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ORIGINAL ARTICLE

Implications of climate change in sustained agricultural productivity in South Asia

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Abstract One of the targets of the United Nations 'Millennium Development Goals' adopted in 2000 is to cut in half the number of people who are suffering from hunger between 1990 and 2015. However, crop yield growth has slowed down in much of the world because of declining investments in agricultural research, irrigation, and rural infrastructure and increasing water scarcity. New challenges to food security are posed by accelerated climatic change. Considerable uncertainties remain as to when, where and how climate change will affect agricultural production. Even less is known about how climate change might influence other aspects that determine food security, such as accessibility of food for various societal groups and the stability of food supply. This paper presents the likely impacts of thermal and hydrological stresses as a consequence of projected climate change in the future potential agriculture productivity in South Asia based on the crop simulation studies with a view to identify critical climate thresholds for sustained food productivity in the region. The study suggests that, on an aggregate level, there might not be a significant impact of global warming on food production of South Asia in the short term (<2°C; until 2020s), provided water for irrigation is available and agricultural pests could be kept under control. The increasing frequency of droughts and floods would, however, continue to seriously disrupt food supplies on year to year basis. In long term (2050s and beyond), productivity of Kharif crops would decline due to increased climate variability and pest incidence and virulence. Production of Rabi crops is likely to be more seriously threatened in response to 2°C warming. The net cereal production in South Asia is projected to decline at least between 4 and 10% under the most conservative climate change projections (a regional warming of 3°C) by the end of this century. In terms of the reference to UNFCCC Article 2 on dangerous anthropogenic (human-induced) interference with the climate system, the critical threshold for sustained food productivity in South Asia appears to be a rise in surface air temperature of ∼2°C and a marginal decline in water availability for irrigation or decrease in rainfall during the cropping season.

Keywords Climatic change and food security · South Asia · Crop simulation models · Net cereal production · Water availability for irrigation

Introduction

The ability of agriculture to support growing populations has been a concern for generations and continues to be high on the global policy agenda. Despite considerable improvements in food production over the past 50 years, food security still remains a problem in many parts of the world. FAO's estimates for the period 2000–2002 (FAO 2005b) show that about 850 million people in the developing world do not have enough to eat, and half of these undernourished people live in Asia. The eradication of poverty and hunger has been included as one of the United Nations 'Millennium Development Goals' adopted in 2000. One of the targets of those goals is to cut in halve the number of people who are suffering from hunger between 1990 and 2015 (World Bank 2003). Meeting this food security goal will be a major challenge. It is estimated that by 2025 global cereal production would need to increase by

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about 40% to meet world food demands. Predictions of food security outcomes have been a part of the policy landscape since Malthus' "Essay on the Principle of Population" of 1798 (Malthus 2003). Over the past few decades, some experts have expressed concern about the ability of agricultural production to keep up with global food requirements (Brown and Kane 1994), whereas others have forecasted that technological advances or expansions of cultivated area would boost production sufficiently to meet the rising demands (Simon 1998). So far, projections of a global food security are antagonistic.

Nevertheless, crop yield growth has slowed down in much of the world because of declining investments in agricultural research, irrigation, and rural infrastructure and increasing water scarcity (FAO 2001). New challenges to food security are posed by accelerated climatic change. Many studies (e.g., Parry et al. 1999) predict that world food supply will not be adversely affected by moderate warming (up to 1°C above the climatological mean) by assuming farmers will take adequate steps to adjust to climate change and that additional CO_2 will increase yields. However, results from Free Air Carbon Dioxide Enrichment (FACE) experiments suggest that direct effects of CO_2 fertilization have been over-estimated and that the yield loss due to seasonally elevated levels of surface ozone could offset yield increases due to CO_2 fertilization effects (Long et al. 2005). Studies also suggest that many developing countries are likely to fare badly where the social and economic costs of responding to the impacts of climate change will emerge (Slingo et al. 2005). Considerable uncertainties remain as to when, where and how climate change will affect agricultural production (Parry et al. 2004). Even less is known about how climate change might influence other aspects that determine food security, such as accessibility of food for various societal groups and the stability of food supply. Not only changes in temperature and rainfall, but as well an increase in extreme weather events, are likely to change food production potential (Challinor et al. 2007). This potentially will disrupt food distribution systems and their infrastructure (Fischer et al. 2002). Climate change would lead to more intense rainfall events between prolonged dry periods (Meehl et al. 2007), as well as to reduced or more variable water resources for irrigation. Such conditions may promote pests and disease on crops and livestock, as well as soil erosion and desertification. Increasing development into marginal lands may in turn put these areas at greater risk of environmental degradation (Easterling et al. 2007).

This paper presents the likely impacts of thermal and hydrological stresses as a consequence of projected climate change in the future potential agriculture productivity in South Asia based on crop simulation studies undertaken by the author (following the tools and methods described below). It also includes a review of related results available in recent scientific literature. The primary goal is to identify critical climate thresholds for sustained food productivity in the region.

Agriculture productivity in South Asia

The average cereal production in South Asia increased from 147 Mt in the triennium ending 1980-81 to 239 Mt in the triennium ending 1999–2000 largely due to productivity increase attained through use of high yielding varieties and improvement in crop management practices (Broca 2002). In the Indo-Gangetic plains of South Asia (almost 12 Mha of land covering large areas of Pakistan, India, Nepal and Bangladesh), the yields and production of two most important staple food crops, namely rice and wheat, registered significant increases during the 1970s and 1980s (Sinha 1997). However, both rice and wheat yields in predominantly rice/wheat-producing regions of South Asia have exhibited an element of stagnation in recent decades (Regmi et al. 2002). A significant part of the trend towards yield decline in rice and wheat, particularly at the potential level of management (adequate availability of inputs), could be ascribed to rising temperatures (particularly minimum temperatures) during the cropping season (Wheeler et al. 2000). The increase in minimum temperature during both wheat and rice cropping seasons increases the maintenance respiration requirement of the crops and shortens the time to maturity thus reduces net growth and productivity. There are published 'direct evidences' that increased night-time temperatures associated with global warming can cause rice yields to fall (Peng et al. 1995). For example, a study conducted at the International Rice Research Institute (IRRI) in the Philippines used local climate data from 1979 to 2003 and data on Philippine rice yields from the last 12 years and reported that rice yields had decreased by more than 10% while the night-time temperatures in the dry season rose by 1.1°C—three times the increase in average maximum temperature over the same period (FAO 2005a). This trend in nocturnal temperatures is consistent with data from elsewhere and is linked to increasing concentrations of greenhouse gases. There is also a growing recognition that, while occurrence of weeds, insects and diseases in the continuous cropping of cereals have shown a tendency to increase in South Asia with rise in surface air temperatures, resistance to weedicides has appeared in large areas under rice–wheat sequence and is a real threat to wheat production in the years to come (Aggarwal et al. 2004).

