Source: Reproduced from Fig. 1 in Aggarwal and Mall (2002).

picture, however, we need to see the effect of both CO_2 fertilisation and temperature rise, as we had noted earlier. Figure 6 sums up the general pattern for rice production in India.[54]

A 2℃ rise in temperature and a concentration of 450 ppm of CO_2 would cause some loss of yield in rice production in all regions of India. This is a critical issue, since the best possible scenario emerging from current climate negotiations suggests that the world is likely to move towards a 2℃ rise in temperature and a CO_2 concentration of 450 ppm. If these negotiations are not successful, the world may head towards higher temperatures and a higher concentration of CO_2. Even if concentrations are lowered eventually, the rising temperatures caused by the total CO_2 emitted till then will continue for some time. In such a situation, which may occur by mid-century

[54] Aggarwal and Mall (2002).

Table 5 *Temperature effects on crop yield, selected crops, India*

Crop	Topt (°C)	Tmax (°C)	Yield at Topt (t/ha)	Yield at 28°C (t/ha)	Yield at 32°C (t/ha)	Per cent decrease (28°C to 32°C)
Rice	25	36	7.55	6.31	2.93	54
Soybean	28	39	3.41	3.41	3.06	10
Dry bean	22	32	2.87	1.39	0	100
Peanut	25	40	3.38	3.22	2.58	20
Grain: sorghum	26	35	12.24	11.75	6.95	41

Notes: Topt = optimal temperature; Tmax = maximum sustainable temperature; t/ha: tonnes per hectare.
Source: Rao (2008).

and later, the beneficial effect of CO_2 will be nullified and yields will fall even further, since the temperature rise will be above 2°C. In the event of an early agreement, on the other hand, the increase in concentrations is likely to peak at 450 ppm or thereabouts by mid-century, with only a 50 per cent probability of temperatures staying below 2°C. Thus, in either scenario, there is little case to be made for the beneficial effects of carbon fertilisation. The primary damage, it appears, will be from temperature rise, and climate adaptation policies in agriculture need to be oriented to take this into account.

In the case of wheat, the study by Sinha and Swaminathan (1991) noted also that a 0.5°C rise in winter temperature would lower yields by 0.45 tonne/hectare. The major findings of subsequent studies are presented in tabular form below. One of the major findings of the study of the Indian Council of Agricultural Research (ICAR) on the impact of climate change is that it is likely to lower the potential yields of wheat.[55] Thus the gap between potential yields and actual yields will narrow, with potential yields likely to fall faster than the rise in actual yields.

The following table shows some examples of the effect of changes in temperature on crop yields.[56]

The annotated bibliography to this paper contains a summary of the main research results from the literature on the effects of climate change on various crops, soil quality, pests and weeds, and water supply. Among these, the impact of climate change on water may be singled out as perhaps the most important. A preliminary survey of hydrology in the era of climate change, presented in a user-friendly format, is available on the website of the Civil Engineering Department of the Indian Institute of Technology, Delhi. The website provides an overview of the impact of climate

[55] Aggarwal (2009). The Executive Summary provides an important summary of some major research findings of the ICAR in the recent period.
[56] Rao (2008).

change in the medium and long term on water resources in various river basins and watersheds in India.[57] Though still not complete, it presents a useful starting point for analysis. Apart from such specific hydrological studies, many issues related to the supply and distribution of water in the era of climate change need independent study. These, however, lie outside the purview of this paper.

Work on adaptation to climate change in agriculture is still largely in its infancy, not only in India but also worldwide, for understandable reasons. There has been considerable enthusiasm among some conservation-inclined groups and researchers for some specific or other of conservation or sustainable agriculture as a panacea (the system of rice intensification, SRI, is one such technique that has widely been discussed). Notwithstanding this enthusiasm, which undoubtedly stimulates increased experimentation in the field, the outlines of future adaptation remain quite unclear. Among the major adaptation options are bio-technology and the utilisation of more recent techniques to develop crop varieties with traits that are specialised to coping with the effect of climate change. Improved management of inputs and shifts in farm practices are also significant options. It is worth emphasising that the adaptation challenge is a substantial one even for the sustainable development community, since what is really required now are not experimental local initiatives alone but the scaling up of such solutions to the level of States or entire regions of the country. What should also be evident is that there is no single solution, nor are solutions to be found by turning one's back on contemporary science and technology.[58] The challenge of developing an agriculture that is both sustainable and economically viable is a major one.

Some Policy Issues

It is clear that climate change presents a significant threat to the future of Indian agriculture. It is, however, important to keep this threat in perspective. While there are a few indications of climate change having affected horticulture and fisheries already, the general increase in gross production and the established potential for yield increases point to the fact that climate change is very much a problem of the future. The fact that much scope exists for improving agricultural yields and production even in the current situation is particularly important in the context of international climate negotiations. This is because some climate-change activists and policy specialists exaggerate the immediacy of the threat from climate change in order to achieve an early international climate agreement. An accurate assessment of the threat to agriculture is essential in order to evaluate the room for manoeuvre that India and other less-developed countries have in international climate negotiations. At

[57] http://gisseserver.civil.iitd.ac.in/natcom/, viewed on October 22, 2010.

[58] Among the interesting theoretical and practical challenges that climate change forces is the challenge of going beyond the usual binary oppositions that characterise the sustainability discourse, such as scientific knowledge versus traditional knowledge, experience versus theoretical or laboratory science, sustainability versus productivity and so on.

the same time, an international agreement that limits temperature rise to 2°C is critical, as the adaptability of agriculture to climate change has definite limits and the damage to agricultural production increases with rising temperatures. As we have noted earlier, the effect of carbon fertilisation cannot be relied upon, and will be undone as concentrations reduce and temperatures increase, even if a 2°C agreement is reached.

The threat of climate change makes the case for the accelerated development of Indian agriculture even more urgent. One of the main points of consensus in the literature on climate vulnerability, which is otherwise marked by many divergent results, is that the poor are the most vulnerable to the effects of climate change. Worldwide, the ability to cope with disasters in various regions is closely correlated to the levels of human development of these regions. All-round development has become ever more urgent in the era of climate change.

