AGRICULTURAL VULNERABILITY AND ADAPTATION IN DEVELOPING COUNTRIES: THE ASIA-PACIFIC REGION

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Abstract. During the last decades, a large number of climate change impact studies on agriculture have been conducted qualitatively and quantitatively in many regions of the Asia-Pacific. Changes in average climate conditions and climate variability will have a significant consequence on crop yields in many parts of the Asia-Pacific. Crop yield and productivity changes will vary considerably across the region. Vulnerability to climate change depends not only on physical and biological response but also on socioeconomic characteristics. Adaptation strategies that consider changes in crop varieties or in the timing of agricultural activities imply low costs and, if readily undertaken, can compensate for some of the yield loss simulated with the climate change scenarios. The studies reviewed here suggest that the regions of Tropical Asia appear to be among the more vulnerable; some areas of Temperate Asia also appear to be vulnerable.

1. Introduction

The Asian-Pacific region includes both the major land mass of Asia as well as thousands of islands in the Indian and Pacific oceans. Agriculture is a key economic sector in the Asian-Pacific region and accounts for a high portion of the national GDPs. For example, 20% of Thailand's GDP is in agriculture. Substantial foreign exchange earnings are derived from exports of agricultural products, (e.g., 70% in the Philippines) and agriculture employs over 50% of the labor force in most countries (60% in Thailand). It was the importance of agriculture to national and regional economy that caused people's attention widely to the possible impacts of climate change on agriculture during the last decade. Many national action plans, regional, international cooperative programs showed up. Large quantities of studies on assessment of vulnerability and adaptation of agriculture to climate change have been conducted in this region. These research results vary widely depending on the climate scenarios, geographic scope, and crop models used, etc.

2. Study Situations of Vulnerability and Adaptation in Asian Countries

2.1. TEMPERATE ASIA

Temperate Asia includes the following Asia-Pacific developing countries: China, North Korea, and Mongolia. Rice, wheat, and maize are the three leading food crops. Several major studies have been conducted in this area.

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For China, past results show generally negative yield effects but range from less than 10% (Zhang, 1993) to more than 30% (Jin et al., 1994). Hulme et al. (1992) concluded that to a certain extent, warming would be beneficial with increasing yield due to diversification of cropping systems. Meanwhile, they estimated that by 2050, when they expect an average warming for China of 1.2°C, increased evapotranspiration would generally exceed increase in precipitation, thus leading to a greater likelihood of yield loss due to water stress for some rice-growing areas even as the area suitable for rice increase. Recent studies show that the impacts vary widely in range, across different scenarios and different sites, the changes for several crop yield by 2050 are projected to be: rice (-78% to +15%); wheat (-21% to +55%); and maize (-19% to +5%) (Lin Erda, 1996). The potential impacts of climate variability on irrigation rice yields and rainfed rice yields (in Guangzhou, Changsha, and Nanjing) were also conducted under regional climate model. Simulated results show that climate variability has negative effect on irrigation rice yields; the greater the climate variability, the worse this kind of effect. For rainfed rice, climate variability has positive effect on its yield in Guangzhou and Changsha area (Luo et al., 1998). The potential impacts of climate variability on China's maize have the same law as rice (Wang et al., 1996). Six areas that will be affected negatively by climate change were identified: the area around the Great Wall; the Huang-Hai Plains; the area north of Huai River; the central and southern areas of Yunnan Plateau; middle and lower reaches of Yangtze River; and the Loess Plateau. Seven provinces with high vulnerability and less adaptation to climate change were also identified: Shanxi, Inner Mongonia, Gansu, Hebei, Qinghai, and Ningxia. As result, the areas along the Great Wall and Huang-Hai Plains are areas that both socioeconomically and agronomically vulnerable to climate change and also are areas where climate projections suggest possible adverse changes in climate (IPCC 1996, WG II, section 13.6.3). Lu and Liu (1991a, 1991b) pointed out climate change will occur against a steadily increasing demand for food in China over the next 55 years. The increased annual cost of government investment only (excluding farmers' additional costs) in agriculture due to climate change through 2050 was estimated at 3.48 billion U.S. dollars (17% of the government investment in agriculture in 1990) (IPCC 1996, WGII, section 13.6.3). In face of above problems, the following adaptations are suggested to lessen the detrimental effects of climate change on China's agriculture: assuring the sown acreage of grain to stabilize at a level of 0.08-0.09ha per capita to attain the product target; strengthening irrigation capacity; transforming medium or low-yield farmland; popularizing a more optimal fertilizer mix and adopting the technique of subsoil application, using superior species of crops; improving standardizing cultural techniques under climate variation; using dryland farming techniques; and developing feed crops instead of grain crops.

