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Climate Change and Rice

With a Foreword by Klaus J. Lampe

With 102 Figures and 67 Tables

Modeling the Impact of Climate Change
on Rice Production in Asia
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Modeling the Impact of Climate Change on Rice Production in Asia

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Our knowledge of the effects of CO₂ and temperature on the growth and development of the rice crop has increased in the past few years as a result of several controlled environment experiments in both the field and laboratory. These results are now being incorporated into rice growth models that simulate the response of the crop to changes in climatic variables. A start has also been made to use these models to assess the likely impact of changes in climate on rice production. Although these models are far from perfect, and sometimes rely on assumptions that have not been fully tested, they are the best method we have at present to investigate the effects of likely climate changes on agricultural production.

Several studies have described how rice yield may be affected by changes in the climate. Yoshino et al. (1988) predicted that lowland rice yields could increase in Japan by about 9% following a doubling of CO₂ and subsequent climatic changes as predicted by the Goddard Institute of Space Studies (GISS) general circulation model (Hansen et al. 1988). Jansen (1990) simulated potential yield, water-use efficiency, and nitrogen-limited yield of rice for combinations of three temperatures and three CO₂ scenarios for the years 2020 and 2100 using weather data from seven sites in Asia. He concluded that the effect would be a reduction in yield in the high temperature scenarios and an increase in the low temperature scenarios. Similar results were obtained by Penning de Vries (1993). These effects were related to predicted increases in photosynthesis at higher CO₂ and a reduction in the length of the growing season at higher temperatures. However, their models did not account for the decrease in phenological development rates

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at supraoptimal temperatures. Rosenzweig et al. (1993), working with collaborators from 22 countries, predicted reductions in yield at low latitudes and increases at high latitudes for a number of major crops. Leemans and Solomon (1993), using a very simple model and long-term monthly average climatic data in a world-wide study, predicted a yield increase of 0.4% for the current rice-growing environments, but little change in the areas sown because of the sharp temperature and moisture gradient along the northern border of the primary distribution of rice in eastern Asia. From these various estimates, it is clear that a wide range of predictions has been made on the likely effect of climate change on the production of rice. These studies contain many uncertainties, partly because of uncertainties in the predictions of the GCMs themselves, partly from the use of limited sites for which historical weather data are available, and partly from the quality of the crop-simulation models, especially for rainfed conditions (Bachelet et al. 1993).

In 1989, the US EPA Environmental Research Laboratory and IRRI initiated a major research project to investigate relationships between climate change and rice production. One component of this project was the integration of knowledge about rice responses to temperature and CO₂ into existing crop simulation models. This simulation component was executed by IRRI in collaboration with four teams of the Simulation and Systems Analysis for Rice Production (SARP) network (a collaborative network of scientists in national research stations in Asia, two institutes in the Netherlands, and IRRI), the Crop Science Laboratory at Kyoto University in Japan, and the US EPA Environmental Research Laboratory in Oregon, United States. The purpose of this chapter is to describe the model used and some of the preliminary results obtained from the study. Further details of the study are given in Matthews et al. (1994).

The ORYZA1 Model

The study used the ORYZA1 rice potential production model developed jointly at IRRI, Wageningen, and the collaborating institutes of the SARP network (Kropff et al. 1993b). ORYZA1 assumes that the potential yield of a crop is determined only by varietal characteristics, the seasonal pattern of temperature, radiation and daylength, and the ambient CO₂ concentration. The model has limitations: it assumes that weeds, diseases, and insect pests are absent, that water and fertilizers are abundant, that there are no adverse soil conditions, and that no extreme weather events (e.g., typhoons) occur. Although this may not be completely realistic, this approach has been found to explain a large part of the current yearly variation in rice yields in Japan because of weather (Horie 1994) and enables an understanding of the effect of climate on the underlying processes that influence crop yield.

The model simulates the processes of photosynthesis, respiration, dry matter partitioning, and leaf-area growth on a daily basis and uses values of solar radiation and minimum and maximum temperatures as inputs. Phenological events (e.g., dates of panicle initiation, 50% flowering, and maturity) are simulated using temperature and photoperiod as driving variables. A detailed description of ORYZA1 is given in Kropff et al. (1993b).