One of the significant features of India's vulnerability to climate change arises from the dependence on agriculture of a significant section of the total population, entirely out of proportion to the contribution of agriculture to total national income. Lessening this over-dependence on agriculture and providing non-farm livelihoods to a sizeable fraction of the population is a task that is even more pressing in the era of climate change.

There are several measures to reduce the impact of current climate variability that can help deal with the impact of climate change in the future. Among these measures are the following:[59]

- Further development of agro-meteorology with particular attention to the delivery of information in timely, accessible and understandable form to the rural population.
- Increasing emphasis on a proper system of agricultural insurance, which deals with not only gross deficiency of rainfall but also takes into account changes in precipitation and temperature patterns, and pays particular attention to the form and outcomes of extreme weather and weather-related events. Such an insurance system needs to be in large part in the public sector, and to be integrated into a larger framework of social protection.
- Building suitable infrastructure, such as coastal protection systems, communication and transport infrastructure, flood protection systems, and so on.
- Development of suitable public institutions to cope with extreme weather events and other shocks.

There are substantial gaps in our knowledge with respect to the impact of climate change. Of these, it is clear from the literature that, given the expertise and capabilities available in India, the purely scientific–agronomic knowledge gaps can be dealt with

[59] The list is adapted from the *Human Development Report 2007/2008* (UNDP 2007).

over time. There is, however, far greater uncertainty regarding the economic and social consequences of climate change. Given the uncertainties regarding future climate change, knowledge of how to cope with it has to evolve over time. Further, coping mechanisms will eventually require suitable institutional linkages between agricultural science, the state and public institutions, and the rural population engaged in agriculture. Thus, while climate change is not yet an immediate threat, it certainly calls for action at many levels.

Climate change adaptation requires enormous financial and other resources; the scale and scope of this requirement have proved to be difficult to quantify, and have been subjects of much uncertainty and debate.[60] What is generally accepted is that the finances required are likely to be large. In a context that calls for a coherent strategy from the state, the withdrawal of public expenditure on agriculture is a very disturbing trend. It is particularly disturbing that state-run systems of agricultural extension in India have largely been undermined by the Government of India from the early 1990s, and that there have been persistent attempts to reorient the strategies and aims of the national agricultural research system. The "Second Green Revolution" is sought to be based on a model of private sector-driven research and extension, with knowledge transfers from the developed world being strongly restricted by strong intellectual property rights (IPR) restrictions.

The Government of India has pursued a two-track approach to climate change adaptation, including in agriculture. In international climate negotiations, it has repeatedly called for state-to-state transfers of adaptation funds from developed to less-developed nations, resisting attempts by the former to consider financial transfers through existing multilateral financial institutions or the private sector. On the domestic front, the Government has announced a Mission on Sustainable Agriculture as one of eight missions under the National Action Plan for Climate Change (NAPCC).[61]

What is paradoxical is that a policy that appears to privilege the public sector is much less evident in domestic policy in agriculture, where in fact the public sector has been in retreat. In this light, the Government of India's emphasis on the need for financial transfers from developed countries for climate adaptation-related work suggests as much a reluctance towards committing domestic finance to this end, as it does a plea for equity in international climate policy.

In conclusion, we re-emphasise what must be one of the foremost social concerns in the study of the impact of climate change, that is, the impact of climate change on

[60] For a brief survey of adaptation economics from an Indian perspective, see Kavikumar (undated). See also Kavikumar (2010).

[61] For the National Action Plan on Climate Change, see Ministry of Environment and Forests, Government of India (2008). For a recent overview of the special Mission on Sustainable Agriculture, see the official presentation at Ministry of Environment and Forests, Government of India (2010).

the poor of the world, especially the rural poor. Although climate change affects all humanity, it has a disproportionately great impact on the poor. The poor will bear the brunt of climate change, particularly in the less-developed countries, though they have contributed the least to the problem of greenhouse gas emissions. In closing, we can hardly over-emphasise the need to ensure that, in an unequal world, the main burden of dealing with climate change is not placed on the poor.

Summary

Even a preliminary consideration of the problem of climate change and agriculture raises three basic questions.

First, what is and will be the nature and extent of the biophysical and agronomic impact of climate change on agriculture? A related issue is the economic and social impact that results from the effects of climate change on agriculture as a system of production. Secondly, since climate change is a phenomenon that is already under way, to what extent is agricultural production already suffering the impact of climate change? Thirdly, what is the nature of the current impact of climate change on Indian agriculture?

Climate change is driven by global warming, which is, in turn, caused by the emission of greenhouse gases as a result of human activity on Earth. The consequent increase in temperatures is, in general, deleterious to plant life. At the same time, the increase in atmospheric concentration of the most potent greenhouse gas, carbon dioxide, has a beneficial effect on plant growth. In general, however, the beneficial effect of this carbon fertilisation is not as significant as was originally estimated. Estimating the actual impact of global warming on crops in the field is a more complex task, and must take into account other factors, including changes in precipitation, water balance, soil conditions, nutrient availability and so on. Agronomic crop models, which relate the productivity of specific crops to a variety of inputs and have been calibrated based on conditions of production for specific regions, provide some of the most convincing estimates of the damage that global warming will inflict on agriculture in different parts of the world. The effect of global warming on various crops also significantly depends on the latitude in which the crop is grown. In higher latitudes, increased temperatures of upto about 1.5 deg C may actually provide for increased productivity whereas any increase in temperature lowers productivity in lower latitudes.

The economic impact of climate change on agriculture is much harder to estimate than the biophysical and agronomic impact. There is a significant body of literature that seeks to provide quantitative estimates of the future production of specific crops, and more detailed estimates, such as predicted rates of future prices of agricultural products. All such estimates, based on a variety of techniques, suffer from many uncertainties. The unreliability of the results of such models arises from the inherent uncertainties of making quantitative economic predictions based on econometric models, particularly on account of the wide range of assumptions that are incorporated in different models, and the uncertainties that are still present in modelling future climate regimes.