For Mongolia, Bayasgalan et al. (1996) researched the effect of climate change (GISS-G1, GFDL-A3) on the yield of spring wheat. Results show that the production of spring wheat could be reduced significantly due to higher evapotranspiration. Simulated adaptive options, such as change planting dates, using different varieties of spring wheat, and applying the ideal amount of nitrogen fertilizer at the optimum time, are potential responses that could modify the effects.

2.2. TROPICAL ASIA

Tropical Asia includes most of the Asian-Pacific developing countries, such as Bangladesh, Bhutan, Cambodia, India, Indonesia, Laos, Malaysia, Myanmar, Nepal, Papua New Guinea, Philippines, Singapore, Sri Lanka, Thailand, and Vietnam. Rice is by far the most important food crop across the humid areas of Tropical Asia. In arid and semiarid areas, a wide variety of other crops are grown, including soybeans, maize, wheat, roots, tubers, fruits, and vegetables. Production is often highly dependent on irrigation.

Many climate change impact studies have been conducted in various regions of Tropical Asia. Studied results show that climate change would amplify frequency and intensity of hazardous weather, such as tropical cyclones, storm surges, floods, and droughts, which damage life, property, and crop production. Agriculture in this area is very vulnerable to climate change. A decrease in rice production due to climate effects and sea level rise, combined with rapidly increasing population, would threaten food security (Iglesias et al., 1996). Anglo et al. (1996) noted that changes in average climate conditions and climate variability will have a significant effect on agriculture in many parts of the region. Particularly vulnerable are the low-income populations dependent on isolated agricultural system. This includes many areas that concentrate on the production of tropical crops such as tea and coconuts as well as regions with limited access to agricultural markets. Changes in climate variability would affect the reliability of agriculture. Matthews et al. (1995) have estimated the impact on rice yields for many countries in this region for equilibrium climate scenarios of three major General Circulation Models (GCMs) that predict temperature, precipitation increases for this region. Simulated results show substantial variation in impact across the region and among the GCMS. Decreased rice yields were projected for low latitude areas in tropical Asia,and increased yields were projected for higher latitudes. Such results indicate a possible shift in the rice-growing regions away from the equatorial regions to higher latitudes. Spikelet sterility emerged as a major factor determining the differential predictions, where current conditions were near critical thresholds, and a difference in mean temperature of less than a degree resulted in a positive yield change rapidly becoming a large decline. However, genetic variability among varieties suggests relative ease in adapting varieties to new climate conditions. Temperature effects alone were generally found to reduce yields, but carbon dioxide (CO_2) fertilization was a significant positive effect in some cases.

In Bangladesh, the impact of climate change parameters such as drought, inundation, and salinity intrusion on rice, a major crop of Bangladesh, was studied by Karim et al. (1996) using the CERES-Rice Model and several scenarios and sensitivity analyses. They found elevated CO_2 levels increased rice yield; considerable spatial and temporal variation ; high temperature reduces rice yield in most locations; the detrimental effects of temperature rise more than offsets the positive effect from increased CO_2 level; 0.8 to 2.9 million metric tons of potential rice output may be lost, representing 13-24% of projected output in the affected zone by the year 2030. These losses increase dramatically after 2030 under both the 45 cm and 1 m sea level rise scenarios. High yielding varieties of rice cultivars are more susceptible to drought, resulting in a considerable decrease in production under water stress conditions. In addition, when land is submerged by flooding, the productivity of the high yielding varieties cultivars also decreases. For lands that are under more than 90 cm of floodwaters, the expected loss would be 100% for high-yielding Boro cultivars. On the other hand, the local varieties are significantly less susceptible to inundation. On the other hand, Brammer et al. (1994) concluded that, among other things, the diversity of cropping systems does not allow a conclusion of magnitude or direction of impact to be made for Bangladesh at this time. Agricultural adaptation strategies also addressed included rice genotype development to sustain rice yield; management options and adjustment of agroecological variability of rice yield with the change in climate; development of mitigating technologies, etc. (Karim et al., 1996).

