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Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation

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Abstract

The Indo-Gangetic plain (IGP; including regions of Pakistan, India, Nepal, and Bangladesh) is generally characterised by fertile soils, favourable climate and an abundant supply of water. Nevertheless, the challenge of increasing food production in the IGP in line with demand grows ever greater; any perturbation in agriculture will considerably affect the food systems of the region and increase the vulnerability of the resource-poor population. Increasing regional production is already complicated by increasing competition for land resources by non-agricultural sectors and by the deterioration of agri-environments and water resources. Global environmental change (GEC), especially changes in climate mean values and variability, will further complicate the agricultural situation and will therefore, have serious implications for food systems of the region. Strategies to reduce the vulnerability of the region's food systems to GEC need to be based on a combination of technical and policy options, and developed in recognition of the concurrent changes in socioeconomic stresses. Adaptation options need to be assessed with regard to their socioeconomic and environmental efficacy, but a greater understanding of the interactions of food systems with GEC is needed to be able to do this with confidence. This paper discusses information needs relating to resource management and policy support to guide the development of research planning for increasing the robustness of IGP food systems to GEC. Further information is needed to develop a range of adaptation strategies including augmenting production and its sustainability, increasing income from agricultural enterprises, diversification from rice–wheat systems, improving land use and natural resource management, and instigating more flexible policies and institutions.

Keywords: Indo-Gangetic plain; GEC; Food systems; Adaptation

1. Food supply in the Indo-Gangetic plain and global environmental change

The demand for food worldwide has increased dramatically over the last 50 years due to the increase in population and wealth. In many regions the supply of food has generally kept pace with the increase in demand, largely due to the introduction of irrigation, the use of synthetic nitrogen fertilizers, and the availability of dwarf wheat and rice varieties in the 1960s and 1970s, the 'Green Revolution' technologies. This transformation was especially successful where agricultural infrastructure was in place, environmental conditions were favourable and support of government policies was available (Swaminathan, 1982). For example, the average cereal production in South Asia increased from 147 Mt in the triennium ending 1980–1981 to 239 Mt in the triennium ending 1999–2000 largely due to productivity increase. Cereal production in South Asia exceeded demand in the latter triennium, yet acute poverty and malnourishment persisted due to low purchasing power (FAO, 2002). Much of this increase in production was within the Indo-Gangetic plain (IGP), an area of land covering large areas of Pakistan, India, Nepal, and Bangladesh. However, projections indicate that South Asia would be deficient in cereal production by about 22 Mt by 2030 (FAO, 2002).

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The IGP is now the 'bread basket' for much of South Asia. Rice and wheat, the major cereal crops of this region are grown in rotation on almost 12 Mha of land. Together they are the principal source of food and livelihood security for several hundred millions of people in this densely populated region (Paroda et al., 1994). Assuming a medium growth scenario this population is predicated to increase by a further 700 million people (about equal to the current population of Europe) in the next 30 years. This will result in a greater demand for food and it is estimated that the food grain requirement by 2020 in the region will be almost 50% more than at present (Paroda and Kumar, 2000; Table 1). It is anticipated that the IGP will have to meet much of this increased demand, but the additional quantities will have to be produced from the same land resource, or less, due to the increase in competition for land and other resources by non-agricultural sectors.

South Asian countries are amongst the most prone areas of the world to degradation of natural resources due to intensive human activities in the region. There is already evidence of gradual deterioration in natural resources, particularly in areas that benefited from the Green Revolution technologies. The introduction of canal irrigation in India has resulted in almost 7 Mha of cultivated land becoming effected by soil salinity and water logging (Joshi and Tyagi, 1994), while the rapid increase in the number of tubewells during the last three decades in north-western India, eastern Pakistan and other regions has resulted in overexploitation of groundwater, leading to a rapid fall in water-tables. There is now growing concern about the decline in soil fertility, changes in water-table depth, deterioration in the quality of irrigation water and rising salinity. The consequence of these changes for food supply is compounded by factors such as increasing resistance to many pesticides (Sinha et al., 1998).

The situation will be further complicated by global environmental change (GEC). GEC includes changes in the biophysical environment caused or strongly influenced by human activities. Principal concerns are changes in land cover, atmospheric composition, climate and climate variability, water availability and quality, nitrogen availability and cycling, biodiversity, and sea level. Broadly, these are reflected as (i) changes in natural resource base and (ii) climatic changes (Fig. 1), many of which directly affect agriculture and hence food provision.

Table 1
Projected demand for food in South Asia for 2010 and 2020 assuming a 5% GDP growth and constant prices (Paroda and Kumar, 2000)

Items	Production (Mt)	Demand for food (Mt)	
	1999–2000	2010	2020
Rice	85.4	103.6	122.1
Wheat	71.0	85.8	102.8
Coarse grains	29.9	34.9	40.9
Total cereals	184.7	224.3	265.8
Pulses	16.1	21.4	27.8
Food grains	200.8	245.7	293.6
Fruits	41.1	56.3	77.0
Vegetables	84.5	112.7	149.7
Milk	75.3	103.7	142.7
Meat and eggs	3.7	5.4	7.8
Marine products	5.7	8.2	11.8

