# The Effect of Increased $CO_2$ Concentration and Temperature on Rice Yield: Experiment and Simulation

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## ABSTRACT

Impact assessment of anticipated global environment change on crop yields in each region is important to form a basis for counter measures. The objectives are to clarity the effects of increased atmospheric $CO_2$ concentration and predicted temperature rise on rice yield, based on experiments with temperature gradient tunnel (TGT) and model simulation. The TGT is a newly developed system to investigate $CO_2$ X temperature effects on rice growth and development with maintaining natural daily and seasonal temperature variations (Horie et al., 1991). Experiments with the TGT showed that, while nearly doubled $CO_2$ concentration gave negligibly small effect on the leaf area development of rice, it promoted the biomass production by 24% on average over the temperature range from 0 to 4°C above outdoor conditions. This indicated that the $CO_2$ promotes rice growth through the increase of conversion efficiency of intercepted radiation to biomass, but not through the increase of radiation interception rate. The enhancement rate in panicle weight of the nearly doubled $CO_2$ concentration was similar to that in the biomass at an outdoor temperature conditoin. With the increase in temperature above the outdoor condition, the panicle weights under the ambient and elevated $CO_2$ both decreased sharply to diminish the $CO_2$ effect due to the increase in high temperature-induced sterility of spikelets. The sterility percentage of spikelets increased drastically as daily maximum temperature averaged over flowering period exceeded 35°C.

These experimental results were incorporated into SIMRIW (Horie, 1987), a model for simulating rice growth and yield from weather conditions, to predict the effects of anticipated global environment change on rice yield in Japan. The model predicted that, in northern Japan, doubled $CO_2$ and global warming predicted by GISS model (Hansen et al., 1984) will increase the average yield of irrigated rice by about 20% with a decreased yearly yield variability, and that, in southern Japan, the global environment change will increase the average yield by about 10% with about 2 times increase in the yearly variabilty due to the increased possibility of high temperature-induced spikelet sterility.

## INTRODUCTION

The increasing $CO_2$ concentration in the atmosphere at a rate of 0.4% per year and anticipated global warming associated with the elevation of greenhouse effect gases are considered to give enormous impacts on crop production in the world. It is, therefore, urgent to clarify effects of the global environment on crops' yield in respective regions, for provision of counter measures to minimize negative effects. Although intensive researches are currently being made to clarify the effects on major crops including rice (Imai et al., 1985; Horie, 1988; Baker et al., 1990 a, b and c), the accumulated information appears not to be sufficient for predicting both the effects of elevated $CO_2$ and global warming on rice production in different regions in the world.

For this reason, we developed a temperature gradient tunnel (TGT) for the investigation of combined effects of $CO_2$ concentration and temperature on growth and yield of rice (Horie et al., 1991), and made experiments with the TGT for three cropping seasons of rice up to now (Kim et al., 1992; Nakagawa et al., 1993). The data obtained from the experiments with TGT have been incorporated into SIMRIW, a simulation model for rice growth, in order to make the model applicable for the prediction of effects of global environment change on rice growth and yield (Horie, 1993). This paper briefly describes the experimental results with TGT on temperature X $CO_2$ effects on rice, the simulation model and results of the model application for impact prediction of the global environment change on rice yield in northern and southern Japan.

## $CO_2$ AND TEMPERATURE EFFECTS ON RICE GROWTH AND YIELD: EXPERIMENTS WITH TGT

### Experimental procedure

Temperature gradient tunnels (TGTs) were developed for the experiments on temperature X $CO_2$ effects on rice. (Horie et al., 1991). The TGT is a tunnel, 25m in length, 2.05m in width at ground level and 1.7m in height, covered with transparent polyester film. Air was ventilated through the long axis of the tunnel at a rate of 0.1m/s during day time, and the direction of ventilation was reversed in night time. TGT provided temperature gradient along the long axis by solar radiation energy in day time, and by natural cooling of the heat from an oil heater in night time. The temperature difference between the air inlet and outlet was maintained at about 4°C throughout the entire growth seasons, while maintaining natural daily and seasonal variations.