Parry et al. (1992) showed yield impacts (-65% to +10%) that varied across the countries of Thailand, Indonesia, and Malaysia and across the growing season, leading to losses in farming income of US$10 to US$130 per year. Coastal inundation was also estimated to be a threat to coastal rice. These authors estimated that a 1-meter sea-level rise could cause a landward retreat of 2.5km in Malaysia; such a rise was estimated to threaten 4200ha of productive agricultural land, an area equal to about 0.63% of Malaysia's paddy rice area (0.61% of total cereal area). Model results showed that under Goddard Institute for Space Studies(GISS) doubled CO_2 climates, erosion rates in three Malaysian river basins increased from 14 to 40%, and soil fertility declined on average by 2-8%. In Thailand, Tongyai (1994) tested GCM climate change scenarios on simulated upland and paddy rice and found that yields decreased by -2 to -17% in two of the scenarios (with direct CO_2 effects included). The third GCM scenario implied little change (-1 to +6%). Amien et al. (1996) found near-term changes in climate could have significant effects on rice yields in Indonesia. For the years 2010 through 2050 the rice yield is estimated to decrease by about 1% annually in East Java and less in West Java due to increase in temperature. The

Climate Change in Asia: Executive Summary reported that production of many crops in Indonesia is likely to decline due to flooding, erosion, the loss of arable land, and greater plant moisture loss during the dry season. Shifts in precipitation patterns are likely to disrupt cropping in both rainfed and irrigated agricultural systems, compounded by changes in soil moisture due to temperature shifts and erosion. Aside from the loss of arable land due to sea level rise, the anticipated effect nationwide of soil degradation due to greater precipitation is that yields of upland crops such as soybean and maize will decline by 20% and 40%, respectively, whereas rice yields will decline by only 2.5%, as rice is planted primarily in lowland regions. That is, impacts are likely to be most serious in upland areas, where farmers will suffer from deteriorating soil quality and abrupt changes in water supplies due to soil erosion and new precipitation patterns. The combined effects of area and soil erosion may diminish economic productivity in the agricultural sector by $6 billion annually. Suggested adaptation measures include soil conservation and water conservation; afforestation through agroforestry, particularly with nitrogen-fixing crops; abandoning cultivation if customary crops can no longer survive; introducing other species better able to withstand the new climatic conditions. In a study of Northwest India, Lal et al. (1996) also found that with the rise in surface air temperature the reduction in yield offsets the effects of elevated CO_2 levels, the projected net effect being a considerable reduction in rice yield. In the Philippines, the agricultural impacts were expected to be more serious in areas vulnerable to typhoons and floods, areas frequently visited by droughts, and those near coastal areas most vulnerable to storm surge and salt intrusion. Higher rainfall scenarios for 2010 and 2070 may affect wetland crops due to floods and typhoons. Overall, the potential impacts are: production losses due to increased frequency of floods; higher costs in maintaining drainage and irrigation systems due to damages from more frequent flooding; more crop diversification due to higher rainfall availability in some areas; higher incidence of pest and disease among crops; increased market prices of agricultural products due to lower supply and higher production costs. Adaptive options were also addressed, including developing cultivars resistant to climate change; putting new farm techniques into place that will respond to the management of crops under stressful conditions, plant pests and disease; design and development of efficient farm implements; and improvement of post-harvest technologies, which include among other things, the use and processing of farm products, by-products and agricultural waste (Climate Change in Asia: Executive Summary). Escano et al. (1994) conducted a study, in which results showed that rice yield in the Philippines declined under GCM scenarios with direct CO_2 effects taken into account in at least one important agricultural region of the Philippines. In Sri Lanka, some adverse impacts on agriculture were found. Agriculture will be affected by salinity intrusion and flooding. A large amount--28,350 hectares of low lying paddy lands already affected by flooding, poor drainage, salt water intrusion and iron toxicity will be lost. Coarse grains and grain legume will be subjected to severe fluctuations in annual production. Rice cultivation, too, will be similarly affected. Analysis of impacts on paddy (rice) using a crop model developed by Seshu and Cady (1983) showed that paddy cultivation will drop by about 6% with a temperature increase of 0.5°C in the year 2010. This will reduce GNP at current prices by 0.2%. Another study on rice using regressive analysis techniques showed an increase in output with small temperature increases, but output drops with further increase in temperature. The following are adaptive options: trying out salt water resistant varieties of crops in the areas where drainage is poor; diversifing agriculture and food habits of the people primarily limited to rice, wheat flour and sugar, available crops, including other grains, yams and tubers and food crops such as jack and bread fruit and nontraditional food fruit crops; improving management of irrigation systems; improving management of wet zone watersheds and catchment areas; implementing crop-livestock integration; changing crop varieties and cropping patterns to suit changing climatic conditions; implementing agro-forestry systems, etc. (Climate Change in Asia: Executive Summary).