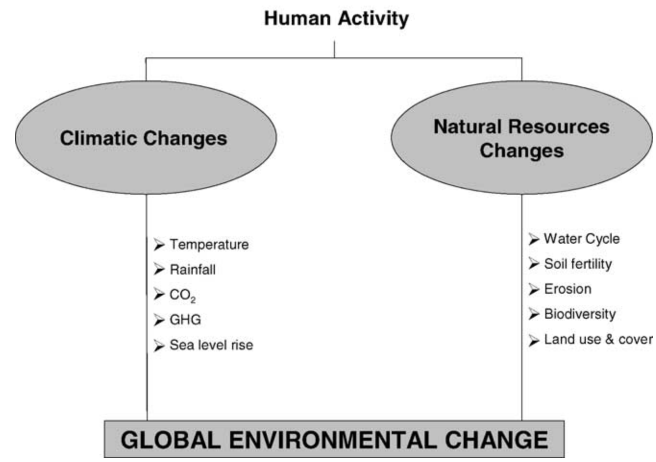

Fig. 1. Major drivers of global environmental change related to human activity.

Climate change is a particular environmental concern for the region, as there are numerous direct and indirect links to agricultural production. The inter-governmental panel on climate change has projected that the global mean surface temperature will rise by 1.4–5.8 °C by 2100 (IPCC, 2001). Climate variability is also projected to increase, leading to uncertain onsets of monsoons and more frequent extremes of weather, such as more severe droughts and floods.

South Asia is expected to be particularly vulnerable to GEC due to its large population, predominance in agriculture and its limited resource base. There is, therefore, now serious concern regarding the vulnerability of food systems in the IGP and the development of robust adapting strategies are high on the political agenda.

Although India and Bangladesh have achieved food self-sufficiency at national level, food provision at sub-regional levels is still sub-optimal and remains a major challenge for the region in the coming decades. Producing enough food for the increasing demand against the background of reducing resources in adverse GEC scenarios, while also minimising further environmental degradation will be a challenging task. Further, it is believed that the future food situation worldwide will be strongly dominated by the changes that occur in Asia because of its large population, developing economies and changes in diet and associated demand for food (Rabbinge, 1999).

2. Information needs for improving policy formulation in the IGP

It is important to identify the key information needs to help improve policy formulation from the perspective of

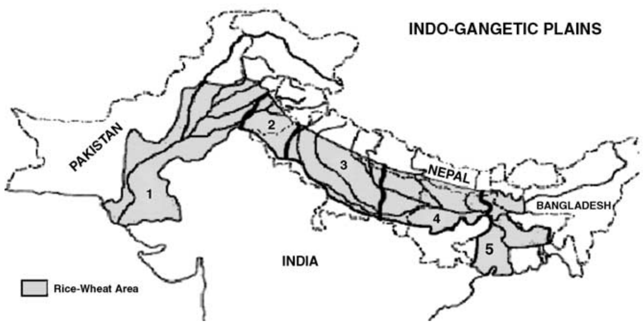

Fig. 2. Generalized map of the Indo-Gangetic plains indicating homogenous regions along the transect. (1) Trans-Gangetic plain (in Pakistan); (2) Trans-Gangetic plain (in India); (3) Upper-Gangetic plain; (4) Middle-Gangetic plain; and (5) Lower Gangetic plain (Gupta et al., 2001).

various stakeholders such as farmers, policy makers and their technical advisors, the scientific community, traders, industrialists and donors. It is also important to understand and take account of the variability in both environmental and socioeconomic parameters across the IGP. Five major regions are recognised (Fig. 2). Based on the biophysical and socioeconomic characterisation and considering the overlap in information needs along the transect of the IGP, this paper further groups these into two major categories: western (consisting of regions 1, 2, and 3 in Fig. 2), and eastern (consisting of regions 4 and 5).

The western region of the IGP is characterised by high investment in infrastructure and institutions and effective policy support, intensive agriculture (using higher inputs of agrochemicals and ground-water for irrigation), surplus food production responsible for regional food security, and seasonal in-migration of male labour. In contrast the eastern region has relatively low productivity, compounded by poor infrastructure and limited capacity for private investment, and is prone to flooding and drought. It is a food deficit region with widespread poverty, hunger and malnutrition, and has out-migration of male labour to other regions. Information needs in relation to research, resource management and policy support vary for the western and eastern IGP.

A series of major issues needing urgent attention by researchers, planners and donors were ascertained by reviewing scientific and policy documents, and by interviewing a large number of farmers, regional and federal planners, environmental officials, donors, and policy makers. Three fundamental questions summarise concerns on the implications of GEC for the food systems of the IGP region as a whole:

- How would food provision and vulnerability in different IGP sub-regions and among different social groups be affected?
- What would be the coping strategies by different sections and different categories of producers against the background of changing demand due to globalisation, population increase, and income growth?
- What would be the socioeconomic and environmental consequences of such adaptations in different sub-regions?

Three planning workshops were organised during 2001–2002 to discuss these general questions with major regional stakeholders in the context of the issues raised during the document reviews and interviews (GECAFS, 2003). The issue of food provision for the growing regional population in the contexts of both changing socioeconomic and biophysical environments is a central issue in regional planning and the workshops derived a series of major research questions. These are summarised in Table 2.