Experiments were made for three cropping seasons (1990, 1991 and 1992) of rice by using two TGTS. In all the years, the day time $CO_2$ concentration in one TGT was kept at ambient level (350ppm) by ventilating the air and that in another at approximately twice the ambient (840ppm in 1990, and 690ppm in 1991 and 1992) by injecting $CO_2$ at the air inlet. Night time $CO_2$ concentrations in both TGTs were set at an ambient level. Rice cultivar 'Akihikari' was used for the three years' experiments. The $CO_2$ and temperature treatments were given in TGTs from immediately after transplanting of the seedlings (around 6 leaf stage) to full maturity. The rice plants in 1990 and 1991 were raised in 1/5000a pots which were displaced at an even distance in TGTs while those in 1992 were raised on the ground in TGTs in a similar condition to a field. Rice pots in 1990 were rotated twice a week in order to give a same environmental condition to each plant, while those in 1991 were fixed. Radiation penetrating from the side edges of the rice populations in 1991 and 1992 was shaded by a densely-woven black fiber cloth to create a canoy condition. In each year three nitrogen plots (low, intermediate and high N) were displaced at each of four different locations in terms of the distance from the air inlet.

Dry and wet bulb temperatures in TGT were measured for entire growth period at four different distances from the air inlet. The temperature condition that each plant experienced in TGT was estimated by linear interpolation with respect to the distance from the two adjacent measurements. Periodic measurements were made of crop dry weight, leaf area and N content for sampled plants from each N plot at different positions in the two TGTs. At maturity, yield and its components were also measured.

**Temperature and $CO_2$ effects on dry matter production**

The ratio of crop dry weight obtained at maturity under nearly doubled $CO_2$ concentration in TGT to that under ambient $CO_2$ was plotted in Fig. 1 as a function of temperature for rice at the intermediate N application in 1991 and 1992 in which the crop was grown under a canopy condition. In Fig. 1 the data obtained by Imai et al. (1985) and Baker et al. (1990c) were also represented for comparison. The relative response of the crop dry weight to nearly doubled $CO_2$ concentrations ranged from 1.09 to 1.51 times the ambient $CO_2$ crops among workers and experimental conditions. However, no consistent trend could be seen in the temperature effects on the responses to $CO_2$. The relative responses obtained from the pot experiments tended to be lower than those from the field experiments, with the exception of one crop by Imai et al. (1985). This indicates that a limited rooting space in the pots would have reduced the rice photosynthetic response to elevated $CO_2$. For this reason, we neglected to use the pot experiment data for further analysis. A value of 1.24 was obtained by averaging relative responses of the field crops to doubled $CO_2$. Temperature has little effect on this value over a wide range. The relative enhancement rate of the crop dry matter production by doubled $CO_2$ was smaller under N limiting conditions, but it reached a ceiling value of 1.24 at N applications above $12gN/m_2$.

**The effects on leaf area development**

Elevated $CO_2$ slightly promoted leaf area development at the intial growth stage, but this effect decreased with growth, reaching almost the same maximum leaf area at the heading both under the elevated and ambient $CO_2$ conditions. At maturity, the higher was the temperature, the larger the leaf area both under the elevated and ambient $CO_2$ conditions. This is reflecting the fact that high temperature-induced sterility of spikelets reduced substrate sink capacity and slowed leaf senescence. The relatively insensitive response of rice leaf area to $CO_2$ observed is consistent to Imai et al. (1985) and Baker et al. (1990c).

Nearly doubled $CO_2$ condition did not give any significant effect on N absorption by rice crop at the low and the intermediate N applications, while it slightly reduced N absorption at the high N (Fig. 3). Since leaf area development is strongly dependent on availability of N, it appears that relatively insensitive response of rice leaf area to $CO_2$ is attributable to the insensitive response to $CO_2$ in the crop N absorption.