The impact of climate change on wheat yield simulated for several locations in India using a dynamic crop growth model WTGROWS indicated that productivity was dependent on the magnitude of temperature change. In North India a 1°C rise in the mean temperature had no significant effect on potential yields, though an increase of 2°C reduced potential grain yields at most places (Aggarwal et al., 1993). In a later study, Rao et al. (1994) used the CERES-Weat simulation model and scenarios from three equilibrium GCMs (GISS, GFDL and UKMO) and from the transient GISS model to assess the physiological effects of increased CO_2 levels. They showed that in all simulations wheat yields were smaller than those in the current climate, even with the beneficial effects of CO_2 on crop yield; and yield reductions were due to a shortening of the wheat-growing season, resulting from scenario temperature increase. Wheat yield decreases could have a serious impacts on food security of India, in view of the increasing population and its demand for grains. Most of the wheat production in India comes from the northern plains, where it is almost impossible to increase the present area of wheat under irrigation. Karim et al. (1996) have also shown that wheat yields are vulnerable to climate change in Bangladesh. Studies on the productivity of sorghum showed adverse effects in rainfed areas of India (Rao et al., 1995), similar to corn yield in the Philippines (Buan et al., 1996).

The likely impact of climate change on the tea industry of Sri Lanka was studied by Wijeratne (1996). He found that tea yield is sensitive to temperature, drought and heavy rainfall. The possibility of an increase in the frequency of droughts and extreme rainfall events could result in a decline in tea yield, which would be greatest in the low country tea growing regions (<600 m). The other important crops of the region are rubber, oil palm, coconut, sugarcane, coffee, spices, etc. but almost no information on the impact of climate change on these crops is available. Sea level rise and climate change could seriously affect Vietnam's agriculture. Drought could occur more frequently during the winter-spring crop season; inundation could occur more frequently during the winter and summer -autumn seasons (Climate Change in Asia: Executive Summary).

2.3. ARID ASIA

Arid Asia includes the following Asian-Pacific developing countries: Afghanistan, Kazakhstan, Kyrgyz Republic, Pakistan, and Uzbekistan.