The agricultural sector contributes 25% to the economy and 65% to the employment in India (Planning Commission 2001); this sector is crucial to the economy of most other countries in the region as well. For example, agriculture remains Nepal's principal economic activity, employing 80% of the population and providing 37% of GDP even though only about 20% of the total area is cultivable (Regmi et al. 2002). In Pakistan, agriculture, small-scale forestry and fishing contribute 25% of GDP and employ 48% of the labour force (Faisal and Parveen 2004). The agriculture sector in Bangladesh also plays an important role in the national economy accounting for 31.6% of total GDP and 63.2% of total national employment (Faruque and Ali 2005). The performance of this sector in most countries of South Asia has an overwhelming impact on major macroeconomic objectives like employment generation, poverty alleviation, human resources development and food security (FAO 2005b). However, in recent years, the cultivation potential has exhausted in many countries of South Asia due to multiple constraints including land degradation and water scarcities (Timsina and Connor 2001). Both wheat and rice crops have been adversely affected by the observed changes in temperature regime and the changes in spatial and temporal variability of rainfall in several South Asian countries (Droogers 2004).

The fortunes of the agricultural sector in South Asia are heavily dependent on monsoon making it highly vulnerable to mercies of weather (Challinor et al. 2003). The summer monsoon rainfall is responsible for almost 50% of the variability in total food grain production anomalies in the region (Planning Commission 2001). A comparison between Indian summer monsoon rainfall (SMR) and food grain production (FGP) in India demonstrates that the interannual variability in SMR and total food grain production anomalies are closely related (Selvaraju 2003). During the years of deficit monsoon (1966, 1972, 1974, 1979, 1982 and 1987) the food grain production declined in India while during the years of excess or normal rainfall (1970, 1975, 1978, 1983 and 1988) it was comparatively higher (Fig. 1a). The correlation between SMR and food grain production (0.71) was significant at the 1% level. The SMR is responsible for 50% of the variability in total food grain production anomalies (Fig. 1b). The SMR exhibits a high correlation ($r = 0.80$) with *Kharif* food grain production and a moderate correlation ($r = 0.41$) with *Rabi* food grain production anomalies. Among the individual crops, rice ($r = 0.66$), wheat ($r = 0.49$) and chickpea ($r = 0.49$) production had significant association with SMR. As a consequence of the continued vulnerability of the traditional agriculture crops (rice, sugarcane, grains, pulses, oilseed, spices, tea, rubber, coconuts) to weather conditions in Sri Lanka, the agriculture sector's contribution to overall national growth was a negative 14% in 2004 (Droogers 2004). In South Asia, serious concern has been raised in recent years about decline in soil fertility, changes in water table depth, deterioration in the quality of irrigation water and rising salinity and the consequence for food productivity (FAO 2005c).

The actual share of agricultural land to total land area in South Asia over the 10-year period (1991–2000) has remained high at 50.0% (FAO 2001). This large share was a result of the significant areas of agricultural land in Bangladesh (62.6% of total land), India (54.9%) and Sri Lanka (35.7%). South Asia also has the largest share of arable and permanent crop land in total agricultural land (91.5%) with 94.0% in India and 93.3% in Bangladesh respectively (FAO 2002). Nonetheless, the arable land resources in all South Asian Countries have reached a limit due to population pressure, urbanization and intensive development activities in the region (Rosegrant and Cline 2003). In India, for example, urbanization and industrialization have rapidly reduced the per capita availability of arable land from 0.48 ha in 1950 to 0.15 ha by 2000 and is likely to further reduce to 0.08 ha by 2020 (Aggarwal and Mall 2002). The pressure on arable land in the twenty-first century will increase in other South Asian countries as well due to the increasing food grain demand for the growing population, booming economic development requiring land to support industrialization and urbanization, and, due to climatic change.

The growth rate of food grain production in India was markedly lower in the 1990s than in the 1980s (Bhalla et al. 1999). Aggregate production increased by about 26 Mt in the 1990s as against 52 Mt in the 1980s. The average yield of rice has grown at a compound rate of 1.1% annually in the 1990s against 3% annually in the 1980s (MOA 1996; Planning Commission 2001). The average yield of wheat has grown at a compound rate of 1.6% annually in the 1990s against 3% annually in the 1980s. Therefore, even though per capita availability of food grains in India increased in the 1990s—up by 12 g day^{-1} from 472 g day^{-1} in 1990 to 485 g day^{-1} in 2000 (DES 2003), the deceleration in food grain production in the 1990s creates the spectre of food shortage in the years ahead (Bhalla et al. 1999). The current food production in India and the targets for 2010 and 2020 are given in Table 1. The situation in Pakistan, Nepal, Bangladesh and other South Asian countries is not different (FAO 2005c). In the early and mid-1980s, Pakistan was self-sufficient in wheat, but in the early 1990s more than 2 Mt of wheat was imported annually owing largely to recurrent floods and droughts (Dyson 1999). By 2025, there will be a shortfall of 28 Mt in the production of all the major food grains and crops in Pakistan due to shortage of water (Dyson 1999). Table 2 lists the supply and demand projections of rice and wheat crops for South Asia until 2020. FAO's recent projections also indicate that South Asia would be deficient in net cereal production by about 22 Mt by 2030 (FAO 2005a). It is thus evident that, in the coming years and decades, the South Asian countries would need to produce more food