Answering the questions listed in Table 2 will help to formulate integrated development plans to maximise food production, minimise environmental degradation and attain socioeconomic goals in a changing global environment. New information and interdisciplinary tools are, however, needed to understand the complex interactions between changes in environmental and socioeconomic conditions, agricultural land use, food provision, and societal well-being. Such advances will help: (i) to understand the vulnerability of food systems in the IGP to GEC, (ii) to devise adaptations needed for ensuring sustainable agricultural development and food provision at different scales, and (iii) to quantify the socioeconomic and environmental consequences of possible adaptation options.

3. Changes in the natural resource base of the IGP

Consideration of the major information needs for ensuring food provision in these two contrasting regions of the IGP starts with a consideration of the state of the natural resource base and its vulnerability to current practice.

3.1. Soil

Soil fertility declines are well recorded for the region. Numerous long-term experiments have shown a declining trend in productivity even with the application of N, P, and K fertilizers, and the use of modern intensive farming (Nambiar and Abrol, 1989; Sinha et al., 1998). It is clear that over time more nutrients have been removed than added through fertilizers, and farmers have to apply more fertilizers to get the same yield, they were getting with less fertilizer 20–30 years ago. Even micro-nutrient deficiencies started appearing in the IGP with the adoption and spread of intensive agriculture (Nayyar et al., 2001). Among other factors, zinc deficiency has become most widespread in the entire IGP region.

Soil salinity and water logging already affects large parts of the IGP in India and Pakistan and to some extent in

Table 2
Key questions relating to major information needs of the IGP regarding vulnerability and impacts, adaptations, and feedbacks in the context of GEC research, as identified by various stakeholders (GECAFS, 2003)

	Western IGP	Eastern IGP
Vulnerability and impacts	How will GEC (especially climatic variability) and increasing non-farm demands affect change in water supply and demand and consequent food system vulnerability?	How will GEC affect vulnerability of resource-poor farmers to flooding and drought, and how will this exacerbate existing socioeconomic inequities?
Adaptations	How can changes in water management (e.g. through enhanced policy instruments, land-use strategies and community participation) and energy-efficient technologies reduce vulnerability of food systems to climate variability and other aspects of GEC?	What early warning systems of environmental change and its potential impacts would assist stakeholders to identify regions and communities of potentially greater insecurity?
	How can increasing urban and agricultural wastes and water of inferior quantity be utilised in agriculture to adapt to reduced land and water availability?	What investment policies (e.g. insurance) would encourage farmers and society to adopt available technological options to reduce vulnerability to GEC?
	Where, what forms and how much additional public and private investment would be needed to increase on-farm income, maintain water balance and diversify from rice–wheat system?	What infrastructure, market opportunities and technical options need to be developed for diversifying crops (e.g. to aquaculture) to make more effective use of flood and groundwater, and what are the social constraints (e.g. food preferences) to their adoption?
	How can policies and institutional arrangements best be adapted to promote adoption of existing technology options to enhance production in the face of GEC while conserving natural resources?	What policy interventions are needed to reduce the number of hungry and/or undernourished people (especially women and children) considering that food production systems may become even more risk-prone?
		What new institutional mechanisms in research and extension (e.g. involvement of NGOs and private sector) would facilitate generating, adapting, disseminating and utilising knowledge in managing increased risks due to GEC?
Socioeconomic and environmental consequences	What will be the consequences of alternative approaches to water management and resource-conservation strategies on rural livelihoods, intra-regional trade, carbon sequestration and GHG emissions, and water tables?	How would diversification and increased government interventions (e.g. markets, roads, credit, flood control and extension services) affect food provision, rural income, equity, labour migration and employment, water use and quality, biodiversity, and GHG emissions?
	What would be the consequences of diversifying from rice–wheat system on food production, government procurement, energy use, income and employment potential, resource conservation and GHG emissions?	

Bangladesh (Joshi et al., 2002). Management practices and technologies are available in the irrigation command areas where these problems are more common, but their adoption is constrained due to lack of appropriate institutional arrangements.

Climate change will further affect soil conditions. Changes in temperature and in precipitation patterns and amount will influence soil water content, run-off and erosion, workability, salinisation, biodiversity, and organic carbon and nitrogen content. The increase in temperature would also lead to increased evapotranspiration. There is a need to quantify the specific regional soil-related problems and the affect that GEC will have on soil fertility and its functioning for crop growth and production.

3.2. Water

The IGP is endowed with rich water resources from monsoon rain and snowmelt-fed rivers and canals. The over-utilisation of groundwater and the vast canal network has, however, led to water logging and soil salinity in many parts of the Gangetic plains. Another serious problem now emerging is in saline aquifer regions in the western IGP. For instance, in Pakistan's Sind province, large areas (about 32%) became saline after the introduction of extensive irrigation, compounded by the depth of the water table rising from 20–30 to 1–2 m within 20 years (Pingali and Shah, 1999). In other areas, the massive expansion of private sector tubewell irrigation schemes (as is occurring in Bangladesh, India, and Pakistan) has led to the rapid depletion of ground water. Furthermore, in Bangladesh, the groundwater that is now used for drinking and irrigation contains high concentration of toxic arsenic in 70% of the 64 districts, mostly in the Gangetic flood plains (Islam et al., 1999).