General assessments have suggested a range of both positive and negative impacts of climate change scenarios on agriculture. Positive examples include decreasing frost risks and more productive upland agriculture, providing water availability does not decline (or irrigation is available) and appropriate cultivars are used. Populations of pests and disease-causing organisms, many of which have distributions that are climatically controlled, may have a negative impact (IPCC SAR WGII, Chapter 5.2.4.1). A more important process-increase in efficiency with which plants use water in atmospheres high in CO_2 was found by Bazzaz et al. (1996). In atmosphere rich in CO_2 plants can take up the CO_2 necessary for photosynthesis with less loss of water from their stomata pores. This gain in water use efficiency has been demonstrated to be most advantageous in plants growing in water limited circumstances and, thus, may lead to higher productivity throughout much of the region. There is also evidence that forage quality and the protein content of some cereals may fall, which may affect farm management system significantly (Diaz, 1995). Suggested adaptation options include: adoption of water conservation techniques; expansion of winter-growing crops that are much less demanding on water; diversification of economic activity; a shift reliance toward more suitable and more intensively managed land areas for food and fiber production (IPCC SAR WGII, Chapter 2, 4).

There are very few studies quantitatively looking at the impact of climate change in this region with the exception of Kazakhstan and Pakistan. The preliminary vulnerability assessments based on the DSSAT model for $2xCO_2$ conditions showed that the spring wheat and winter wheat yields would decrease by 12% in Northern Kazakhstan. But the crop model of KazNIGMI gave spring wheat yields twice below those of 1991 if the warming is 2-3°C compared with current climate. Potato productivity is decreased by 6-10% if the warming will be 2°C (Kavalerchik et al., 1995). Pilifosova et al. (1996) estimated the possible effects of climate change on yields of spring wheat and winter wheat in Kazakhstan. Reductions of spring wheat yield are anticipated to be 56% under CCCM, 51% under GFD3, and 12% under GFD1 scenarios. Winter wheat yield could increase about 21% under GFD1 and 17% under GFD3 and CCCM scenarios. Confronted with this situation, the following adaptation alternatives are recommended: changing planting dates; switching from spring wheat to winter wheat; irrigating; increasing fallow area; implementing snow reserving; switching to more suitable wheat varieties; applying fertilizer, pesticides, and weed control; and last, applying zonal growing technology. Average summer monsoon rainfall in Pakistan's inland would increase by 17 to 59%. This would be associated with a doubling in the frequency of magnitude rainfall. The resulting floods could destroy the irrigation infrastructure and crops, particularly cotton. Cotton planted in June and July is extremely susceptible to field flooding in its early stages of growth. This would be detrimental to the economy as cotton is the main cash crop of Pakistan. On the other hand, the GISS model projected opposite results: a decline in the summer monsoon and associated water resources. This could severely stress winter (Rabi) crop production, including wheat, the main food staple (Climate Change in Asia: Executive Summary). Qureshi et al. (1994) used GCMs and dynamic crop models to estimate the potential agricultural effects of climate change in Pakistan. Under present climate conditions, wheat is currently under stress due to high temperatures and arid conditions. Projected climate change caused simulated wheat yields to decrease dramatically in the major areas of agricultural production, even under fully irrigated conditions. Decreases in modeled grain yields were caused primarily by temperature increases that shortened the duration of the life cycle of the crop, particularly the grain-filling period. These decreases were somewhat counteracted by the beneficial physiological CO_2 effects on crop growth. Adaptation strategies that were considered in the analysis included development of more heat resistant cultivars, delayed planting, and other changes in farming practices. Together, these adaptation strategies offset some, but not all, of the yield losses estimated to occur with the changed climate.

Estimates of yield impacts from various studies and factors considered in each study are provided in table I and table II respectively.