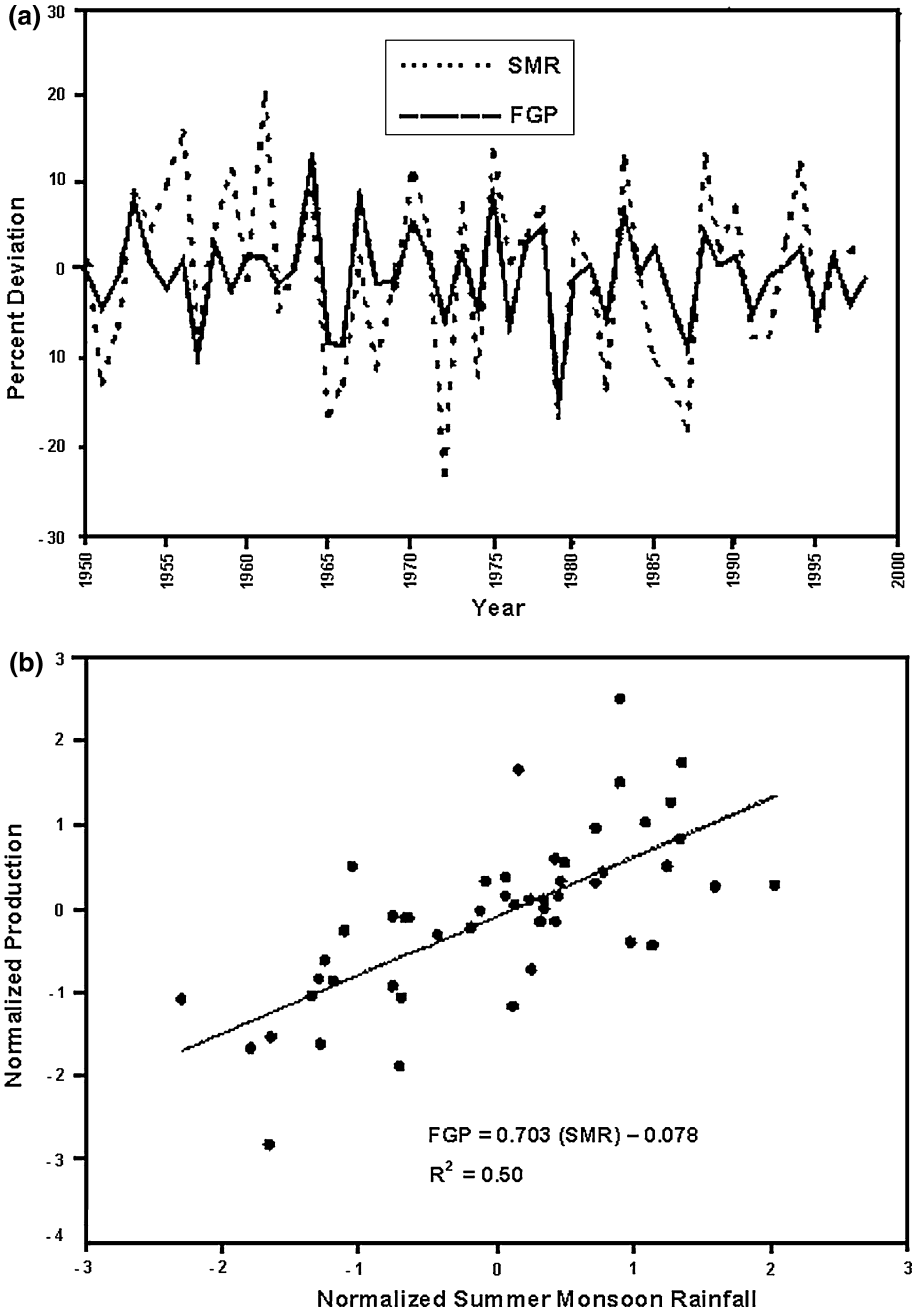

Fig. 1 Relationship between summer monsoon rainfall (SMR) and food grain production (FGP) in India: **a** per cent deviation from normal and **b** scatter between normalized SMR and FGP

and other agricultural commodities under conditions of diminishing per capita arable land and irrigation water resources and expanding biotic as well as abiotic stresses including the climatic constraints (Sinha et al. 1998).

Water availability and demand in South Asia

Water availability in most countries of South Asia is gradually decreasing because of increases in population, irrigated agriculture and growth in the industrial sectors. For example, the per capita availability of water in Pakistan has decreased from 5,650 m^3 in 1951 to 1,000 m^3 in 2001-02 accompanied by sharp deterioration in quality of water (Kahlown et al. 2003). Similarly, in India, the per capita availability of water has fallen to 1,869 m^3 from 4,000 m^3 two decades ago, and it could dip to below 1,000 m^3 in next 20 years (Gupta and Deshpande 2004). On the other hand, water demand in most countries of South Asia is gradually rising because of increases in population, irrigated agriculture and growth in the industrial sectors (Mirza and Ahmad 2005). Simultaneously, the inefficient management of the resources has led to the problem of water quality deterioration posing new challenges on water management

Table 1 India's current food production and targets (DES 2003)

	Production (Mt), 2000	Target production (Mt), 2010	Target production (Mt), 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	16.1	27.8
Food grains	200.8	245.7	293.6

Table 2 Supply and demand projections of rice and wheat crops for South Asia to 2020 (compiled based on data in Dyson 1999; FAO 2005a, b, c; Rosegrant and Cline 2003; Royal Society 2005)

Country/region	Crop	Projections for 2020 (× 1,000 tons)	
		Supply	Demand
Bangladesh	Rice	26,270	27,070
	Wheat	2,185	4,885
India	Rice	1,20,100	1,20,976
	Wheat	94,780	1,00,595
Pakistan	Rice	6,524	4,826
	Wheat	25,963	33,517
South Asia[a]	Rice	1,57,940	1,58,710
	Wheat	1,27,370	1,47,060

[a] Includes Bangladesh, India, Pakistan, Nepal, Afghanistan, Maldives and Sri Lanka

and conservation front (Molden and de Fraiture 2004). Figure 2 depicts the observed changes in the contribution of ground water and surface water irrigation to agricultural GDP in India over a period of 20 years (DES 2003). Interestingly, as is evident from Table 3, the water consumed for cereal production in India (and in other South Asian Countries as well) is significantly more compared to other parts of the world. While the agriculture sector remains on top in terms of water use (Table 4), the hydrological cycle is being modified quantitatively and/or qualitatively in most river basins of India, Pakistan, Nepal and Bangladesh by human activities such as land use change, water storage, inter-basin transfers, irrigation and drainage.

South Asian countries have been blessed with valuable groundwater resources for exploiting their vast arable lands by undertaking year-round irrigated agriculture (Shah et al. 2000). The growing demand for food in India is being managed by over-pumping groundwater, a measure that virtually assures a drop in food production when the aquifer is depleted. Several states in India are overdrawing aquifers, including the Punjab (the country's "bread basket"), Haryana, Gujarat, Rajasthan, Andhra Pradesh, and Tamil Nadu. The latest data indicate that in the Punjab and Haryana, water tables are falling by up to 1 m year^{-1} (Lal 2004). The aquifer depletion could reduce India's grain harvest by one-fifth (Kataki et al. 2001). Pakistan, a country with 140 million people and still growing by 4 million per year, is also over-pumping its aquifers. In the fertile Punjab plain, the drop in the water table appears to be similar to that in India (Kataki et al. 2001). In the province of Baluchistan, a more arid region, the water table around the provincial capital of Quetta is falling by 3.5 m year^{-1} (Moshabbir and Khan 1994). Within 15 years, Quetta will run out of water if the current consumption rate continues (Qureshi 2005). The general response to water scarcity in this region has, until recently, been to build more dams or drill more wells which have made it more difficult to expand supply (Seckler and Seckler 1996). The available options are now limited to reducing demand by stabilizing population and raising water productivity (Lal 2004). A mega project on interlinking of Indian rivers has been proposed to meet the future water demands through increase in the water availability in India from around 535 billion m^3 now to more than 1,000 billion m^3 by 2025 requiring investments estimated at about US$ 116 billion during the next 20 years (TF–ILR 2003). With the long gestation period involved due to the complex political, technological and financial requirements of such long-term water projects, and nearly all the 3 billion people to be added by 2050 being born in developing countries where water is already scarce, achieving an acceptable balance between water and people may depend more on stabilizing population than on any other single action (GWP 2000).