Dry Matter Production

Total daily canopy photosynthesis is calculated from the daily incoming radiation, temperature, leaf area index, and canopy nitrogen level by integrating instantaneous rates of leaf CO₂ assimilation at different levels in the canopy and at different times of day. After subtraction of respiration requirements, net daily growth is obtained. Dry matter produced is then partitioned among the various plant organs.

The relationship between photosynthesis rate and incident light level is commonly described by the light-response curve, a negative exponential relation that is characterized by two parameters: P_{max} the (asymptotic) maximum rate of photosynthesis attainable under high light conditions, and ε light-use efficiency at very low levels of light (Goudriaan 1982). There is a gradual decline in ε as temperature increases, mainly because of the increased affinity of the carboxylating enzyme rubisco for O₂ in relation to that for CO₂ (Ehleringer and Pearcy 1983). There is little effect of temperature on P_{max} between 20 and 37 °C, but outside these limits, photosynthetic rate declines rapidly (Penning de Vries et al. 1989).

The effect of CO₂ on the photosynthetic parameters was included according to the function derived by Jansen (1990) for the effect on ε, and a new relationship was derived from unpublished data collected at IRRI (Weerakoon et al.) for the effect of CO₂ on P_{max}. This relationship was derived by correcting the data for differences in the N concentration of the leaf. The relationship derived by Jansen from data of Akita (1980) for ε (g CO₂/MJ) is:

$$\varepsilon = \varepsilon^* [1 - \exp(-0.00305 C - 0.222)] / [1 - \exp(-0.00305 \times 340 - 0.222)], \quad (1)$$

where ε* is the initial light-use efficiency at standard values of 340 μl l⁻¹ CO₂ and 25 °C, and C is the atmospheric CO₂ concentration (μl l⁻¹). For P_{max} (g CO₂ m⁻² h⁻¹) the following relationship was derived:

$$P_{\max} = P_{\max}^* \left(49.57 / 34.26 \left\{ 1 - \exp \left[-0.208 (C - 60) / 49.57 \right] \right\} \right), \quad (2)$$

where P_{max}^{*} is the value of P_{max} at 340 μl l⁻¹ CO₂ and 25 °C.

In the process of maintenance respiration, part of the carbohydrates produced by photosynthesis are converted back into CO₂ and water to provide the energy for maintaining existing biomass. Although this process consumes

between 15 and 30% of the carbohydrates produced by a crop in a growing season (Penning de Vries et al. 1989), it is poorly understood at the biochemical level. In the model, we use an adapted version of the simple approach developed by Penning de Vries and van Laar (1982), in which maintenance requirements are approximately proportional to the dry weights of the plant organs to be maintained. The effect of temperature on maintenance respiration is described by:

$$R_m = R_m^* 2^{[(T_{av} - 25)/10]}, \quad (3)$$

where R_m is the actual rate of maintenance respiration ($\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), R_m^* is the maintenance respiration rate at 25 °C ($\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), and T_{av} is the daily mean temperature (°C). The rate of maintenance respiration increases proportionately more as temperature increases.

Any carbohydrates in excess of maintenance requirements are available for conversion into structural plant material, during which a relatively constant fraction of assimilate is lost because of growth respiration. We have assumed that there is no direct effect of either temperature or CO_2 on this fraction.

After the daily increment in dry matter has been calculated, this is partitioned according to fixed ratios (depending on the stage of development of the crop) into that required for growth of the leaves, stems, roots, and panicles. We have assumed that there is no direct effect of temperature and CO_2 on these partitioning ratios.

Phenology

Because many physiological and morphological processes change with the phenological stage of the plant, an accurate description of phenological development is essential. We divided the life cycle of the rice crop into four phenological phases: basic vegetative phase (BVP), from sowing to the start of the photoperiod-sensitive phase; photoperiod-sensitive phase (PSP), during which daylength influences development rate (the PSP lasts until panicle initiation (PI); panicle formation phase (PFP), starting at the switch from the vegetative to the reproductive phase at PI, and lasting until 50% flowering; and grain filling phase (GFP), from 50% flowering to physiological maturity. The model assumes that there is a variety-specific constant number of developmental days required for completion of each phase.