Special attention needs to be paid to the increased vulnerability of agriculture in less-developed countries to climate change. While all societies are exposed to the risk of climate change, these risks are not uniform. Less-developed countries with low levels of human development, agricultural productivity, industrial capabilities, and infrastructure are at a greater disadvantage than others in dealing with the complex challenges posed by climate change.

At the heart of the question of climate vulnerability is the inability of various socio-economic groups to withstand climate shocks without permanent or long-term losses of well-being. From the perspective of human development, climate-related risks could lead to low human development "traps" – to what has been described as "a one-way downward descent" into further disadvantage.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that climate change has already had an impact on crop phenology (phenology refers to the growth and development of different parts of plants) and associated farm-management practices. The bulk of this evidence comes from developed countries in the temperate zone. There is no significant evidence that climate change has begun significantly to affect total agricultural production and the yields of different crops across the world. Yield gaps for various crops, that is, the gap between the potential yields of crops and the actual yields from farmers' fields, measured both nationally and globally, suggest that agricultural production and yields still have much potential for advance. Whether the corresponding intensification of various crop-management and land-use practices, extrapolating along current trends, will be sustainable without damaging ecosystems remains unclear. Such negative consequences could occur independently of climate change, although it is also possible that they are exacerbated by climate change.

The impact of climate change on Indian agriculture, both in the present as well as in a future of increasing temperatures, appears to be broadly in line with the considerations that we have already described with respect to the global case. Providing more specific predictions of the impact of climate change will require improved regional climate models that accurately model specific features of the sub-continental climate, features such as the monsoon.

There are two interesting cases that indicate that climate change has begun to have some impact on Indian agriculture. The first is the retreat of apple production from lower altitudes to higher altitudes in Himachal Pradesh as a consequence of the decrease in the number of sufficiently cold days in winter. The second is the advance, between the early 1980s and the early 2000s, of the commencement of the breeding season for tank-bred major Indian carp varieties in Eastern India from late

May to mid-April, and a lengthening of the breeding season from 110-120 days to 160-170 days. These shifts have been attributed to increases in both maximum and minimum water temperatures, and increases in precipitation levels. In this case, total production has not yet shown any decrease.

A positive aspect of India's response to climate change and agriculture has been the significant body of research work and results that has been published on the subject (though more research is necessary). These results include studies of the likely impact of climate change on the yields and productivity of several major crops in India, studies of the impact of climate change on water-related parameters such as evaporation, water runoff and soil moisture, and of the impact of climate change on soil productivity, pests and crop diseases.

In conclusion, we re-emphasise what must be one of the foremost social concerns in the study of the impact of climate change, that is, the impact of climate change on the poor of the world, especially the rural poor. Although climate change affects all humanity, it has a disproportionately great impact on the poor. The poor will bear the brunt of climate change, particularly in the less-developed countries, though they have contributed the least to the problem of greenhouse gas emissions. In closing, we can hardly over-emphasise the need to ensure that, in an unequal world, the main burden of dealing with climate change is not placed on the poor.

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Abbreviations

AR4	Fourth Assessment Report of the IPCC
CGE model	Computable General Equilibrium model
CO_2	Carbon Dioxide
GHG	greenhouse gas
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
ISMR	Indian summer monsoon rainfall
NATCOM I	India's Initial National Communication to the United Nations Framework Convention on Climate Change (see Government of India, Ministry of Environment and Forests, 2004)
NDVI	Normalised Differential Vegetation Index
ppm	parts per million
TAR	Third Assessment Report of the IPCC
SAR	Second Assessment Report of the IPCC
FAO	Food and Agriculture Organization
HDR	Human Development Report

Research on Climate Change and Agriculture in India: An Annotated Bibliography of Selected Research Papers

This is a bibliography of selected research publications on climate change and agriculture in India, with summaries of the findings of each publication. The summaries are quotations taken either directly from the source mentioned in the reference, or from the compendium or review cited in the source of each table.

Crop Productivity: Specific Crops

Table A1 *Rice*

Sinha and Swaminathan (1991)

- A 2°C increase in temperature could decrease rice yield by about 0.75 tonne/hectare in high-yield areas and by about 0.06 tonne/hectare in low-yield coastal regions.

Achanta (1993)

- For irrigated yields in Pantnagar district of Uttarakhand under doubled CO_2 levels and increased temperature, the impact on rice production would be positive in the absence of nutrient and water limitations.

Mohandass *et al.* (1995)

- Used the ORYZA1 model to simulate rice yields under current and future climates.
- They predicted increase in rice production mainly because in the main season, crops' enhanced CO_2 levels more than offset the negative effects of increased temperatures.
- Though large decreases were predicted for second-season crops at many of the locations due to high temperatures, the relatively low proportion of total rice produced in this season meant that its overall effect on rice production was small.

Hundal and Kaur (1996)

- In the case of Punjab (using the CERES rice model), with other climate variables held constant, a temperature rise of 1, 2 and 3°C from present-day level would reduce rice yield by 5.4, 7.4 and 25.1 per cent respectively.

Lal *et al.* (1998)

- In northwest India (using the CERES rice model), under a doubling of CO_2 levels, rice yield increased by 15 per cent.
- However, a 2°C rise cancelled out the positive effect of elevated CO_2.
- The combined effect of enhanced CO_2 and temperature increase leads to a 4 per cent increase in rice yield for the irrigation schedule presently practised.
- The adverse impact of water shortage would be a net decline in rice yields.

Saseendran *et al.* (2000)

- For Kerala, an increase in CO_2 concentration led to yield increase of rice and also enhanced water-use efficiency.
- For increasing temperature up to 5℃, there is a continuous decline in rice yield. For every 1℃ rise, the yield fell by about 6 per cent.
- The physiological effect of ambient CO_2 at 2℃ compensated for yield losses at 425 ppm CO_2.