Himalayan glaciers cover about 3 Mha or 17% of the mountain area compared to 2.2% in the Swiss Alps (Fushimi 1999). They form the largest body of ice outside the Polar caps and are the source of water for the innumerable rivers that flow across the Indo-Gangetic plains (WMO 1999). Himalayan glacial snowfields store about 12,000 km^3 of freshwater (Meier 1998). About 15,000 Himalayan glaciers form a unique reservoir which supports perennial rivers such as the Indus, Ganges and Brahmaputra which, in turn, are the lifeline of more than 2 billions of people (Dyurgerov and Meier 2005). The Gangetic basin alone is home to 500 million people, about 10% of the total human population. Melting of glaciers in South Asia contribute substantially to the freshwater supplies in the region (Singh and Kumar 1997). However, there is an overwhelming evidence of deglaciation in the Himalayas (Naithani et al. 2001). Most Himalayan glaciers in South Asia have continued to vacate large areas during the recent decade, resulting in seasonal increases in glacial runoff and rapid growth of lakes on the glacier surfaces. Glaciers in the Himalayas are receding faster than in any other part of the world (Hasnain 2002). For example, the Imja Glacier in the Himalayan Khumbu Range of Eastern Nepal, southeast of Mount Everest is retreating at nearly 10 metres per year

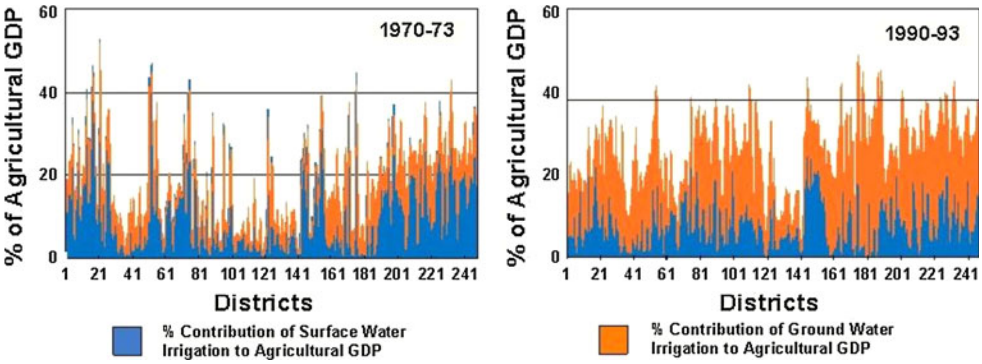

Fig. 2 Change in contribution of ground water and surface water irrigation to agricultural GDP in India from 1970s to 1990s (based on data from CWC 2001)

Table 3 Water consumed for food production (litres evapotranspired per kilogram)

Crop	USA	France	China	India	Japan	World
Wheat	1,390	660	1,280	2,560	1,350	1,790
Rice	1,920	1,270	1,370	3,700	1,350	2,380
Maize	670	610	1190	4,350	–	1,390

Source de Fraiture et al. (2004)

Table 4 Water budget for key South Asian countries

	India	Pakistan	Bangladesh	Nepal
Annual internal renewables (km^3)	1,850	298	1,357	170
Annual withdrawal (km^3)	380	153.4	22.5	2.68
From outside the country borders	235	170	1,000	0
Sectoral withdrawal (%)				
Domestic	3	2	3	4
Industry	4	2	1	1
Agriculture	93	97	96	96

Data Source Shiklomanov (1997), WMO (1999), FAO (2002) and Zimmer and Renault (2004)

(Shrestha 2004). Numerous glacier lakes have formed in recent years and are in risk of outburst. The frequency of glacial lake outburst flood is on the rise in the Himalayan region (Cenderelli and Wohl 2003). As a consequence, an increased frequency of mudflows and avalanches affecting human settlements has been reported in Nepal, Bhutan and northern India (Mool et al. 2001). Over 1% of water in the Ganges and Indus Basins (South Asia) is currently due to runoff from wasting of permanent ice from glaciers (Qureshi 2005). This contribution is expected to increase as melting rates accelerate, though ultimately the added runoff is predicted to disappear as glaciers decline few decades from now (Singh and Bengtsson 2004). Such changes are important since water use in these basins is already approaching capacity as populations continue to grow.

The potentials of the non-glacier fed rivers are strongly associated with the health of the monsoons (Lal 2005). Considerable spatial and temporal variations in rain water availability have also taken place in the recent years as a result of observed swing in the onset, continuity and withdrawal patterns of summer monsoon (Mirza 2002). The southwest Bangladesh suffers from extreme water shortages as well as from acute moisture stress during the dry months adversely affecting both the ecology of the region and its agriculture (Faruque and Ali 2005). Also, floods during monsoon season inundate 20.5% area of Bangladesh, and this can reach as high as about 70% during an extreme flood event (Mirza et al. 2005). Salinity ingress is a major hazard faced here. Water resources will come under increasing pressure in South Asia as changes in climatic conditions will affect demand, supply and water quality (Yohe and Strzepek 2005). In regions that are currently sensitive to water stress (arid and semi-arid regions), any shortfall in water supply will enhance competition for water use for a wide range of economic, social and environmental applications. Changes in water supply and demand caused by climate change will be overlaid on top of changing water use.

In the developing countries of South Asia, the remaining natural flood plains are disappearing at an accelerating rate, primarily as a result of changing hydrology (GWP 2000). Up to the 2025 time horizon, the future increase in human population will lead to further degradation of riparian areas, intensification of the hydrological cycle and increase in the discharge of pollutants (Seckler et al. 1997). The commonalities of monsoonal climate, temporal and spatial variations in rainfall, shared river systems, the occurrence of floods and droughts, the predominance of agriculture, the growth of population and the increasing pressure on scarce natural resources necessitate continued collaboration among the South Asian countries in relation to water.

Observed changes in climate and future projections for South Asia

Globally, the Earth's climate is warmer today than at any time during the last one hundred and forty years. An annual mean global warming of 0.74°C has been reported during the last 100 years (IPCC 2007). Surface temperature records also indicate that eleven of the last 12 years (1995–2006) rank among the twelve warmest years in the instrumental records of global surface temperature (since 1850s). There is evidence that El Niño episodes since the mid-1970s have been relatively more frequent than the opposite La Niña episodes ("La Niña") (Sarkar et al. 2004). The observations also suggest that the atmospheric abundances of almost all greenhouse gases have reached their highest values in recorded history in the twenty-first century (IPCC 2007). Anthropogenic CO_2 emissions due to human activities are virtually certain to be the dominant factor contributing to the observed global warming (Parker 2004).