There are many reasons for high water usage, such as zero or negligible tariffs on farm power in some states of India; no additional costs for extracting extra water; inadequate canal water; the cultivation of crops with a high water requirement (e.g. rice and sugarcane) in the low rainfall regions; and assured markets. Table 3 lists water table data for the Indian Punjab. Another problem in parts of the eastern IGP (largely West Bengal and Bangladesh) associated with tubewell irrigation is that the groundwater used extensively for boro rice cultivation has a high arsenic content which leads to serious health problems if it is also used for drinking.

Table 3
Changes in water tables (m) during June 1984–1994 in some districts of Punjab (Joshi and Tyagi, 1994)

Districts (paddy predominant blocks only)	Average fall (m)
Amritsar	2.3
Jallandhar	2.5
Ludhiana	1.9
Ferozpur	4.5
Kapurthala	1.8
Patiala	4.8
Sangrur	5.1
Bhatinda	1.9
Faridkot	4.5
Fatehgarh Sahib	2.7

In addition to these management-related changes in water quality and quantity, rising temperatures associated with climate change will affect water resources by decreasing snow cover and accelerating the rate of snow melt. In the short-term, this may increase water flow in many rivers in the IGP, which in turn, may lead to an increased frequency of flooding especially in those river systems where the water carrying capacity has decreased due to sedimentation. In the longer term, however, reduced snow cover would result in reduced water flow in rivers. A warmer climate change scenario, with delayed and/or more uncertain onset of summer monsoons in the region will have a direct bearing not only on rain-fed crops, but also on water storage putting additional stress on water available for irrigation. Increasing demand for water by industry and urban areas will further reduce water available for agriculture and so a range of socioeconomic and environmental factors need to be included in scenarios of changed conditions while estimating future spatial and temporal availability of irrigation water.

3.3. Genetic diversity

The Green Revolution technologies of the 1960s promoted the production and distribution of seeds of high yielding varieties, which now occupy more than 90% of wheat and 60% of rice growing areas in the IGP. This has very successfully increased crop production, but an analysis of parentage of several of the most popular varieties of these two crops revealed that the genetic diversity of the farmer's fields has been rapidly decreasing (Paroda, 1996). While not high-yielding, the traditional land races provided a wide spectrum of genetic variability, including resistance to pests and diseases, characteristics which may be increasingly important if future conditions favour biotic stressors.

4. Adaptation strategies and information needs

4.1. Background

Large parts of the IGP are currently food insecure (Swaminathan, 2002). In the eastern region this is largely due to the low purchasing power of the vast majority of the subsistence-agriculture population, coupled with the high risk of drought and flood. In contrast, the livelihoods in the western IGP are currently largely secure (due to assured markets and government support prices) but changes in subsidies may not remain indefinitely, and water supplies are being threatened. Regional inequities are a current source of several social conflicts in the IGP, and the spatial and temporal differences in GEC may further exacerbate such inequities. The region's capacity to respond adequately to the additional stresses GEC will bring needs to be increased, but there is also need to understand which sectors of the population are more vulnerable, and to identify and analyse policy and technical options that can reduce this vulnerability.

GEC will have direct, significant effects on food production. Elevated CO_2 increases yields in important crops of the region such as wheat and rice, but the degree of change is modulated by changes in temperature and rainfall. Often, these interactions may result in production decline. The increased incidence of weather extremes such as onset of rainfall, and duration and frequencies of drought and floods will also have major effects, and indeed preliminary reports indicate that the recent declines in yields of rice and wheat in the region could have been partly due to changes in weather extremes (Aggarwal et al., 2000a). GEC will also bring indirect effects, such as changes in vector-borne diseases of both crops and livestock. Given the high population with low income, it is also important to know where, how, and at what cost food can be produced against the background of GEC with current technologies, and what alternative technologies would be needed to meet the future needs. The competition between the livestock and cropping sectors for different resources is critical in the IGP food system.

While there is clearly a need to understand both the direct and indirect impacts of GEC on agricultural production and to develop technological solutions to significant problems, there is also a need to consider socioeconomic and political interventions; adaptation to GEC will require a combined approach. Major issues relating to different potential adaptation components in both areas are discussed below, and key information needs highlighted.

4.2. Augmenting production

The potential yields of the rice–wheat system in the IGP are very high (ranging from 12.0 to 19.5 t ha^{-1}) due to the favourable climate factors (Aggarwal et al., 2000b). Some progressive farmers in north-western India harvest almost 16 t ha^{-1} from the rice–wheat system, indicating a small 'yield gap'. Nevertheless, this region has also been showing stagnation in yield for some time (Dawe et al., 2000; Aggarwal et al., 2000a). In contrast, yields in the eastern IGP are low (i.e., showing a large 'yield gap') and are also unstable. While agronomy, plant breeding and policy options could increase the yield potential in the western IGP still further, information on how to increase yield stability and reduce the yield gap in the eastern IGP is urgently needed; given the large yield gap, this region could be the future source of food security for the whole of South Asia. The role of biotechnology may be critical in alleviating abiotic and biotic constraints.