The original version of ORYZA1 used a linear relationship between the daily mean temperature above a base temperature and the rate of development toward a given phenological event. A plateau was reached at about 30 °C, beyond which development rate did not change (Kropff et al. 1993b). However, data for many crops indicate that at temperatures above an optimum, the development rate decreases (Mohamed et al. 1988; Hammer et al. 1989; Hodges 1991). Although comprehensive data are lacking in rice for temperatures greater than 33 °C, recent data collected at IRRI suggest that there is a similar response (Manalo

et al. 1994). Therefore, for the higher temperatures encountered in climate-change scenarios, we modified the temperature versus phenology function.

The new temperature versus phenology function assumes that the rate of progression through each phase is linearly related to daily mean temperature above a base temperature (T_{base}) up to an optimum temperature (T_{opt}), beyond which the rate decreases, again linearly, until a maximum temperature (T_{high}) is reached (Kiniry et al. 1991). For temperatures below the base temperature or above the maximum temperature, development rate is zero. This bilinear response is generally observed only when daily temperatures are constant (Mohamed et al. 1988). If temperatures fluctuate between a minimum and a maximum value, the response becomes curvilinear, particularly near each cardinal temperature. To account for this, we superimposed a sine wave representing the diurnal fluctuation in air temperature onto the bilinear response (Matthews and Hunt 1994). We also assume that there is no effect of CO_2 concentration on development rate.

Spikelet Fertility

In rice, spikelet fertility is influenced adversely by extreme temperatures immediately before and during flowering (Yoshida 1981). A reduction in spikelet fertility reduces the number of grains that can form, so that even if carbohydrate production in the grain-filling period is unaffected, yields are reduced. For this reason, ORYZA1 computes numbers of spikelets formed and the fraction of spikelets that form grains.

In experiments at IRRI, we found a good relationship between spikelet number at flowering and total crop growth from PI to 50% flowering. This relationship holds across wet and dry seasons, across nitrogen application levels from 0 to 285 kg/ha, across planting densities from 25 to 125 plants m^{-2} , and for severe drought stress. Effects of solar radiation, temperature, nitrogen, competition, and water on spikelet formation, therefore, can seemingly be integrated by their effects on crop growth over the panicle-formation period. We call the slope of this relationship the spikelet formation factor (γ). For a given variety, the relationship is remarkably consistent, although there are differences between genotypes. For example, γ has a value of about 65 spikelets/g of shoot dry matter for IR72, but ranges from 45 to 70 spikelets/g in other genotypes.

The model tracks the amount of growth from panicle initiation, and then calculates the number of spikelets at flowering (S_f , m^{-2}) as the product of this growth and γ :

$$S_f = \left(\sum_{i=P}^F G_i \right) \gamma, \quad (4)$$

where P and F are the dates of panicle initiation and 50% flowering, respectively, and G_i is the increase in crop dry weight on day i ($\text{g m}^{-2} \text{day}^{-1}$). Therefore, at

flowering, a certain number of spikelets have been produced, of which only a certain fraction may develop into fertile grains.

Effects of extreme temperatures on γ are simulated using relations developed by Uchijima (1976) for low temperature and by Horie (1994) for high temperature. Data of Horie (1994) suggest that there is no effect of CO_2 concentration on the shape of the high temperature relationship; this is also assumed for the low temperature relationship. The combined temperature response of spikelet fraction to form grain, $f(T_m)$ has a nearly linear increase from 0 at 17 °C to 0.9 at 22 °C, a plateau at 0.9 from 22 to 30 °C, a nearly linear decrease from 30 °C to 0.1 at 35 °C, and an exponential decay from 35 °C to 0 at 40 °C. Maximum yield (Y_{\max} , g m^{-2}) is therefore given by:

$$Y_{\max} = S_r f(T_m) (G_{\max} \times 10^3), \quad (5)$$

where G_{\max} is the grain size (mg grain^{-1}) and is assumed to be constant for a variety (Yoshida 1981).

Actual grain yield (Y , g m^{-2}) depends on the amount of assimilate produced from flowering to maturity, plus any translocated assimilate from vegetative tissues, provided Y does not exceed Y_{\max} :

$$Y = \min \left[Y_{\max}, \sum_{i=F}^M (G_i + T_i) \right], \quad (6)$$

where F and M are the dates of 50% flowering and maturity, respectively, and G_i and T_i ($\text{g m}^{-2} \text{ day}^{-1}$) are crop weight increase and amount of assimilate translocated, respectively, on day i . The model stops simulation when $Y = Y_{\max}$, or when maturity is reached, whichever occurs first.