Rathore *et al.* (2001)

- Used the CERES rice model and concluded that by the middle of the 21st century, an increase in rice yield is possible in central and south India under the climate change scenarios projected by Lal *et al.* (1995).
- In north west India, a decrease in yield may take place under irrigated conditions as a result of the significant decrease in rainfall during the monsoon season due to climate change.
- Reduction in crop duration may occur at all locations in the country due to increase in temperature associated with the build-up of atmospheric greenhouse gases.

Aggarwal and Mall (2002)

- Studied the impact of climate change on yields of irrigated rice using CERES-Rice and ORYZAIN models.
- They used two scenarios: an optimistic scenario (a 0.1℃ increase in temperature and 416 ppm CO_2 in 2010, and a 0.4℃ temperature rise and 755 CO_2 in 2070) and a pessimistic scenario (0.3℃ and 397 ppm CO_2 in 2010 and 2.0℃ temperature and 605 ppm CO_2 in 2070).
- The direct effect of climate change on rice crops in different agro-climatic regions in India would always be positive irrespective of various uncertainties.
- Rice yields increased between 10.0 and 16.8 per cent in the pessimistic scenario, depending on the level of management and model used.
- For the optimistic scenario these increases were between 3.5 to 33.8 per cent.
- These conclusions are highly dependent on the specific thresholds of phenology and photosynthesis with respect to the change in temperature used in the models.

Sources: Extracted from Khan, Kumar, Hussain and Kalra (2009), and Mall, Singh, Gupta, Srinivasan and Rathore (2006).

Table A2 *Wheat*

Sinha and Swaminathan (1991)

- A 0.5℃ increase in winter temperature would reduce the duration of wheat crops by seven days and reduce yield by 0.45 tonne/hectare. This translates into a 10 per cent drop in wheat production in the high-yield states of Punjab, Haryana and Uttar Pradesh.

- The reduction was lower in eastern India than in all other regions.
- The mean grain yields of control crops in the eastern region were 7.9 tonnes/hectare, and 8.7–9.9 tonnes/hectare in other regions.

Aggarwal and Sinha (1993)

- At 425 ppm CO_2 and no rise in temperature, wheat yield (potential, irrigated and rainfed) increased significantly.
- In north India, a 1°C rise had no significant effect on potential yields, but irrigated and rainfed yields increased in most places.
- A 2°C rise reduced potential wheat yields at most places, while the effect on irrigated and rainfed productivity varied with location. The natural climatic variability also had considerable effect on the magnitude of response to climate change. Evapotranspiration was reduced in irrigation as well as rainfed environments.

Rao and Sinha (1994)

- In all climate simulations (using GISS, GFDL, UKMO and transient GISS models), wheat yields were smaller than those in the current climate, even with the direct beneficial effects of CO_2 on crop yield considered.
- Yield reductions were due primarily to a shortening of the wheat-growing season resulting from the temperature increases.

Hundal and Kaur (1996)

- In the case of Punjab (using the CERES wheat model), with other climate variables held constant, a temperature rise of 1, 2 and 3°C from the present-day level would reduce wheat yield by 8.1, 18.7 and 25.7 per cent respectively.

Lal *et al.* (1998)

- In northwest India (using the CERES wheat model), under a doubling of CO_2 levels, wheat yields increased by 28 per cent.
- However, a 3°C temperature rise cancelled out the positive effect of elevated CO_2.
- The combined effect of enhanced CO_2 and temperature increase led to a 21 per cent increase in wheat yields for the irrigation schedule presently practised.
- The adverse impact of water shortage would be minimised to a certain extent under elevated CO_2 levels.

Attri and Rathore (2003)

- Used CERES wheat dynamic simulation model and climate change scenarios to find an increase in wheat yield between 29–37 per cent and 16–28 per cent under rainfed and irrigated conditions, especially in different genotypes under a modified climate.
- A 3°C increase in temperature or more cancelled out the positive effects of enhanced CO_2.

Government of India, Ministry of Environment and Forests (2004), NATCOM I

- Impact assessment of climate change for regional wheat production using crop models indicate that no significant effect on wheat production should be expected due to climate change up to 2010.
- Only in climate scenarios beyond 2020, and without any new technological interventions and adaptation mechanisms, was a reduction in wheat production noticed.

Aggarwal (ed.) (2009)

- Simulation results indicate that with simple adaptation, a 1°C increase and associated CO_2 increase would not cause any significant loss to wheat production in India.
- Benefits of adaptation gradually decrease as temperatures increase to 5°C.
- In the absence of adaptation and CO_2 fertilisation benefits, a 1°C increase alone could lead to a loss of 6 million tonnes in India as a whole in annual wheat production (with respect to current production). This loss is likely to increase to 27.5 million tonnes at 5°C increase.
- Increase in CO_2 to 450 ppm is likely to reduce these losses by 4 to 5 million tonnes at all temperatures.
- Climate change is also likely to reduce the wheat yield gap, since both potential yields and current yields are likely to reduce with time even after taking into account improvement in crop management.
- Potential yields are likely to decrease much more than current yields, leading to a reduction in the yield gap.
- Considering the slow process of bridging yield gaps and the costs involved in creating an appropriate environment for this, it can be concluded that global warming will constrain the progress in increasing wheat production in future, unless some new technologies are introduced.

Sources: Extracted from Khan, Kumar, Hussain and Kalra (2009); Mall, Singh, Gupta, Srinivasan and Rathore (2006); Aggarwal (2009); and Government of India, Ministry of Environment and Forests (2004), NATCOM I.

Table A3 *Groundnut*

Gadgil (1995) and Gadgil *et al.* (1999a, 1999b)

- Used PNUTGRO model and showed that for rainfed groundnut, the sowing period of 22 June to 17 August is optimum for minimising the risk of failure.
- The incidence of locally triggered pests/diseases (leaf miner and late leaf spot) is low when sowing is postponed to after mid-July.

Hundal and Kaur (1996)

- In the case of Punjab (using the PNUTGRO model), with other climate variables held constant, a temperature rise of 1, 2 and 3°C from present-day level would reduce groundnut yields by 8.7, 23.2 and 36.2 per cent respectively.