In both sub-regions, the contribution that technological change brings to agricultural growth is gradually diminishing, and there is evidence that the total factor productivity

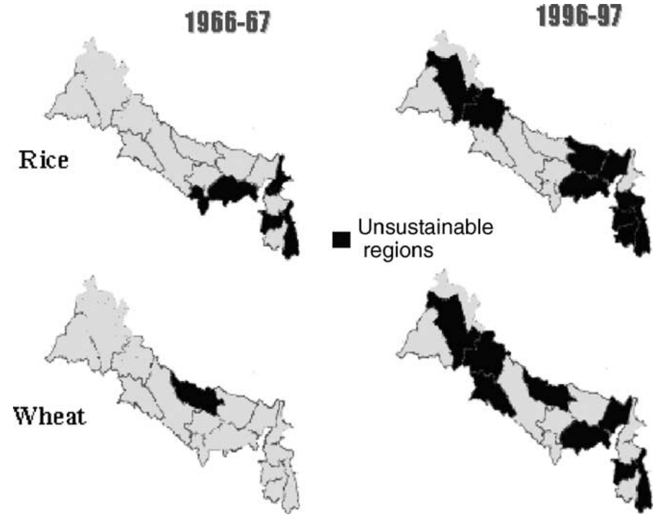

Fig. 3. Change in unsustainable area of rice and wheat in the Indian IGP as calculated by decline in the total factor productivity (Joshi et al., 2003).

(TFP, a proxy of technological change) is decelerating (Fig. 3). The annual growth in TFP in the Indian IGP was about 3% during the 1976–1985 period but it reduced to 0.4% during the 1985–1992 period (Kumar et al., 1998). Similar trends were noted in Pakistan (Ali and Byerlee, 2000). Deceleration in TFP in the IGP was mainly due to intensive input use. This was also due to the increasing occurrence of weeds, insects and disease in the continuous cropping of cereals (Pingali and Shah, 1999): aphids, stem borers and a range of diseases (e.g. *Heliothis*, false smut, sheath rot, sheath blight, spot blotch, foliar blights, head scab, and Karnal bunt) have shown a tendency to increase under the rice–wheat system (Aggarwal et al., 2000a). In addition, *Phalaris minor* has become the major weed in South Asia and is resistant to most herbicides (Hobbs and Morris, 1996). Changes in edaphic conditions and seasonal weather could also be related to the TFP decline (Aggarwal et al., 2001). An index of sustainability that included economic (agricultural production, income, and risk) and environmental (water table, land degradation, and biodiversity) indicators clearly shows that the IGP is under threat and needs immediate attention (Joshi et al., 2003).

Options that would reverse deceleration in agricultural growth in the region need strengthening. Improved technologies developed at research institutions such as universities, are however not reaching the farmers. A fragile seed sector, poor technological dissemination mechanisms, lack of adequate capital and information are the key reasons for the slow transfer of technologies. The key information need is to identify technologies available for enhancing productivity and policy options that can increase their adoption.

4.3. Increasing income from agricultural enterprises

Vulnerability to GEC can be reduced by enhancing rural livelihoods. This can be achieved by increasing income through reduced costs, minimising risk, exploring new trade opportunities, improving the quality of the product, agricultural diversification in favour of high value commodities, and exploring new income opportunities. Raising the unit cost of production and stagnating yield levels are adversely affecting the income of the farmers of the IGP. Experience in India showed that the growth in income in rice and wheat in the majority of the regions in the 1990s was largely driven by artificially-raised output prices, whereas earlier it was mainly attributed to technological contribution in the form of yield enhancement.

GEC may further increase the costs of crop production due to associated increases in nutrient losses, evapotranspiration and crop–weed interactions. The requirement of fertilizers, irrigation, and pesticides may consequently increase. Suitable actions are needed for reducing or stopping such trends through appropriate technology and policy interventions. For example, accelerated evolution of location-specific fertilizer practices, improvement in extension services, fertilizer supply and distribution, and development of physical and institutional infrastructure can improve the efficiency of fertilizer use (Desai, 1988). Policies, such as financial compensation or incentives for green manuring, should to be developed to encourage farmers to enrich organic matter in the soil and thus improve soil condition. Similarly, there is a considerable need to develop agronomic and policy initiatives to increase water-use efficiency at the farm and regional level.

The globalisation of agriculture brings apprehensions that an influx of cheap food imports under new economic regimes (under the Uruguay Round of Agreement on Agriculture of the WTO) would adversely affect agriculture in the IGP. These challenges have come at a time when South Asia is struggling with stagnating technological advancement and declining investment in agriculture (Joshi et al., 2002). New trade opportunities are nevertheless emerging for the agrarian sector in developing countries; non-traditional items (e.g. vegetables, fruits, poultry, dairy products, and fish) are in great demand in the export market and opportunities for the potential production of these items in the IGP should be explored to augment income of the farming communities. Such options should receive the urgent attention of policy makers of the IGP due to the immediate implications on socio-politico and economic fabric.

The potential export market requires high quality food that commands a premium price. Marginal changes in temperature and rainfall, and in atmospheric constituents can have significant effects on the quality of fruits, vegetables, cereals, and medicinal plants. Agronomic management practices, as well as varieties that have a better quality of acceptability in the national and international market, need to be developed. While issues related to the quality of crops is important, attention must also be paid to the processing, packaging and marketing.