Overall Response of Grain Yield to Temperature and Carbon Dioxide

Incorporation of these relationships into ORYZA1 gives an overall response of grain yield to temperature and CO_2 (Fig. 1). Temperature responses of spikelet fertility constrains the upper and lower boundaries of the total response. The highest yields are obtained at 20–22 °C. Yields decline as temperatures increase further because of a shortening of crop duration. Between 28 and 32 °C there is a leveling of this response as crop duration reaches its minimum and then increases again because of a decrease in development rate at supraoptimal temperatures, before high spikelet sterility again reduces yields. At all temperatures, increased CO_2 concentration increases the yield. The model does not simulate any interactive effect between temperature and CO_2 . The exact change in yield expected at a given site under a changed climate depends, therefore, on the current temperature and the magnitude of the temperature change predicted for the site.

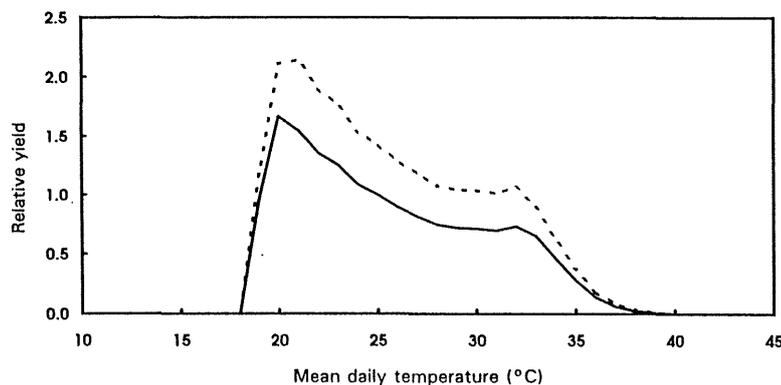


Fig. 1. Overall effect of temperature on grain yield predicted by the ORYZA1 model at current ($340 \mu\text{l l}^{-1}$) and doubled CO_2 concentrations. — $340 \mu\text{l l}^{-1}$; --- $680 \mu\text{l l}^{-1}$ (base 25°C , $340 \mu\text{l l}^{-1}$).

Input Data

Weather Data

Daily weather data from 70 stations from eleven countries in Asia were used in the analysis (Table 1). For most of the stations, more than 10 years of data were available, giving a total of about 780 years of weather data. To enable extrapolation over a wider area, weather stations were classified according to agroecological zone (AEZ, Harris and Goebel 1987). Simulated yields were averaged for each weather station to represent the yield potential for the whole zone.

Simulations were made for both fixed-change scenarios and for scenarios predicted by three general circulation models (GCMs) for a doubled- CO_2 climate. A total of 15 different scenarios were simulated. In the fixed-change scenarios, temperature was increased by 1, 2, or 4°C above current values for each site, and CO_2 concentration was increased from 340 to 510 or $680 \mu\text{l l}^{-1}$ (1.5 or 2 times the current CO_2 level). Temperature and CO_2 were changed independently and in various combinations. The three GCM scenarios used were those of the General Fluid Dynamics Laboratory model (GFDL, Hansen et al. 1988), the Goddard Institute of Space Studies model (GISS, Manabe and Wetherald 1987), and the United Kingdom Meteorological Office model (UKMO, Wilson and Mitchell 1987). Details of each GCM are shown in Table 2.

For both fixed-change and GCM scenarios the historic daily temperature values at each site were adjusted by the fixed-change increment or the predicted change. Solar radiation was not altered from the current values in the fixed-change scenarios. In the three GCM scenarios, predicted changes in solar radiation were also used to adjust observed values at each site. We assumed that the pattern of day-to-day temperature and solar radiation in each scenario would be

Table 1. Details of the countries used in the study, including the agroecological zone (AEZ), number of weather stations, total years of weather data, number of planting seasons, and planting dates used in the simulations. Because of unavailability of weather data in AEZ 8 in China and in India, simulated changes from AEZ 8 in Japan were used for these regions

Country	AEZ	No. of sites	Total years	Seasons	Planting dates (Julian date)
Bangladesh	3	4	43	3	105, 160, 350
China	5	2	18	1	136
	6	2	17	1	105
	7	6	53	2	91, 180
	8	—	—	—	—
India	1	6	65	1	161
	2	2	9	1	213
	5	—	—	—	—
	6	1	3	1	191
	8	—	—	—	—
Indonesia	3	7	49	2	270, 80
Japan	8	9	108	1	96–139 ^a
Malaysia	3	3	30	2	228, 80
Myanmar	2	4	26	2	140, 290
Philippines	3	9	148	3	166, 4, 100
South Korea	6	11	158	1	120
Taiwan	7	1	8	2	350, 120
Thailand	2	3	44	2	180, 350
Total	—	70	779	—	—

^a Planting dates vary according to latitude in Japan.