The analysis of seasonal and annual surface air temperatures for a number of stations in South Asia has shown a significant warming trend of 0.7°C per 100 years (Lal 2003). The warming over the Indian subcontinent is found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in most parts of India except for a significant negative trend over northwest India (De and Mukhopadhyay 1998). Diurnal temperature range has also decreased, with night-time temperature increasing at twice the rate of day-time maximum temperature (Sen Roy and Balling 2005). Increasing trends in surface air temperature have also been reported in Pakistan, Nepal, Bhutan, Sri Lanka and Bangladesh (Siddiqui et al. 1999). A rise in mean temperature of 0.6–1°C has been reported in arid coastal areas of Pakistan since the beginning of twentieth century (Farooq and Khan 2004). In Nepal, the warming trend has been more pronounced in the trans-Himalaya and Himalaya regions (0.09°C year^{-1}) than in the Terai region (0.04°C year^{-1}) and more during winter than in other seasons (Shrestha 2004).

The rainfall fluctuations in South Asia have been largely random over a century, with no systematic change detectable on either annual or seasonal scale (Kripalani et al. 2001). However, areas of increasing and decreasing trends in the seasonal rainfall have been found in some parts of South Asia during recent years (Lal 2003). Furthermore, the spatial and temporal distribution of rainfall has become increasingly uncertain. The western Himalayas receive more snowfall than the eastern Himalayas during winter, while, during the monsoon season, there is more rainfall in the eastern Himalayas and Nepal than in the western Himalayas (Shrestha et al. 2000). In India, recent decades have exhibited an increase in extreme rainfall events over northwest India during the summer monsoon (Sen Roy and Balling 2004). Moreover, the number of rainy days during the monsoon along east coastal stations has declined (Lal 2005). In Bangladesh, decadal rainfall anomalies are reported to be above long-term averages since the 1960s (Mirza and Dixit 1997). A 10–15% decrease in both winter and summer rainfall in coastal belt and hyper-arid plains of Pakistan has been observed (Farooq and Khan 2004). The annual mean rainfall in Sri Lanka has no trend (Chandrapala 1996); however, positive trends in February and negative trends in June have been reported on a long-term basis.

In general, climatic variability and the frequency of occurrence of extremes of weather events such as heat waves, droughts, floods and timing of rainfall have increased over the past few decades over South Asia (De et al. 2005). For example, the state of Orissa in India has been reeling under contrasting extreme weather conditions for more than a decade: from heat waves to cyclones and from droughts to floods (De et al. 2004). In coastal Orissa, almost 4,90,000 ha of fertile lands have been waterlogged, salinated, and sandcasted by cyclones and floods in recent years. Intense rainfall events have become more frequent in recent years in many parts of South Asia. The calamities such as heat waves, floods and droughts in Pakistan, India, Bangladesh, Nepal and Sri Lanka are not only becoming more frequent but striking areas that never had a vulnerability record (Pai et al. 2004). The heat wave of 9–15 May 2002 in Andhra Pradesh (more than 1,000 people died when surface air temperatures soared to almost 51°C, more than 7% above the monthly average), caused the highest one-week death toll from thermal stress in Indian history (IMD 2000–3). The death toll due to heat waves during March to May in Rajasthan, Punjab, Gujarat and Bihar is on the rise in recent years (Kalsi and Pareek 2001). Erratic summer monsoon during the past few years in the region has also sparked worries about yearly agricultural output and economic growth in the region. The coastal regions in India and Bangladesh have been undergoing stronger wind and flood damage due to storm surges associated with more intense tropical storms in recent years (Sridharan and Muthuchami 2002). Frequent inundation of low lying areas, drowning of coastal marshes and wetlands, enhanced erosion of beaches, more flooding and increase in the salinity of rivers, bays and aquifers in the coastal regions of India and Bangladesh have occurred more often during the past decade (Mirza et al. 2005).

The Fourth Assessment Report (AR4) of the Intergovernmental Panel of Climate Change (IPCC) suggests that increasing trends of greenhouse gases in the earth's atmosphere could accelerate in the future as a consequence of which the best estimates of increases in average global surface temperature is likely to be in the range from 1.8° to 4°C (IPCC 2007). Globally averaged precipitation is projected to increase, with great deviances at regional scale (Meehl et al. 2007). For South Asia, the projected seasonal and annual mean changes in area-averaged surface air temperature and precipitation under SRES A1FI (highest future emission trajectory) and B1 (lowest future emission trajectory) pathways for three 20 year time slices averaged over 2020s, 2050s and 2080s as inferred from an ensemble of results from five coupled Atmosphere–Ocean Global Climate Model (AOGCM) experiments, namely those of CCSR-NIES (Japan), CSIRO (Australia), ECHAM4 (Germany), HADCM3 (UK) and NCAR-PCM (USA) and reported in Ruosteenoja et al. (2003) are given in Table 5. It may be noted from Table 5 that the area-averaged annual mean surface temperature rise over South Asia by the end of twenty-first century is projected to range between 2.6° and 4.7°C. The projected increase in area-averaged summer monsoon rainfall over South Asia is within the currently observed range of interannual variability which is sufficiently large to cause devastating floods or serious drought (Lal 2005). During winter, South Asia may experience between 5 and 15% decline in rainfall (Lal et al. 2001b). The decline in wintertime rainfall is likely to be significant and may lead to droughts during the dry summer months (Lal 2003).

An intensification of the summer monsoon and an enhancement in precipitation variability with increased greenhouse gases have been projected in the Third Assessment Report (Giorgi and Hewitson 2001) and reiterated in the Fourth Assessment Report (Christensen et al. 2007) of the IPCC. The aerosols could weaken the intensification of the mean monsoon circulation, but the magnitude of the change would depend on the size of the forcing (Auffhammer et al. 2006). The effect of aerosols on summer monsoon precipitation would be to dampen the strength of the monsoon compared to that seen with greenhouse gases only (Givati and Rosenfeld 2004). The overall effect of the combined forcing would be at least partly dependent on the land/sea distribution of the aerosol forcing and if the indirect effect were included as well as the direct effect (Chung and Ramanathan 2006).

Several studies (e.g., Giorgi 2006) have confirmed an increase in the interannual variability of daily precipitation in the Asian summer monsoon with increased anthropogenic forcings. The primary cause for enhanced monsoon variability in the future has been attributed to alterations in Walker circulation due to higher sea surface temperatures in the central and eastern tropical Pacific (Vecchi et al. 2006). It has also been reported that, while the warmer Indian Ocean would contribute to increases in summer monsoon precipitation over South Asia, the warmer Pacific Ocean would weaken the monsoon flow and reduce the monsoon precipitation (Meehl and Arblaster 2003). An intensification of the Asian summer monsoon with increased greenhouse gases has also been projected. Large increases in rainfall intensity over northern Pakistan, northwest India and Bangladesh are also projected (May 2004). However, these projections are subject to choices in the future emission scenarios of greenhouse gases and aerosols. None of these studies consider the likely changes in the aerosol forcings.