A further potential source of income is via carbon trading. Analysis, monitoring, and documentation of carbon, water and nutrient cycling in agro-ecosystems of the IGP are urgently required; increasing carbon sequestration in agro-ecosystems of IGP while meeting future food demands would provide a 'win–win' situation. Farmers using resource-conservation and environment-friendly technologies, and promoting carbon sequestration may be considered eligible for payments under the Kyoto Protocol. Similarly, the role of farmers in mitigating greenhouse gases needs to be recognised within the Clean Development Mechanism of the Kyoto Protocol.

4.4. Diversifying from rice–wheat systems

Rising incomes, growing urbanization, changing relative prices of cereals and non-cereal foods and changing tastes are leading to diet diversification in the South Asian countries away from cereals and towards high value agriculture including fruits, vegetables, dairy, meat, eggs, and fish. Studies have also shown that high-value commodities offer immense opportunities to increase income level of small holders, generate employment opportunities, and improve the productivity of scarce resources (Joshi et al., 2002). The emerging opportunities of agricultural diversification towards high-value commodities need to be harnessed for the benefit of smallholders and rural poor in the IGP.

Production of high-value commodities (fruits, vegetables, milk, meat, eggs, and fish) increased at a much faster rate than food grain commodities in South Asia during the 1990s. For example, growth in production of milk, poultry and fruits during the 1990s increased more than 5% per annum as compared to 2.45% for cereals (Joshi et al., 2002). The export of these commodities from South Asian countries has witnessed a quantum jump.

A gradual shift in the production portfolio towards high-value commodities and away from rice cultivation could also result in reducing groundwater pumping (especially in the western IGP) which would both help in arresting the decline in the water table and reduce fossil fuel usage.

Information is required on diversification at the farm-level related to identification of crops, technologies and market niches. At the regional level, the information requirement relates to prospects for processing and value-addition of high value commodities. In terms of policy development, promotion of diversification would require knowledge on its possible implications on income, employment, resource conservation, and linkages between production and marketing.

4.5. Improving policies and institutions for land use and natural resource management

Adapting farming practices in response to GEC could be made easier for the farmer by improved (or introduced) socioeconomic factors such as crop insurance, and subsidies and pricing policies related to water and energy. Such provision needs to be a key aspect of development plans aimed at the twin objectives of improving resource-use productivity and reducing further environmental degradation. Rational pricing of surface and groundwater, for example, could stop its excessive and injudicious use. Further policy-relevant options need to be explored, but recognising that policy changes will have different impacts in different regions and different sections of the society. For example, the availability of assured prices and infrastructure could readily lead to better utilisation of groundwater in western IGP whereas an equivalent impact in eastern IGP would require infrastructure upgrades (e.g. power, irrigation network, input and output markets) and the dissemination of new knowledge and improved technologies.

Investment in agriculture in most South Asian countries is declining. For example, the annual public investment in Indian agriculture decreased to Rs. 188/ha during the Eighth Five-Year Plan (1992–1993 to 1996–1997) from highs of Rs. 311/ha and Rs. 258/ha in Fifth and Sixth Five-Year Plans, respectively (Ramesh-Chand, 2000). A large share of this declining public investment was used to provide subsidies for canal irrigation and power tariffs, which have not been utilised efficiently and have, in fact, encouraged inefficiencies in the overall system. This could be reversed by rationalised subsidies which can be used in water-saving technologies. Creating awareness of the impact of subsidies on the environment and other sectors of development would also be beneficial to the IGP.

Agricultural research and extension systems in South Asia are traditionally dominated by government agencies. The increasing complexity of agriculture, coupled with the availability of new tools and information technology needs a more flexible institutional structure in which NGOs, the private sector and universities dealing with basic sciences could participate and assist in technology generation, evaluation, extension and adoption. Information is needed on novel approaches such as ‘agri-clinics’, set-up and managed by private entrepreneurs across the region to disseminate agricultural knowledge and inputs so as to increase the pace of technology transfer from research establishments to the farmer.

4.6. Reducing dependence on agriculture

Many countries of the world have progressed in recent times by reducing their dependence on agriculture. In India, for example, agriculture’s share in the gross domestic product has declined to 24% in 2000–2001, although 58% of the population continues to remain dependent on it (Fig. 4). Similarly, the share of agriculture in the gross domestic product in Bangladesh varied between 50 and 60% during the stagnation growth period of 1966–1978, before declining to 25% in 2000. Pakistan experienced a slower decline in the share of agricultural in gross domestic product from 37% in 1970 to 26% in 2000. In Nepal, the decline in the share of agriculture in the gross domestic product was more marked from 71% in mid-1960s to 40% in 2000 (Doorjee et al., 2002). Declines in the share of agriculture in gross domestic product was not commensurate with the fall in dependency in agriculture in all these countries. Such trends have resulted in fragmentation and decline in the size of land holdings which leads to agronomic inefficiency, a rise in unemployment, a low volume of marketable surplus. These factors could contribute to increased vulnerability to GEC.