Table 2. Details of the three General Circulation Models used in the study

GCM	Year ^a	Base		Change in global average		
		CO ₂ conc. ($\mu\text{l/l}$)	Resolution (°)	Temp. (°C)	Precip. (%)	Reference
GFDL	1988	300	4.4 × 7.5	4.0	8	Hansen et al. (1988)
GISS	1982	315	7.8 × 10	4.2	11	Manabe and Wetherald (1987)
UKMO	1986	323	5.0 × 7.5	5.2	15	Wilson and Mitchell (1987)

^a Refers to the year in which the GCM simulation run was made.

the same as for the present observed climate, and that only the daily mean values would change by the amount predicted in the scenario.

Dates of sowing and transplanting were, in general, supplied by the collaborating institutions. Where this information was not given, transplanting dates were obtained from IRRI (1991), and the date of sowing in the seedbed was assumed to be 25 days prior to this. For sites where more than one rice crop was grown per year, simulations were made for all crops.

Genotype Characteristics

Indica varieties are usually grown in the tropical regions (Bangladesh, India, Indonesia, Malaysia, Myanmar, Philippines, southern China, Taiwan, and Thailand in our study) and japonica varieties in the northern latitudes (Japan, northern China, and South Korea). We used genetic coefficients for the indica variety IR64 and the japonica variety Ishikawi. IR64 is early maturing and weakly photoperiod-sensitive, whereas Ishikawi is a very early maturing, photoperiod-insensitive variety, developed from selections that have been made over 100 years of rice breeding in the Hokkaido region (Yoshino et al. 1988).

Results and Discussion

Fixed-change scenarios enable an evaluation of the separate effects of temperature and CO₂ on potential yields at each site. Figure 2A shows the effect of increasing CO₂ level to 510 or 680 $\mu\text{l l}^{-1}$. At all sites, increasing CO₂ alone increased simulated yields. Comparison of regression coefficients of the simulated current yield against the simulated yield under each scenario indicated that the average yield increase was 23.6% for 510 $\mu\text{l l}^{-1}$ and 36.8% for 680 $\mu\text{l l}^{-1}$. Increments in temperature decreased simulated yields (Fig. 2B). Regression analysis indicated yield declines of 6.7, 14.1 and 29.4% for temperature increases of 1, 2 and 4 °C, respectively (a yield decrease of 6.7 and 7.4% for each 1°C increase in temperature). These values are similar to the 7–8% yield decrease per 1 °C increase measured by Baker et al. (1992a). The decrease in correlation coefficient (r^2) with increased temperature reflects an increase in variability of yields associated with temperature increases (Fig. 2B). This impact on yield variability will have some significance for risk assessment studies. Figure 3 shows the overall effect of combinations of fixed changes in temperature and CO₂ levels on potential yields, averaged across all sites and years. Similar patterns have also been found using other models (Bachelet et al. 1993).

Although fixed-change scenarios provide a 'sensitivity-analysis' of the effect of temperature and CO₂ on potential rice yields, scenarios predicted by the GCMs represent the best estimates we have at present of the likely changes in climate caused by an increase in CO₂ levels. Linking these predictions to crop simulation models, therefore, provides some idea of the effect that climate change will have on rice productivity. Table 3 shows the estimated changes in overall rice production for the individual AEZs and countries in the study, and for the whole region. In this analysis, the current production of each country is adjusted by the predicted fractional change in potential yield for each of the three GCM scenarios. Predicted change is the mean of all sites and planting seasons for an AEZ within the country. It is, therefore, assumed that proportional changes at the potential production level are the same at suboptimal levels of management, and that the area of production does not change. Model simulations predict a 6.5%