Pronounced year to year variability in climate features in South Asia has been linked to ENSO (Krishnamurthy and Goswami 2000). As global temperatures are increasing, the Pacific climate will tend to resemble a more El Niño-like state (Timmermann et al. 1999). The future seasonal precipitation extremes associated with a given ENSO event are likely to be more intense in the tropical Indian Ocean region; anomalously, wet areas could become wetter and anomalously dry areas could become drier during future ENSO events (Meehl and Washington 1996). The enhanced anomalous warming of the eastern equatorial Pacific Ocean (El Niño-like state) in the future has implications for increasing the likelihood of droughts and floods during summer. A week Asian summer monsoon has been suggested following a strong wintertime El Niño and increased spring and summer snow pack on the Tibetan Plateau (Shaman and Tziperman 2005). Moreover, the state of ENSO during Northern Hemispheric summer may influence monsoon rainfall more directly via changes in circulation, temperature and subsidence patterns within the tropics (Knutson and Manabe 1998). An increased frequency of ENSO events and a shift in their seasonal cycle has been projected in a warmer atmosphere: the maximum occurs between August and October rather than around

Table 5 Projections of likely changes in surface air temperature and precipitation in South Asia under SRES A1FI (highest future emission trajectory) and B1 (lowest future emission trajectory) pathways for three time slices, namely 2020s, 2050s and 2080s (Lal 2005)

Region	Season	2010–2039				2040–2069				2070–2099			
		Temperature, °C		Precipitation, %		Temperature, °C		Precipitation, %		Temperature, °C		Precipitation, %	
		A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1
South Asia	DJF	1.17	1.11	−3	4	3.16	1.97	0	0	5.44	2.93	−16	−6
	MAM	1.18	1.07	7	8	2.97	1.81	26	24	5.22	2.71	31	20
	JJA	0.54	0.55	5	7	1.71	0.88	13	11	3.14	1.56	26	15
	SON	0.78	0.83	1	3	2.41	1.49	8	6	4.19	2.17	26	10
	Annual	0.94	0.90	3	5	2.71	1.73	9	7	4.67	2.62	15	9

January as currently observed (Collins 2000). In many of the South Asian countries, drought disasters are reported to be more frequent during years following ENSO warm events than in normal years (Goswami and Xavier 2005). The projected enhanced anomalous warming of the eastern equatorial Pacific Ocean will have implications for the frequency of droughts and floods during summer (Kripalani et al. 2003). Future seasonal precipitation extremes in South Asia associated with a given ENSO event are likely to be more intense (Ashrit et al. 2003).

South Asia is already vulnerable to extreme climate events and changes in climate could exacerbate these vulnerabilities. Moreover, while there is no evidence that tropical cyclone frequency may change (Trenberth 2005), a possible increase in cyclone intensity (including the near-storm precipitation rates and destructive potential) of 8–16% for a rise in sea surface temperature of 2–4°C relative to the current threshold temperature is very likely (Emanuel 2005; Walsh 2004). Thus, the available data strongly suggest that an increase in cyclone intensity is most probable (Knutson and Tuleya 2004). Amplification in storm surge heights should result from stronger winds and low pressures associated with tropical storms (IPCC 2007). This could lead to higher storm surges and an enhanced risk of coastal disasters along the coastal regions of South Asian Countries.

Current efforts on climate variability and climate change studies increasingly rely upon diurnal, seasonal, latitudinal, and vertical patterns of temperature trends to provide evidence for anthropogenic signatures. Such approaches require increasingly detailed understanding of the spatial variability of all forcing mechanisms and their connections to global, hemispheric, and regional responses. Since the anthropogenic aerosol burden in the troposphere would have large spatial and temporal variations in the atmosphere, its future impact on regional scale would be in striking contrast to impacts from anthropogenic greenhouse gases. Considerable uncertainty still prevails about the indirect effect of aerosols on tropospheric clouds, which could strongly modulate the climate (Ramanathan et al. 2001). We are still unclear about the implications of localized radiative forcing on deep convection in tropical Asia and on Hadley circulation (Lal et al. 2000). It has also been suggested that aerosols produced by tropical biomass burning could lead to additional negative radiative forcing (Hansen and Nazarenko 2004). The radiative forcing due to tropospheric ozone increases as a consequence of biomass burning has been found to be of same magnitude but opposite in sign to that due to the direct effect of biomass burning aerosols (Kiehl et al. 1999). However, the geographical extent of increases in tropospheric ozone is considerably larger than that of aerosols. Anthropogenic perturbations of planetary albedo due to changes in the concentrations of scattering aerosols and land cover conversion could trigger a transition to a summer monsoon regime over South Asia characterized by much lower precipitation than today's (Zickfeld et al. 2005). This finding acquires particular relevance in the light of observational evidence revealing that a large cloud of anthropogenic haze spreads over South and Southeast Asia (Krishnan and Ramanathan 2002). It is likely that, after a partial suppression of the Asian summer monsoon over the next decades, aerosol control policies (meant to mitigate intolerable impacts on human health, food production and ecosystems) take effect, while global economic growth pushes atmospheric CO_2 concentrations to record levels. The latter developments could re-establish the 'wet monsoon' mode—possibly at increased strength—within a few years only. Such a dynamics would seriously challenge the adaptive capabilities of the rural society in South Asia.

Tools and methods

The crop simulation models employed in this study are CERES-Rice (Alocilja and Ritchie 1988) and CERES-Wheat (Godwin et al. 1989). These are process-oriented generic and physiological crop growth simulation models and simulate soil water balance and nitrogen balance on daily incremental basis during the crop life cycle. The models simulate the transformation of seeds, water and fertilizers into grain and straw through the use of land, energy (solar, chemical and biological) and management practices, subject to environmental factors such as solar radiation, maximum and minimum air temperatures, precipitation, day length variations, soil water properties and soil water conditions. Phenological phases are simulated in the models using the concept of thermal time or degree days and photoperiod as defined by the genetic characteristics of the crop. Crop growth is simulated employing a carbon balance approach in a source-sink system. Photosynthetic process is initially assumed to be controlled only by solar radiation and temperature and later modified by the effect of stresses due to temperature, water and fertilizer.

The models require input data on soil, crop and weather for its calibration and validation in different environments. Weather (observed radiation, maximum and minimum temperatures and rainfall data), soil and crop management data (dates of sowing, plant and row spacing, fertilizer etc. based on current field practice) were compiled for over 60 locations spread over six countries of South Asia and prescribed as input to the models. The genetic coefficients of several prevalent cultivar varieties of rice and wheat as inferred from field studies at selected locations in South Asia were also collected and used in the model validation and application. The readers may refer to Lal et al. (1998b) for further details on model calibration and other experimental details.

Climate change scenarios for South Asia on annual and seasonal mean basis were obtained from an ensemble of results as inferred from the above-said five AOGCM experiments (Lal 2007). The projections on likely increases in area-averaged surface air temperatures and per cent change in area-averaged precipitation (with respect to the baseline period 1961–1990) were derived for two extremes of the SRES scenarios corresponding to the highest (A1FI) and lowest (B1) emission pathways and for the four seasons and three 30 year time slices averaged over 2020s, 2050s and 2080s. Since not all of the said AOGCM simulation experiments were conducted for all the six SRES scenarios at the time of the analysis reported here, a pattern scaling approach (Ruosteenoja et al. 2003) was followed for inferring the regional projections.