Factors that encourage institutional arrangements (for example, through cooperatives and contract farming) that

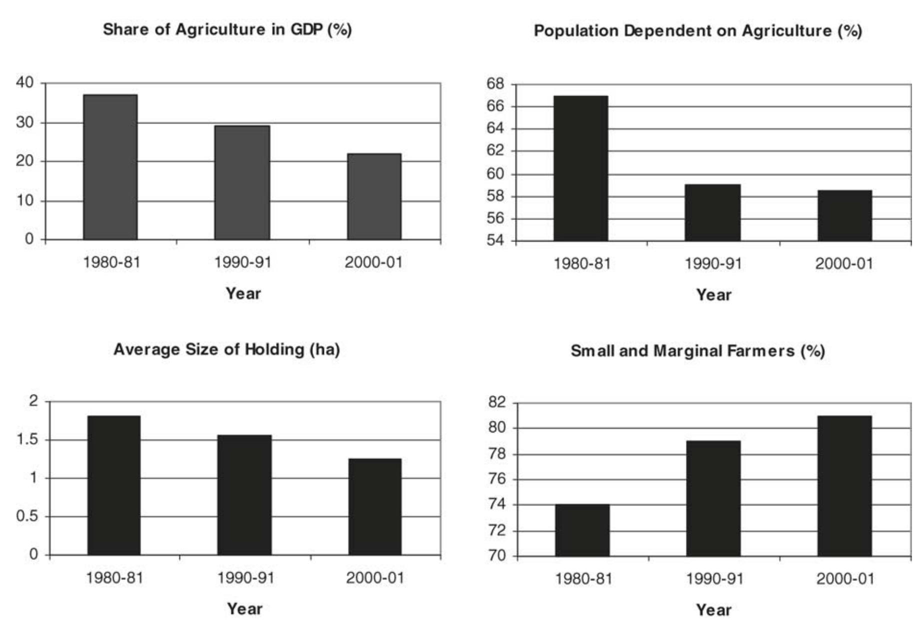

Fig. 4. Change with time in the importance of agriculture in national GDP, population dependent on agriculture, number of small and marginal farmers, and the size of landholdings. Data is average for all India (compiled from various publications).

bring small and marginal farmers together to increase production and marketing efficiencies need to be better understood. This will make the IGP competitive and also create rural jobs through agri-industries to improve income for a large number of smallholders and landless people and thus reduce their vulnerability to GEC.

Policies relating to labour migration also need further consideration. Higher returns from improved rice and wheat technologies in recent decades, coupled with the absence of appropriate machinery for smallholders, have generated considerable employment opportunities in the labour-scarce western IGP. The wage earnings of such migrant labourers in the western IGP are much higher than the returns from agriculture in the eastern IGP. Many agricultural workers from the labour-surplus eastern IGP (where technology adoption has generally been lower) consequently migrate to these regions. This has further reduced the agricultural growth in the eastern IGP and agriculture here is now considerably managed by farmwomen. An increased understanding of the relationships between technological options and policy and institutional arrangements is required to create employment opportunities in farm and non-farm sectors in the eastern IGP. This will control labour migration and induce technology-led growth in the agriculture sector in this sub-region.

4.7. Improving risk management though crop insurance and early warning systems

The eastern IGP frequently witnesses floods, droughts, uneven precipitation distribution and severe incidence of insect pests. This increases the risk of exposure of the farmers and adversely affects the crop yields and production. Lack of adequate markets and high fluctuation in output prices also affect farming profits. Information is needed on insurance opportunities so that policies that encourage crop insurance can provide protection to farmers in the event — their farm production is reduced due to natural disasters. This is perceived to be a more efficient risk management tool than the traditional risk-reducing strategies, such as crop diversification, intercropping and mixed farming. Farmers that are assured of financial compensation when income is reduced for reasons beyond their control are expected to grow more profitable crops even if they face higher risk. Farmers are also more likely to adopt advanced technologies despite the high risk of failure. Historical climatic databases, GIS and remote sensing can be used to characterise the spatial and temporal profile of risk probabilities and to establish its relationships with crop failures and price fluctuations for evolving methods for covering risks and uncertainties.

In view of a potentially increasingly variable climate and uncertain magnitudes of global warming, an early warning system for the spatial and temporal magnitude of any changes would be very valuable. Such a system could help in determining the potentially-food insecure areas and communities at risk, and information technology could greatly help researchers and food administrators develop contingency plans that could be implemented once clear climate signals are visible.

4.8. Assessing feedback of adaptations on socioeconomic development and environment

Different adaptation measures will have differing feedbacks on both the environment and socioeconomic welfare. Aggarwal et al. (2001), for example, showed a simulation approach to trade-offs among food production, irrigation water used, NO_3 leaching, biocide residue, employment, and income when the land use of Haryana state in the western IGP was diversified and optimised for different objectives (Table 4). When regional food production is maximised, income and employment levels are reduced due to a shift in production-portfolio towards food grain crops, which yield lower income levels. When the objective is set to maximise income, savings in water occur due to a reduced emphasis on rice production and a greater area is allocated to cash crops. When the objective is maximisation of employment, there is a trade-off with income due to an emphasis on labour-intensive activities. Similarly reducing the area under cultivation results in an increase in biocide residue due to higher biocide use over the limited area. Similarly, there is a trade-off between legumes and competing crops (namely rice and wheat) in the IGP. It was reported that when food grain legumes substituted rice and wheat, there was a loss in profit, food

Table 4
Production of different commodities, income, resource requirements, and environmental impacts at aggregated levels when different objective functions were maximised in Haryana (Aggarwal et al., 2001)