Government of India, Ministry of Environment and Forests (2004), NATCOM I

- Simulation results for rainfed groundnut indicated that yields would increase under doubled CO_2 levels and temperature would increase up to 3°C if rainfall did not decline. Reduction of rainfall by 10 per cent reduced the yield by 12.4 per cent.

Sources: Extracted from Khan, Kumar, Hussain and Kalra (2009); Mall, Singh, Gupta, Srinivasan and Rathore (2006); and Government of India, Ministry of Environment and Forests (2004), NATCOM I.

Table A4 *Soybean*

Lal *et al.* (1999)

- Using the CROPGRO soybean model, they projected a 50 per cent increase in soybean yield in response to a doubling of CO_2 levels in central India. However, a 3°C increase in temperature almost negates the positive effects of doubling CO_2 concentration.
- A 10 per cent decline in daily rainfall restricts grain yield to about 32 per cent.

Mall *et al.* (2004)

- Used the CROPGRO soybean model and three GCM climate scenarios: GISS-2, GFDL-R30, UKMO–HadCM3.
- Showed that all climate scenarios (at the time of doubling of CO_2 concentrations) predicted decreased yields for almost all locations.
- Mean decline in yields across different scenarios ranged from 14 per cent in Pune (western India) to 23 per cent in Gwalior (central India).
- Decline in soybean yield was found to be less in west and south India than in other parts of the country.
- The mean yield was found to be significantly affected under UKMO model-generated climate scenarios for both current and doubled levels of CO_2 in the atmosphere.

Government of India, Ministry of Environment and Forests (2004), NATCOM I

- Using a crop model, the response of soybean at a few places in Madhya Pradesh showed that an increase of 3°C in temperature nullified the positive effect of doubled CO_2 on yield. The magnitude of the beneficial effect of elevated CO_2 was also seen to be significantly reduced under water stress conditions.

Sources: Extracted from Khan, Kumar, Hussain and Kalra (2009); Mall, Singh, Gupta, Srinivasan and Rathore (2006); and Government of India, Ministry of Environment and Forests (2004), NATCOM I.

Table A5 *Maize*

Hundal and Kaur (1996)

- In the case of Punjab (using the CERES maize model), with other climate variables held constant, a temperature rise of 1, 2 and 3°C from present-day level would reduce maize yield by 10.4, 14.6 and 21.4 per cent respectively.

Sahoo (1999)

- Temperature rise decreased maize yield under both irrigated and rainfed conditions.
- For CO_2 concentration of 350 ppm, maize yield decreased continuously till 4°C.
- At 700 ppm CO_2, grain yield increased by about 9 per cent.
- The effect of elevated CO_2 concentration on the growth and yield of maize was established, but found to be less pronounced than the effect on wheat, chickpea and mustard crops.
- The beneficial effect of 700 ppm CO_2 was cancelled by an increase of only 0.6°C.

Sources: Extracted from Khan, Kumar, Hussain and Kalra (2009), and Mall, Singh, Gupta, Srinivasan and Rathore (2006).

Table A6 *Sorghum*

Rao *et al.* (1995)

- Used the CERES sorghum model and climate change scenarios generated by the three GCMs: GISS, GFDL and Met Office, UK.
- Results indicated a decrease in the yield and biomass of rainy-season sorghum at Hyderabad and Akola under all climate change scenarios.
- Post-rainy-season sorghum grown at Solapur on stored soil water showed a marginal increase in yield. The positive effects of increased CO_2, if any, were masked by the adverse effects of predicted increase in temperature resulting in shortened crop-growing seasons.
- The study also showed that the effects of climate change on the same crop would depend upon the season in which it is grown.

Chatterjee (1998)

- For a 1 and 2°C rise in, sorghum yields decreased by 7–12 per cent on average. A further increase in temperature drastically reduced the potential yields by 18–24 per cent on average.
- An increase in 50 ppm CO_2 increased yields by only 0.5 per cent.
- The beneficial effect of 700 ppm CO_2 was cancelled out by a temperature rise of 0.9°C.

Sources: Extracted from Khan, Kumar, Hussain and Kalra (2009), and Mall, Singh, Gupta, Srinivasan and Rathore (2006).

Table A7 *Chickpea*

Mandal (1998)

- Showed that using the CROPGRO chickpea model, a temperature increase of up to 2°C did not influence potential and irrigated yields of chickpea.
- Pre-anthesis and total crop duration got reduced with temperature rise. Nitrogen uptake and total water use were not significantly different up to 2°C.

- The elevated CO_2 levels increased grain yield under potential, irrigated and rainfed conditions.
- A linear increase in grain yield as CO_2 concentration increased from 350 to 700 ppm.

Source: Extracted from Mall, Singh, Gupta, Srinivasan and Rathore (2006).

Table A8 *Pigeonpea*

Mandal (1998)

- Potential grain yield decreased when temperature increased by 1°C (using WOFOST).

Source: Extracted from Mall, Singh, Gupta, Srinivasan and Rathore (2006).

Table A9 *Brassica (Oilseed)*

Uprety *et al.* (1996)

- Concluded that with the type of climate we have in the northern belt of the Indian subcontinent (i.e. variation in temperatures and CO_2 concentration), production is likely to increase and to shift to relatively drier regions, compared to where it is grown presently.

Source: Extracted from Mall, Singh, Gupta, Srinivasan and Rathore (2006).

General Results

Table A10 *Results from Government of India, Ministry of Environment and Forests (2004), NATCOM I*

- Most of the simulation studies have shown a decrease in the duration and yield of crops as temperature increased in different parts of India. These reductions were, however, generally offset by the increase in CO_2.
- Rice and wheat yields decreased as temperature increased; a 2°C increase resulted in 15–17 per cent decrease in the grain yield of both crops, but beyond that the decrease was very high in wheat.
- These decreases were compensated by an increase in CO_2 level. Atmospheric CO_2 concentration has to rise to 450 ppm to nullify the negative effect of a 1°C increase in temperature, and to 550 ppm to nullify a 2°C increase in temperature.
- If CO_2 stabilises early and the temperature continues to rise for a longer time, Indian agriculture could suffer significantly in the long term.
- The rice–wheat productivity in north western India may already be showing signs of stagnation or decline.
- A crop simulation study with weather as the only varying factor showed a similar trend.