Attempts have been made recently to generate climate change scenarios at local scales using the data from climate change experiments performed with high resolution regional climate model (RCM) following rigorous mathematical/statistical procedures (Lal et al. 1998a; Lal 2003). Location-specific scenarios on probable changes in daily surface air temperature, precipitation and solar radiation (a function of cloudiness) during the growing seasons (including the key characteristics of likely changes in variance of surface temperature and monsoon rainfall) for the selected sites in South Asia were developed using high resolution regional projections for the middle of twenty-first century described in Lal (2003). These location-specific future climate scenarios (changes in mean and variance) were used as input in crop simulation experiments (apart from a series of sensitivity experiments) to obtain likely changes in potential productivity of each crop at the selected sites by the middle of the twenty-first century. Increased intra-seasonal and interannual climatic variability is expected to go hand-in-hand with broader trends in temperature and rainfall at the selected sites; hence, the future scenarios included daily changes in mean and variance of meteorological parameters. Extreme weather events also result in significant crop losses from wind damage, flooding, or inadequate soil moisture. Although it is recognized that extreme weather will affect future yields, it is very difficult to model such stochastic events in a way that provides realistic assessment of their yield impacts. The potential effects of climate change in crop damage due to pests and diseases was not considered in this study and assumed to remain at the current level. At present damage due to pests and diseases is estimated to reduce potential global crop yields by 30% each year (Royal Society 2005). Future changes in temperature and precipitation will undoubtedly affect the prevalence and geographical extent of specific pests and insects, which in turn will impact upon crop losses. The crop modelling exercises reported here also do not take into consideration the plausible technological innovations likely in agricultural practices.

Implications for sustained agriculture productivity

While there are uncertainties on the nature and extent of impending changes, an overall decline in agricultural productivity has been envisaged due to projected climate change in most tropical countries (Easterling et al. 2007). The impact of declining food productivity will be felt more severely in developing countries of South Asia whose economy is largely dependent on agriculture and is already under stress due to current population increase and associated demands for energy, fresh water and food (Lal et al. 2001a). In South Asia, the socio-economic environment of several countries is characterized by high population density and relatively low rates of economic growth (UNEP 1999). Many countries here are already vulnerable to extreme climate events and changes in climate could exacerbate these vulnerabilities.

In view of the fact that the water and the agriculture sectors are likely to be most sensitive to climate change induced impacts in South Asia, climate projections, as discussed above, have been used to simulate potential crop yields to obtain the range of possible impacts of change in climate mean/variance until 2050 on the productivity of both irrigated and rain-fed wheat and rice (the two most important staple food crops in South Asia). The findings of these simulation studies have been summarized in Tables 6 and 7 below. Investigations have also focused on the determination of the critical thresholds (envisaged as “dangerous anthropogenic interference with the climate system” under Article 2 of the Framework Convention on Climate Change) beyond which cereal crop productivity in five selected regions of South Asia (South India and Sri Lanka; Central Plains of India; northern India and Nepal; northeast India and Bangladesh; northwest India and Pakistan) would be adversely affected in the future and on possible region specific adaptive options.

It is evident from Table 6 that both the wheat and rice yields would increase in a doubled CO_2 atmosphere due to CO_2 fertilization effects provided there are no thermal or water stress. The yield gains due to CO_2 fertilization effects would be offset by the negative impacts of a 2°C increase in mean daily surface temperature on irrigated rice and wheat yields (when the enhanced thermal variability and projected decline in diurnal temperature range is imposed in crop model simulations, but there is no water stress on the crop at any stage of development) in most of South Asia. Thus, if the increase in surface temperature exceeds 3°C, the combined effect of rising surface air temperatures

Table 6 Per cent change in irrigated cereal crop yields in South Asia due to CO_2 increase and thermal stress

Scenarios	Irrigated rice yield		Irrigated wheat yield	
	Region 1[a] (%)	Region 2[b] (%)	Region 1 (%)	Region 2 (%)
2 X CO_2	+17	+18	+26	+25
2 X CO_2; +1°C	+5	+3	+23	+23
2 X CO_2; +2°C	+1	+1	+12	+9
2 X CO_2; +3°C	−8	−5	+1	−2
2 X CO_2; +2°C; projected temperature variance	−7	−6	−1	−3

[a] Region 1 includes Pakistan, north, northeast and northwest India, Nepal and Bangladesh

[b] Region 2 includes Central Plains of India, South India and Sri Lanka

Table 7 Per cent change in rain-fed cereal crop yields in South Asia due to CO_2 increase and thermal and water stresses

Scenarios	Rain-fed rice yield		Rain-fed wheat yield	
	Region 1[a] (%)	Region 2[b] (%)	Region 1 (%)	Region 2 (%)
2 X CO_2	+15	+18	+26	+24
2 X CO_2; +1°C	+4	+6	+21	+22
2 X CO_2; +2°C	−1	−1	+11	+7
2 X CO_2; +3°C	−12	−8	+2	−1
2 X CO_2; +2°C; +10% rain	+2	+3	+16	+9
2 X CO_2; +2°C; −10% rain	−5	−4	−3	−8
2 X CO_2; +2°C; −20% rain	−24	−21	−11	−19
2 X CO_2; +2°C; −20% rain Projected climate variability	−31	−30	−18	−23

[a] Region 1 includes Pakistan, north, northeast and northwest India, Nepal and Bangladesh

[b] Region 2 includes Central Plains of India, South India and Sri Lanka

and carbon dioxide concentrations are bound to have adverse consequences on wheat and rice productivity under irrigated cropping system.

Rice production in South Asia will need to grow by at least 1.5% $year^{-1}$ (as against the current 1% growth rate) in the next two decades (Zimmer and Renault 2004). Maintaining and increasing productivity growth in the irrigated rice systems have been severely constrained by the looming water crisis in South Asia. The water usage in the current rice production agriculture system in India is extremely high; it takes about 3,000 l of water to produce 1 kg of rice (Tuong and Bouman 2003). This profligate usage of water in irrigated rice production is unsustainable, given the increasing demand for freshwater due to growth in rice demand and growing competition from other agriculture and non-agriculture sectors. It is also important to increase rice productivity in rain-fed (non-irrigated) fields, which occupy over 50% of the areas planted to rice in South Asia (Royal Society 2005). Despite their large share in total paddy areas, rain-fed fields produce only a quarter of South Asia's rice output, largely because the constant threat of drought prevents poor farmers from investing in yield-increasing technology (FAO 2002). The major droughts of 2000 and 2002 seriously affected rice production in India (DES 2003). In the eastern states of Jharkhand, Orissa, and Chattisgarh alone, rice production losses in severe droughts (about 1 year in 5) averaged 40% of total production with an estimated value of $650 million (Pandey et al. 2005). In South Asia, water shortage and droughts are endemic. It is estimated that, by 2025, even 12 Mha of irrigated rice in South Asia may suffer from severe water shortage, with serious effects on sustained food productivity and social stability of the region (Bruinsma 2003). We have, therefore, also assessed the impacts of projected climate change in the potential yields of rain-fed rice and wheat in South Asia and the salient findings are reported in Table 7.