	Objective function maximised					
	Food	Income	Employment	Area	Water	Biocide residue
Food (Mt) (rice + wheat)	11.1	10.6	10.5	10.5	10.5	10.5
Income (billion rupees)	54.9	56.3	53.2	51.8	51.6	51.2
Land used (%)	100	100	100	86.4	100	100
Irrigation (billion m^3)	15.5	14.8	15.3	15.7	13.8	15.4
Employment (million labour days)	347	354	373	332	341	338
N loss (thousand tons)	37.4	36.8	35.4	34.2	35.1	37.9
Biocide index	125	121	124	149	121	106

Table 5
Cereal yields (t ha^{-1}) and estimated total annual (on-site) emissions of greenhouse gases (kg C-equivalent ha^{-1}) from irrigated rice–wheat systems in the Indo-Gangetic plain in terms of carbon equivalents[a] (Grace et al., 2003)

Treatments	No fertilizer	Recommended fertilizer	Recommended + FYM
Rice yield (t ha^{-1})	3.74	5.67	6.41
Wheat yield (t ha^{-1})	1.71	3.97	4.60
Conventional tillage and resides retained (kg C-equivalent $ha^{-1)}$	3496	4721	7137
Conventional tillage and residues burnt (kg C-equivalent $ha^{-1)}$	3953	5510	8032
No tillage and residues retained (kg C-equivalent $ha^{-1)}$	2966	4362	6724

[a] Carbon equivalent calculated based on CO_2 released during all agricultural operations. A global warming potential of 21 and 310 was used for CH_4 and N_2O respectively.

grain production, and use of fixed resources. However, there were substantial gains in conserving groundwater and nitrogenous fertilizers (Joshi et al., 2000).

Adaptation options will also have a range of environmental feedbacks. The increased adoption of the rice–wheat system in the IGP during the last three decades has resulted in the heavy use of irrigation, fertilizers, electricity, and diesel. These have a direct impact on the emissions of greenhouse gases (especially CO_2, CH_4 and N_2O). Depending on the management practices used, emissions are estimated collectively to have a global warming potential equivalent to 3000–8000 kg C/ha/year (Grace et al., 2003; Table 5). Multiplying this figure by the total area under such cultivation suggests emissions of global significance. Increasing production in the future, through intensification, may further increase the emissions of GHGs. Alternative management can help reduce GHG emissions: surface seeding and/or zero tillage, and the establishment of upland crops after rice gives similar yields to, when planted under normal conventional tillage over a diverse set of soil conditions. This reduces costs of production and allows earlier planting, which offers higher yields. It also results in less weed growth and shows improvements in efficiency of water and fertilizers. Further, it reduces the use of natural resources such as steel for tractor parts and fuel. (It is estimated that zero tillage saves 29.9 l of diesel per hectare as compared to the conventional tillage which leads to a 77.7 kg/ha/year reduction in CO_2 production, assuming 2.6 kg CO_2 production/l of diesel burnt.) In addition, resource-conserving technologies restrict the oxidation of soil carbon thus mitigating increases of CO_2 into the atmosphere.

Improved land use policies and institutions would also have considerable positive socioeconomic and environmental feedbacks. For example, irrigation pricing in the western IGP would be important in efforts to increase the efficiency of water use and improve other associated environmental impacts. However, since this adversely affects income from the rice–wheat system, there is considerable socio-political resistance to its implementation. Planners, policy makers and civil society in the IGP need to be made aware of the long-term benefits of resource conservation to ensure sustainable development.

5. Conclusions

Adaptation strategies need to be devised to reduce the vulnerability of the IGP food systems to GEC and which also bring both near and longer term socioeconomic and environmental benefits. It is however of paramount importance to sustain the natural research base during the drive for socioeconomic development, and there are several promising avenues warranting further research. For example, resource conservation technologies result in a higher production while saving considerable amounts of energy, costs, and GHG emissions. Enhancing the organic matter content of soils will ensure better soil fertility and also sequester carbon helping to mitigate global warming. Moreover improved policies for watershed-level resource management can assist in overcoming the impact of rainfall variability as well as increase water-use efficiency.

New information and tools are needed to analyse the trade-offs between the joint socioeconomic and environmental goals, and possible adaptation strategies need to be assessed in a collaborative exercise involving science and policy. Suitable analytical tools such as simulation models of cropping systems, water allocation and economic parameters need to be brought together within purpose-built decision support systems (DSS). (Some individual aspects will need refinement, in particular methods to upscale biophysical research conducted at the field and farm scale to the regional scale; and to downscale to farm and field scale the socioeconomic opportunities, constraints and policies which are usually defined at the regional scale.) If developed collaboratively by a range of stakeholders including scientists, policy makers, administrators, trade, industry and farmer's organisations, and donors such DSS would provide an effective framework for exploring quantitatively the socioeconomic and environmental consequences of the potential adaptation options outlined in Section 4. They would also help deliver and interpret answers to the questions given in Table 2.

Sustainable economic development and poverty reduction remain top priorities for developing countries to ensure improved quality of life and to meet future needs for food provision. The dynamic nature of GEC, and its associated uncertainties, will make achieving these goals more difficult.

Scenarios of environmental change will have to be continuously revised to take account of changes in government policies, international negotiations on trade, reduction targets for GHGs, and new technological innovations. The knowledge base needs to be integrated more effectively to analyse trade-offs between development and environment concerns so as to assess the efficacy and consequences of potential adaptation policies. Decision support systems offer an effective framework to do this.

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