- A significant part of this yield decline/stagnation trend could be ascribed to rising temperatures during the crop season.
- These changes are not statistically significant, but do indicate the possible effects on crop production of a warming trend.
- Simulation studies done at different levels of nitrogen management indicate that crop response could vary depending upon the nitrogen management and the climate change scenario. In future, much higher levels of fertiliser may be needed to meet the increasing demand for food.
- There is a high probability of significant effects of increased climate change on short-season crops (vegetables and fruits) if changes occur during critical periods in growth.
- In hilly regions, global warming is likely to prolong the growing season and this could result in potentially higher crop yields, provided water remains available.
- The positive perspectives for total biomass production, however, may not always ensure higher economic yields, since many temperate crops also need a minimum chilling period to stimulate better flowering.
- Global warming will push the snow line higher and dense vegetation will shift upwards. This shift will be selective and species-specific, due to the differential response of plants to changing environmental conditions.
- An increase in temperature may have significant effect on the quality of cotton, fruits, vegetables, tea, coffee, aromatic and medicinal plants.
- The nutritional quality of cereals and pulses may also be moderately affected, which, in turn, will have consequences for our nutritional security. Research has indeed shown that the decline in grain protein content in cereals could partly be related to increasing CO_2 concentrations.

Source: Government of India, Ministry of Environment and Forests (2004), NATCOM I.

Table A11 *Results from Aggarwal (2009)*

- Climate change is likely to reduce cereal yields significantly in Tamil Nadu.
- A simulation study showed kharif rice to be more vulnerable to climate change than maize and sorghum.
- The mean reduction in rice production was 6.7, 15.1 and 28.2 per cent by 2020, 2050 and 2080 respectively. For the same time-periods, reductions in maize and sorghum yields were 3.0, 9.3 and 18.3 per cent, and 4.5, 11.2 and 18.7 per cent respectively, if no new management interventions are made.
- Cross-sectional analysis indicates negative impact on the area and productivity of major crops in Tamil Nadu due to past changes in rainfall and temperature.
- The analysis further suggests a reduction in both area and yields of major crops, by 3.5 to 12.5 per cent, in Tamil Nadu due to climate change by 2050. Consequently, overall production is likely to decrease by 9–22 per cent.
- The overall impact, however, is likely to be somewhat smaller due to non-consideration of the CO_2 fertilisation effect in the cross-sectional analysis.

- Simulation experiments (using a dynamic coconut simulation) showed that coconut yields are likely to increase by 4 per cent, 10 per cent and 20 per cent by 2020, 2050 and 2080 respectively, due to a positive impact of climate change in the western coastal areas of Kerala, Maharashtra, Tamil Nadu and Karnataka, and a negative impact in the eastern coastal areas of Andhra Pradesh, Orissa, Gujarat, Tamil Nadu and Karnataka.
- Studies using free-air CO_2 enrichment rings (FACE) as well as Open-Top Chambers indicate that increase in CO_2 concentration is likely to enhance the growth and yields of several field crops in future.
- The increase in yield at 550 ppm was 9 to 15 per cent in mungbean, soybean and chickpea, 24 per cent in tomato, 26 per cent in onion, and 35 per cent in castor (FACE studies).
- Field experiments showed that high temperature around the time of flowering reduced fertility of the pollen grains as well as pollen germination on stigma in both rice and wheat crops.
- These effects were relatively more pronounced in basmati cultivars of rice.
- Durum wheat cultivars were more sensitive to temperature increase than were aestivum cultivars.
- Field experiments in Temperature Gradient Tunnels showed that an increase from 1–4°C reduced the grain yield of rice (0–49 per cent), potato (5–40 per cent), green gram (13–30 per cent) and soybean (11–36 per cent).
- The linear decrease per 1°C temperature increase was 14 per cent, 9.5 per cent, 8.8 per cent, 7.3 per cent and 7.2 per cent in rice, potato, soybean, wheat and greengram respectively.
- Chickpea, however, registered a 7 to 25 per cent increase in seed yield by an increase in temperature up to 3°C, but was reduced by 13 per cent at 4°C increase in temperature.
- Rice showed no significant change in yield up to an increase of 1°C.
- A significant decrease has been observed in the average productivity of apples in Kullu and Shimla districts of Himachal Pradesh in recent times. A key reason for this could be a trend of inadequate chilling, crucial for good apple yields. As a consequence, there has been a shift of the apple belt to the higher elevations of Lahaul-Spiti and upper reaches of Kinnaur district.
- Increase in temperatures during the grain development phase of rice and wheat affect their grain quality.
- High temperatures reduced 1000-grain weight and amylose content, and adversely affected important quality traits, that is, grain elongation and aroma, in basmati cultivars.
- In wheat, high temperatures reduced both 1000-grain weight and hectolitre weight, and increased grain protein content. The impact was more pronounced on bread wheat than durum wheat cultivars.

Source: Aggarwal (2009).

Table A12 *Miscellaneous Results: National and Regional*

Lal and Chander (1993)

Indian subcontinent:

- Increase in monsoonal and annual runoff in the central plains
- No substantial change in winter runoff.
- Increase in evaporation and soil wetness during the monsoon and on an annual basis.

IPCC (1992)

Orissa and West Bengal:

- One-metre sea level rise would inundate 1,700 sq. km. of prime agricultural land.

Mall, Bhatla and Pandey (2007)

Indian coastline:

- One-metre sea level rise on the Indian coastline is likely to affect a total area of 5,763 sq. km., and put 7.1 million people at risk.

Chattopadhyay and Hulme (1997)

India:

- Using GCM climate simulation, found increases in potential evaporation that were related largely to increases in the vapour pressure deficit resulting from higher temperature.