The results highlighted in Table 7 suggest that there is no significant difference in the CO_2 fertilization effect on both the wheat and rice yields in rain-fed system with that inferred for irrigated system. A 2°C increase in mean daily surface temperature will offset the positive role of CO_2 fertilization effect on rain-fed rice yields in most part of South Asia. The temperature rise of 3°C is critical for decline in potential wheat productivity in the region. The combined effects of a 2°C increase in surface air temperatures and a 20% decline in rainfall are bound to have serious consequences on wheat and rice productivity in the region under rain-fed cropping system.

This study further suggests that for each 1°C increase in mean nocturnal temperatures, the decline in rice yield would be about 6–10% on an average in the South Asian countries. This finding is consistent with many earlier studies with focus on site-specific results including those of Sinha and Swaminathan (1991) who reported that an increase of 2°C in the current mean daily temperature could decrease the rice yield by about 0.75 t ha^{-1} in the high-yield areas, and a 0.5°C increase in current mean winter temperature would shorten wheat crop duration by 7 days and reduce wheat yield by 0.45 t ha^{-1}. Our findings also confirm those reported in Lal et al. (1998b) that 2°C increase in surface air temperature would decrease wheat yields in most of South Asian countries. This study reaffirms that CO_2 fertilization effects would not be able to offset the negative impacts of increase in temperatures beyond 2°C on rice and wheat yields in South Asia. This study suggests that the average change in wheat yields in

South Asia would range between +4 and −34% for the mid-twenty-first century under projected climate scenarios. The potential yields in non-irrigated (rain-fed) wheat and rice will significantly decline in South Asia for a temperature increase of between 2.5 and 3.5°C which, according to Kumar and Parikh (1998), could incur a loss in farm-level net revenue of between 9 and 25%. An enhanced intra-seasonal and interannual variability of rainfall would substantially affect the average output of agriculture in monsoon region of South Asia.

This study re-iterates that climate-induced variability will continue to affect strategic grain supplies and sustained food productivity of many nations in South Asia. The alterations in the patterns of extreme events, such as increased frequency and intensity of droughts (prolonged dry spells), will have more serious consequences for chronic and transitory food insecurity than would have shifts in the patterns of average temperature and rainfall. On an aggregate level, there might not be a significant impact of global warming on food production of South Asia in the short term (<2°C; until 2020s), provided that water for irrigation is available and agricultural pests could be kept under control (with improvement in management practices). The increasing frequency of droughts and floods would, however, continue to seriously disrupt food supplies on year to year basis.

While the productivity of *Kharif* crops (summer monsoon season) would decline due to the increased climate variability and pest incidence and virulence in long term (2050s and beyond), the productivity of *Rabi* crops (winter season) is likely to be more seriously threatened in response to rise in surface air temperature above 2°C. The simulation results suggest that even under the most conservative climate change projections (a regional warming of 3°C), net cereal production in South Asia will decline by at least between 4 and 10% at the end of twenty-first century. Overall crop productivity in Central and South India, Bangladesh and Sri Lanka would be more adversely affected than in northern India, Pakistan and Nepal. In terms of the reference to UNFCCC Article 2 on dangerous anthropogenic interference with the climate system, the critical threshold for sustained food productivity in South Asia appears to be a rise in surface air temperatures of ~2°C and a marginal decline in water availability for irrigation or decrease in rainfall during the cropping season. This implies that the risk of food insecurity in South Asia could be minimized if the European Union (EU)'s target of limiting the global mean warming to 2°C above pre-industrial level could be achieved. If the increase in surface temperature exceeds 3°C, its consequences on food productivity in South Asia could be catastrophic.

A more precise understanding of the relationship between location-specific climatic variability, crop management and agricultural productivity will be critical in assessing the impacts of climatic variability and change in crop production, the identification of adaptation strategies and appropriate management practices, and the formulation of mitigating measures to minimize the negative effects of climate variability and change including extreme events on agricultural productivity.

Conclusion

The water demand in most countries of South Asia is gradually increasing because of increases in population, irrigated agriculture and growth in the industrial sectors. Changes in water supply and demand caused by climate change will be overlaid on the top of changing water use. The projected changes in hydrological parameters over South Asia (apart from rising surface air temperatures and carbon dioxide) would have considerable direct effects (on crop physiology) and indirect effects (changes in pest population dynamics, irrigation availability, soil fertility, and socio-economic changes, none of which are considered here) on the crop productivity in the region. The development and use of water-efficient rice cultivars should be accorded high priority in the region.

The crop simulation study reported here and focusing on direct effects suggest that on an aggregate level, there might not be a significant impact of global warming on food production of South Asia in the short term (<2°C; until 2020s), provided water for irrigation is available and agricultural pests could be kept under control. The increasing frequency of droughts and floods would, however, continue to seriously disrupt food supplies on year to year basis. In long term (2050s and beyond), productivity of *Kharif* (summer monsoon season) crops would decline due to increased climate variability and pest incidence and virulence. Production of *Rabi* (winter season) crops is likely to be more seriously threatened in response to 2°C warming. The net cereal production in South Asia is projected to decline at least between 4 and 10% under the most conservative climate change projections (a regional warming of 3°C) by the end of this century. Overall crop productivity in Central and South India, Bangladesh and Sri Lanka would be more adversely affected than in northern India, Pakistan and Nepal. In terms of the reference to UNFCCC Article 2 on dangerous anthropogenic (human-induced) interference with the climate system, the critical threshold for sustained food productivity in South Asia appears to be a rise in surface air temperature of ~2°C and a marginal decline in water availability for irrigation or decrease in rainfall during the cropping season. However, if EU's goal of limiting the global warming to 2°C above the pre-industrial level is not achieved, the production losses due to climate change may drastically increase the number of undernourished, severely hindering progress against poverty and food insecurity in this region.

A large proportion of adverse effects on crop yield and production in South Asia could be avoided or absorbed by suitable crop adjustments, developing proper genotypes and adopting appropriate technology for the changed environmental conditions. Adaptation measures to mitigate the potential impacts of climate change in crop productivity should include possible changes in sowing dates and genotype selection. Changes in the cropping sequence, irrigation and use can be additional options for adaptation in agriculture. Ensuring food security may remain an unaccomplished dream for many Asian countries unless appropriate adaptation and mitigation strategies are put in place to ensure environmental and ecological protection and conservation of natural resources.

In the twenty-first century, the dual demands for food and ecological security in South Asian countries would have to be based on the appropriate use of biotechnology, information technology and eco-technology (Swaminathan 2003). Practical achievements in bringing about the desired paradigm shift in sustainable agriculture will depend upon public policy support and political action.

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