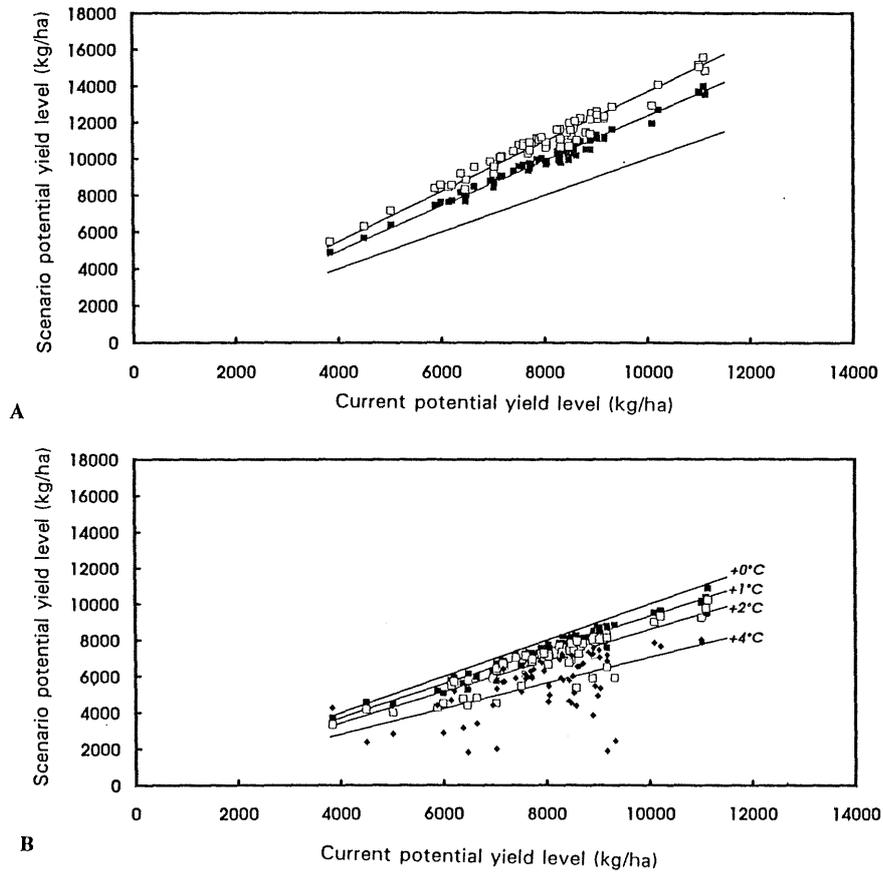


Fig. 2. **A** The relationship between predicted current yields and predicted yields at two levels of increased CO₂. Temperature at each site is unaltered from current values. Regression lines are forced through the origin (510 μl l⁻¹: $y = 1.23 x$, $r^2 = 0.982$; 680 μl l⁻¹: $y = 1.368 x$, $r^2 = 0.962$). - - - 340 μl l⁻¹, ■ 510 μl l⁻¹, □ 680 μl l⁻¹. **B** The relationship between predicted current yields and predicted yields at three temperature increments (1, 2, and 4 °C above current values). The CO₂ level at each site is set to 340 μl/l. Regression lines are forced through the origin (+1 °C $y = 0.933 x$, $r^2 = 0.954$; +2 °C $y = 0.859 x$, $r^2 = 0.795$; +4 °C $y = 0.706 x$, $r^2 = 0.400$)

increase in rice production under the GFDL scenario, a 4.4% decrease under the GISS scenario, and a 5.6% decrease under the UKMO scenario.

There were, however, substantial differences in predicted yield changes between countries. Averaged across all three GCM scenarios, the mean change predicted in total production for China was -4.2%, which agrees closely with the -7.4% predicted by Zhou (1991). Similarly, decreases in production were predicted for Thailand under the GISS and UKMO scenarios. Changes in production in both of these countries is likely to have serious repercussions on regional trading patterns as China is the major importer of rice in the region (43% of total