Mehrotra (1999)

Central India:

- Basin located in a comparatively dry region is more sensitive than others to climatic changes.

Sharma *et al.* (2000a, 2000b)

Kosi Basin:

- Found runoff increase was higher than precipitation increase in all the potential climate change scenarios applying contemporary temperature.
- Contemporary precipitation and a rise in temperature of 4℃ caused a decrease in runoff by 2–8 per cent, depending upon the areas considered and model used.

Lal and Singh (2001)

Southern and central India:

- Soil moisture increased marginally by 15–20 per cent in monsoon months.
- The rest of the year, there was either no change in soil moisture or a marginal decline possibly due to the increase in temperature leading to enhanced evapotranspiration.

Roy *et al*. (2003)

Damodar basin:

- Decreased river flow.
- Projected an increase of 14.8 per cent of total evapotranspiration demand with increase in temperature.

Goyal (2004)

Rajasthan:

- Evapotranspiration is less sensitive to increase in solar radiation, followed by wind speed, than to temperature.
- Increase in water vapour has a negative impact on evapotranspiration (−4.3 per cent).

Gosain, Rao and Basuroy (2006)

River basins in north west and central India:

- Increase in heaviest rainfall and reduction in number of rainy days.

Source: (a) Mall, Gupta and Kumar (2010).

Table A13 *Miscellaneous Results II*

Government of India, Ministry of Environment and Forests (2004), NATCOM I

River basins across the country:

- *Runoff*: Though an increase in precipitation is projected for the Mahanadi, Brahmani, Ganga, Godavari and Cauvery basins for the climate scenario (using HadRM2), the corresponding total runoff for all these basins does not necessarily increase.
- For the remaining basins, a decrease in precipitation is projected. The resultant total runoff for the majority of the cases, except for the Narmada and Tapi, is projected to decline.
- *Droughts and floods*: Severity of droughts and intensity of floods in various parts of India are projected to increase in the climate scenario (HadRM2).
- Luni is likely to experience acute physical water scarcity conditions.
- The river basins of Mahi, Pennar, Sabarmati and Tapi are likely to experience constant water scarcities and shortage.
- The Cauvery, Ganga, Narmada and Krishna river basins are likely to experience seasonal or regular water-stressed conditions.
- The river basins of the Godavari, Brahmani and Mahanadi are projected to experience water shortages only in a few locations.

Aggarwal (2009)

Brahmani basin:

- An increase of 26, 28, and 53 per cent in annual streamflow was projected by 2080 under HadCM3 A2a, HadCM3 B2a and PRECIS scenarios.

- Though all the scenarios indicated likely increase in annual stream flow in the Brahmani basin, a decrease in stream flow is projected during winter and summer (June) in most cases.

Sources: Aggarwal (2009); and Government of India, Ministry of Environment and Forests (2004), NATCOM I.

Productivity and Erosion

Table A14 *Soil Productivity*

Results based on recent research work done at the Indian Council of Agricultural Research (Aggarwal 2009)

- Increase in temperature could result in higher mineralisation and CO_2 emissions from the soil.
- Experimental studies on soil warming indicated that small incremental increase in temperature results in high CO_2 emissions in low carbon soil, when compared with medium and high carbon soil, thereby making low carbon soil more vulnerable to warming.
- Greater availability of nutrients because of increased mineralisation of soil organic matter led to increased abundance of gram-positive bacteria.

Results from NATCOM I (Ministry of Environment and Forests, Government of India 2004)

- Increased temperature coupled with reduced rainfall may lead to upward water movement, leading to accumulation of salts in upper soil layers.
- A rise in sea level due to increased temperature may lead to salt-water ingression in the coastal lands, making them unsuitable for conventional agriculture.
- Organic matter content (already quite low in most parts of India) will continue to remain low, but climate change through temperature and precipitation-mediated processes may affect its quality.
- An increase of 1°C in the soil temperature may lead to higher mineralisation, but nitrogen availability for crop growth may still decrease due to increased gaseous losses.
- Biological nitrogen fixation under elevated CO_2 may show an increase, provided other nutrients are not strongly limiting.

Table A15 *Runoff and Soil Erosion*

Government of India, Ministry of Environment and Forests (2004), NATCOM I

- Changes in rainfall amount and frequency, and wind, may alter the severity, frequent and extent of soil erosion. These changes may further compound the direct effects of temperature and CO_2 on crop growth and yield.

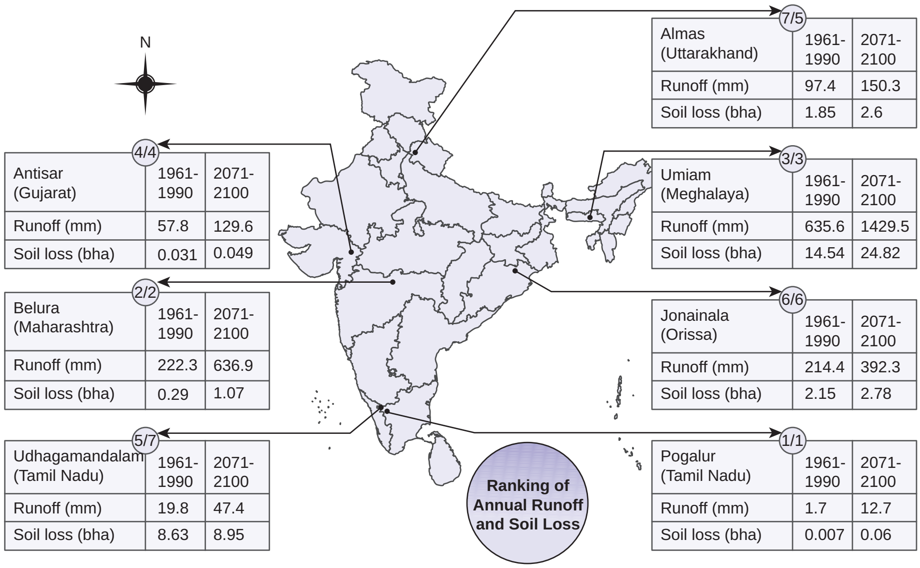

Figure A1 *Annual runoff and soil loss during 1961–90 and 2071–2100 from different agro-ecological regions of the country*

Notes: (i) mm = millimetres; (ii) t/ha = tonnes/hectare.