3. Further Research Needs

Most of the studies reviewed in this paper used dynamic crop models to simulate yield effects. A few studies used statistical models (regression analysis) to study the potential impacts of climate change on agriculture. Most applications of statistical models introduce weather and climate effects in a highly simplified fashion and thus are unable to simulate the effects of the extremes of weather as it varies on a daily basis as is possible with dynamic crop growth models. With the development of science and technology, dynamic crop simulation models have been developed and have become the main method of analyzing the potential impacts of climate change on agriculture. As a tool to assess the vulnerability and adaptation of agriculture to climate change, it is more accurate,

TABLE I

Estimates of yield impacts from various studies

Study	Geographic scope	Crops	Yield impact(%)	Scenario	Direct effect of CO2	Other comments
Zhang, 1993	China	Rice	-11 to -7	+1.5°C	Yes	Double- Crop
Jin *et al.*, 1994			-78 to +15	GCMs	No	Range across GISS, GFDL, and UKMO Scenarios
Lin, 1996		Wheat	-21 to +55	GCMs	No	Range across GFDL, MPI and UKMOH Scenarios
Lin, 1996		Maize	-19 to +5	GCMs	No	Range across GFDL, MPI and UKMOH Scenarios
Wang *et al.*, 1996		Irrigated corn	-0.1 to -9.3	GCMS	No	Range across GFDL, MPI and UKMOH Scenarios, Considered Climate Variability
		Riainfed corn	-1.2 to -12			
Bayasgalan *et al.*, 1996	Mongolia	Spring Wheat	-74.3 to 32	GISS, GFD3	No	
Matthews *et al.*, 1995	India	Rice	-12 to +23	3GCMs	Yes	GISS, GFDL, and UKMO Scenarios
	Bangladesh		-12 to -2			
	Indonesia		-6 to +22			
	Malaysia		+21 to +26			
	Myanmar		-9 to +30			
	Philippines		-2 to +12			
	Thailand		-20 to -34			
Parry *et al.*, 1992	Indonesia	Rice	-4	GISS	No	Estimated overall loss of farmer income ranging from $10 to $130 annually
		Soybean	+10 to -10			
		Maize	-25 to -65			

	Malaysia	Rice	-12 to -22			
		Maize	-10 to -20			
		Oil Palm	increase			
		Rubber	-15			
	Thailand	Rice	5 to 8			
Karim *et al.*, 1996	Bangladesh	Rice	-35	GCMs	Yes	Range across CCCM and GFDL
		Wheat	-31			
Tongyai, 1994	Thailand	Rice	-17 to +6	GCMs	Yes	
Amien *et al.*, 1996	Indonesia	Rice	-1	GCMs	No	Range across GFDL, GISS, and UKMO; considered the impact of Climate Variability
Climate Change in Asia: Executive Summary, 1994	Indonesia	Soybean	-20			Crop yields decrease due to soil degradation
		Maize	-40			
		Rice	-2.5			
Escano *et al.*, 1994	Philippines	Rice	decline	GCMs	Yes	
Rao *et al.*, 1994	India	Wheat	decrease	GCMs	Yes	Range across GFDL, GISS, UKMO, and Transient GISS
Wijeratne, 1996	Sri Lanka	Tea	decrease			Using linear regression analysis
Buan *et al.*, 1996	Philippines	Corn	decline	GCMs	Yes	Range across GFDL, GISS, and UKMO
Kavalerchik *et al.*,1995	Kazakhstan	Patato	-6 to -10	+2°C	No	
		Spring wheat	-12 to -56	GCMs	No	Range across CCCM, GFD3, and GFD1
Pilifosova *et al.*, 1996		Winter wheat	+17 to +21			
Qureshi *et al.*, 1996	Pakistan	Wheat	decrease	GCMs	Yes	

TABLE II
Effects considered in each study

Studies	Yield	Areal extent	Pest	Soil erosion	Market effect	Water availability
Zhang, 1993	X	X				
Jin *et al.*, 1994	X	X				X
Luo *et al.*, 1998	X					X
Lin, 1996	X	X				X
Wang *et al.*, 1996	X	X				X
Lu *et al.*, 1991a, b		X			X	
Bayasgalan *et al.*, 1996	X	X				X
Iglesias *et al.*, 1996	X	X			X	
Matthews *et al.*, 1995	X	X				X
Parry *et al.*, 1992	X	X		X	X	X
Karim *et al.*, 1996	X	X				X
Tongyai, 1994	X	X				X
Amien *et al.*, 1996	X					X
Climate Change in Asia: Executive Summary,1994	X	X		X	X	X
Lal *et al.*, 1996	X	X	X		X	
Escano *et al.*, 1994	X	X				X
Aggarwal *et al.*, 1993	X					X
Rao *et al.*, 1994	X	X				X
Wijeratne, 1996	X	X				
Buan *et al.*, 1996	X					X
Kavalerchik *et al.*, 1995	X	X				X
Pilifosova *et al.*, 1996	X	X				X
Qureshi *et al.*, 1996	X	X				X