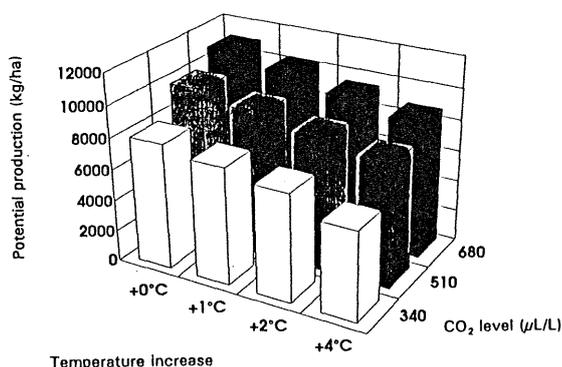


Fig. 3. The effects of increasing CO₂ level and temperature on potential yield. Data for main planting season only; mean of all weather stations and all years

Table 3. Estimated changes in total rice production for each country and in the region under the three GCM scenarios. Current actual production figures in each AEZ on a country basis (IRRI 1991) are adjusted by the simulated changes in total annual production (see text for explanation)

Country	AEZ	Current (t × 10 ³)	GFDL		GISS		UKMO	
			(%)	(t × 10 ³)	(%)	(t × 10 ³)	(%)	(t × 10 ³)
Bangladesh	3	27691	14.2	31621	-5.0	26298	-2.8	26919
China	5	8854	-7.4	8201	0.3	8881	-25.2	6619
	6	79872	0.8	80484	-21.7	62514	-19.5	64334
	7	91828	5.8	97196	5.8	97135	3.1	94695
	8	2361	-6.4	2209	-14.2	2026	-27.6	1710
India	1	32807	4.6	34305	-10.8	29272	-5.5	31017
	2	49949	1.8	50849	-2.9	48493	-7.9	46002
	5	227	-7.4	210	0.3	228	-25.2	170
	6	26628	5.4	28069	3.2	27480	-1.3	26287
	8	1011	-6.4	946	-14.2	867	-27.6	732
Indonesia	3	44726	23.3	55155	9.0	48748	5.9	47387
Japan	8	12005	-6.4	11231	-14.2	10300	-27.6	8696
Malaysia	3	1744	24.6	2173	17.6	2050	26.8	2211
Myanmar	2	13807	21.5	16776	-10.5	12356	1.2	13974
Philippines	3	9459	14.1	10797	-11.8	8340	-4.7	9018
South Korea	6	8192	-13.6	7078	-5.3	7755	-21.9	6401
Taiwan	7	2798	11.8	3128	12.8	3156	28.0	3583
Thailand	2	20177	9.3	22044	-4.7	19230	-0.9	19989
Total		434136		462472		415129		409743
% change				6.5		-4.4		-5.6

regional imported rice; IRRI 1991), while Thailand is one of the major rice exporting countries of the region (87% of total regional exported rice). Similarly, in Bangladesh, the predicted decline in production by both crop models in the GISS and UKMO scenarios is likely to increase the country's need to import even more rice than at present. On the other hand, countries such as Indonesia,

Malaysia, and Taiwan, and parts of India and China, are all predicted to benefit from any change in climate. There are, however, some striking discrepancies in predicted changes between the three scenarios. In AEZ 6 of China, as one example, a +0.8% increase in yields was predicted for the GFDL scenario, but a -21.7% decrease for the GISS scenario. These large fluctuations are mainly due to the sensitivity of spikelet sterility to temperatures in the region of 33 °C, where a difference of 1 °C can result in a modest yield increase becoming a large yield decrease. In many areas, therefore, it seems that the accuracy of any prediction of changes in rice production depends on the exact nature of changes in the climate there; until there is some consensus in predictions of climate change for an area, therefore, accurate prediction of potential production changes is difficult.

The use of simulation models to predict the likely effects of climate change on crop production is, of necessity, an evolving science. As both general circulation models and crop simulation models become more sophisticated, as more high-quality historical weather data for a larger number of sites become available, and as better physiological data become available to model rice responses to climate change variables, predictions will become more accurate. Some predictions have already been revised. Horie (1991), for example, calculated that there would be an overall decline in rice production in Japan under predicted climate-change scenarios, but Horie et al. (1994) now conclude that, although there will be a shift in the rice-producing regions within the country, the overall rice production of Japan will not be appreciably altered.

This study, therefore, can be seen as part of this evolutionary process, and complementary to previous studies. A number of studies that use models of differing complexity and assumptions but reach similar conclusions may help to reduce the general reluctance by many governments to take action to mitigate both the rate of change of climate and the detrimental effects these changes may have.

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