Source: Reproduced from Sharda and Tripathi (2010), p. 93.

Aggarwal (2009)

- Runoff and soil loss are expected to increase significantly throughout the different agro-climatic regions in India due to global climate change.

Sharda and Tripathi (2010)

- Their predictions for the annual runoff and soil loss for seven watersheds in India are in Figure A1.

Pests and Crop Disease

Impact on Pests Due to Changes in Temperature, Rainfall and Relative Humidity

Table A16 *Studies of impact on pests due to increased temperature*

Dury *et al.* (1998)

O. brumata insects:

- Increased temperature influenced the larval development and fecundity of these insects.

Williams *et al.* (2003)

O. brumata insects:

- Long-term exposure to increase in temperature of 3.5°C shortened the insect development.

Veteli *et al.* (2002)

Chrysomelid beetles:

- Temperature enhancement increased the relative growth rate of these beetles.

Government of India, Ministry of Environment and Forests (2004), NATCOM I

Aphid:

- Cloudy weather with sufficient relative humidity favours the occurrence of aphids. Under most favourable conditions, a population density of a 1,000 million per hectare in wheat fields has been reported.

Aggarwal (2009)

Leptocorisa acuta or rice gundhi bug:

- A mechanistic population dynamics simulation model showed that a 1°C rise in daily average temperature of Delhi would not affect the gundhi bug population but further increase would cause appreciable decline in it.

Source: Rao, Rao and Venkateswarlu (2010).

Table A17 *Impact of increased temperature on insects: some general results*

Dewer and Watt (1992)

- Under climate change scenarios, increased asynchrony between host plant and insect herbivore, with obvious adverse consequences.

Pollard and Yates (1993)

- Higher temperatures, keeping all other variables equal, allow faster development of insects and may allow for additional generations of insects within a year.

Gaston and Williams (1996)

- Climatic warming will allow the majority of "temperate" insect species to extend their ranges to higher latitudes and altitudes.

Parmesan *et al.* (1999)

- Certain insect species will expand their geographic ranges to higher latitudes and altitudes, as has already been observed in a number of common butterfly species.

Williams *et al.* (2000)

- Elevated temperature is known to alter the phyto-chemistry of host plants, and to affect insect growth and development directly or indirectly through effect on host plants.

Bale *et al.* (2002)

- Diversity of insect herbivores and the intensity of herbivory increases with rising temperatures at constant latitude. Individuals may develop faster at higher temperatures and survival may even be enhanced, but these insects may consequently have lower adult weight and fecundity.

Source: Rao, Rao and Venkateswarlu (2010).

Table A18 *Effect of Elevated CO_2 on Insect Population*

Generally, the impact of CO_2 on insects is observed to be "indirect", i.e. increased CO_2 will alter the quantity and quality of plant foliage, which in turn can influence the growth and development of insect herbivores.

Rao, Rao and Venkateswarlu (2010)

Findings for two caterpillars: *Achaea janata* or the castor (castor oil) semilooper, and *Spodoptera litura* or the tobacco caterpillar.

- Larval duration (time from hatching to pupation in larvae) of both the species was significantly influenced by the CO_2 condition under which leaves offered to them were produced. Larval duration for both larvae was extended by about two days when fed with elevated CO_2 foliage.
- Larvae ingested significantly higher quantity of elevated CO_2 foliage compared to ambient CO_2 foliage. For instance, *A. janata* consumed 62.6 per cent more of 700 CO_2 foliage than 350 CO_2 chamber foliage.
- The rate of consumption was also higher in the case of elevated CO_2 foliage. Larvae fed with elevated CO_2 foliage consumed more each day and over a longer period.
- Larval growth rates were significantly lower with elevated CO_2 foliage in the case of *A. janata*, while in the case of *S. litura*, the differences were not significant.
- The efficiency with which ingested food was converted into body mass was lower with elevated CO_2 foliage in the case of *A. janata*, but in S. litura, there were no significant differences.
- The efficiency of conversion of digested food into body mass was lower with elevated CO_2 foliage for both species of larvae.
- The digestibility of elevated CO_2 foliage was significantly higher than ambient CO_2 foliage for both the species, more so in the case of *S. litura.*
- The daily growth rates of *S. litura* were considerably lower with elevated CO_2 foliage .While the daily growth rate was 30.99 per cent with 350 CO_2 foliage, it was just 18.53 per cent with 550 CO_2 foliage. In *A. janata* also, the daily growth rates were markedly lower with elevated CO_2.
- Leaf consumption and larval weights were positively and significantly correlated with leaf carbon, polyphenols and C:N ratio, and negatively (−0.804 to −0.834) with leaf nitrogen content.

Table A19 *Impact of elevated CO_2 on natural enemies of pests*

Roth and Lindroth (1995)

- Dietary differences that prolong developmental time, increase food consumption and reduce growth by insect herbivores serve to increase the susceptibility of these herbivores to natural enemies.

Chen *et al.* (2005)

- Showed that increasing CO_2 concentrations could alter the preference of lady beetle to aphid prey and enhance the biological control of aphids by lady beetle in cotton crop.

Source: Rao, Rao and Venkateswarlu (2010).

Table A20 *Climate effects on crop disease*

Government of India, Ministry of Environment and Forests (2004), NATCOM I

Yellow Rust:

- At 16°C, the length of the latent period is small for yellow rust. Above 18°C, this latent period increases, but that of yellow and stem rusts decreases.

Black Rust:

- The appearance of black rust in northern India in the 1960s and 1970s was related to the temperature-dependent movement of spores from southern to northern India.

Source: Government of India, Ministry of Environment and Forests (2004), NATCOM I.

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