"X" indicates the study considered the effect because of the reality of the mechanism of dynamic models. Such models were extensively used in the above studies. Generally, the outputs of GCMs, such as CCCM, GISS, GFDL, UKMO, MPI, GFD3, and GFD1 including equilibrium and transient GCMs and Regional Climate Model (RCM) with climate variability (increasing standard deviation of temperature 10%, 20%; increasing variation coefficient of precipitation 10%, 20%) considered or not were combined with various dynamic crop models to study the potential impacts of climate change on crop yields with the CO_2 fertilization effect taken into account or not by using the Stochastic Weather Generator.

Even with this substantial progress there remain some uncertainties and methodological problems in assessing the potential impacts of climate change on crop yields:

First is the problem of reliability of the GCMs that were used, which were based on runs performed at a coarse grid horizontal resolution of $5^{\circ}X5^{\circ}$. More reliable regional climate model and transient climate scenarios should be developed and used in future research in this area. Only a few studies have used higher resolution climate scenarios reviewed here.

Second, the crop modeling studies are site-specific, and the results need to be tested at other sites with different agro-climatic characteristics.

Third, this research did not consider the impacts of climate change on soil, water, meteorological disaster, pest and disease. In fact, normal variation in these factors has significant consequences for crop production.

Fourth, and finally, half of these studies did not take the CO_2 fertilization effect into account, which may compensate for some of the predicted decrease in crop yields.

Continuing uncertainty in projections suggests four critical, high-priority research needs:

1. *Assessment of the direct effects of CO_2 on crop production* Although many experiments have confirmed the beneficial effect of CO_2 on the mean response of crops (+30% for C3 crops, including rice), variation in responsiveness between plant species and ecosystems persists. Response depends on available nutrient, species, cultivar, temperature, and other stresses, as well as differences in the experimental technique.
2. *Development and broad application of integrated agricultural modeling efforts (those that consider interactions of biophysical and socioeconomic factors), and modeling approaches particularly applicable at the regional scale, including increased attention to validation, testing, and comparison of alternative approaches.* Climate effects on soil and plant pests, consideration of other environment changes, and adaptation options and economic responses should be an integrated part of the models rather than treated on an *ad hoc* basis or as a separate modeling exercise. Inclusion of these multiple, joint effects may significantly change our "mean" estimate of impacts, and more careful attention

to scale and validation should help to reduce the range of estimates for specific regions and countries across different methodologies.

3. *Development of the capability to readily simulate agriculture impacts of multiple transient climate scenarios.* Study of the sensitivities of agriculture to climate change and the impacts of doubled-CO_2 equilibrium scenarios has not led to the development of methods that can readily be applied to transient climate scenarios. To deal credibly with the cost of adjustment, about which there is significant uncertainty, the process of socioeconomic adjustment must be modeled to treat key dynamic issues such as how the expectations of farmers change, whether farmers can easily detect climate change against a background of high natural variability, and how current investments in equipment, education, and training may lead to a system that only slowly adjusts or adjusts only high cost and significant disruption. The ability to readily simulate effects under multiple climate scenarios is necessary to quantify the range of uncertainty.

4. *Evaluation of the effects of variability rather than changes in the "mean" climate, and the implication of changes in variability on crop yields and markets.* Extreme events have severe effects on crops, soil process, and pests. The more serious human consequences of climate change also are likely to involve extreme events such as drought, flooding, or storms, where agriculture production is severely affected.

Only when the four aspects above have been considered in crop modeling can the assessment of climate change on regional crop production be more accurate and serve as a sound basis on which to formulate policies.

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