Since leaf area response to $CO_2$ is very small in rice, the enhancement rate of crop dry matter production by nearly doubled $CO_2$ is mainly attributable to the enhancement in the conversion efficiency from absorbed radiation to biomass, but not to that in the radiation absorption rate. Hence, it may be concluded that the doubling of $CO_2$ concentration increases the radiation conversion efficiency of rice by 24%.

**The effects on the yield**

Fig. 4 represents panicle dry weight as a function of temperature and N application rate for rice grown under ambient and nearly doubled $CO_2$ conditions in 1991. Appreciable effects of the elevated $CO_2$ on the panicle dry weight was observed only at the temperature condition nearly equal to outdoor in Kyoto (about 27°C) in all N application levels. With the increase of average temperature above 28°C the panicle dry weights at all N levels both under the elevated and ambient $CO_2$ decreased sharply. This decline in the panicle dry weight was derived from the increase of both the numbers of unfertiled grains and development-interrupted grains at early stages due to increased temperature. The relative enhancements of the elevated $CO_2$ on the panicle dry weight under near outdoor temperature conditions were 17, 38, and 13% at the low, intermediate and the high N levels, respectively. Thus, the maximum effects of elevated $CO_2$ on the panicle weight was obtained at the intermediate N level.

Rice spikelets have the highest sensitivity to high temperature at anthesis, and are liable to be steriled due to a failure in pollination when the flowering temperature exceeds about 35°C (Satake and Yoshida, 1978; Matsui and Horie, 1992). Since flowering of rice is usually in day time, a daily maximum temperature is considered to be more closely related to high temperature-induced spikelet sterility of rice than the average temperature. Based on this idea, the fertility percentage (100-sterility percentage) of spikelets were plotted against average daily maximum temperature over 10 day-period around the heading stage for rice grown under the elevated and ambient $CO_2$ conditions in 1990 and 1992 (Fig. 5). Results shown in Fig. 5 indicate that the $CO_2$ concentration has no effect on the temperature and fertility relationship. The relation shown in Fig. 5 may be approximated by,

$$\delta = \frac{100}{1 + \exp\{0.853(T_M - 36.6)\}} \quad (1)$$

where $\delta$ is the fertility percentage and $T_M$ the average daily maximum temperature during the flowering period.

## MODEL PREDICTION OF THE EFFECTS OF GLOBAL ENVIRONMENT CHANGE ON RICE YIELD IN JAPAN

### Basic structure of the model

The model applied for the prediction of effects of global environment change on rice yield in Japan was SIMRIW (Horie, 1987 and Horie et al., 1992), or a simulation model for rice growth from weather conditions, with a minimum modification to meet the objectives. Since the details of this model have already been reported, only a brief description is made here about the basic structure of SIMRIW.

The ontogenetic development process of rice from emergence to heading is represented in SIMRIW by a continuous variable, developmental index DVI, of which value is defined to be zero at emergence, 1.0 at heading and 2.0 at maturity. The value of DVI at any moment of crop development is given by integrating the developmental rate DVR with respect to time. The DVR is given by a nonlinear function of daily mean temperature and day length as described in Horie and Nakagawa (1990).

The dry matter accumulation process of rice crop is simulated based on the relation that a crop dry weight at any moment is proportional to the absorbed radiation accumulated up to the moment (Monteith, 1977). This process of biomass accumulation is characterized by only one crop parameter, the radiation conversion efficiency Cs. The Cs is assumed to be constant up to the heading (DVI=1), and thereafter is given by a decreasing function with respect to DVI to simulate maturation or senescence process. The growth rate in leaf area which governs the radiation absorption rate is modeled as an unique function of temperature. This is in contrast to the traditional approach in which leaf area growth are calculated from its weight growth by multiplying by a simple conversion factor, the specific leaf area. The leaf area growth is modeled independently of its weight growth in this model, by taking into account of largely independent nature each other, as described in Horie et al. (1979).

The grain yield is simulated in SIMRIW from calculated total biomass by multiplying by a harvest index. The harvest index is given by a functions of DVI and sterility percentage of spikelets. The harvest index and DVI relationship is employed to make the yield formation process dynamic and to simulate premature cessation of growth when crop encounters autumn coolness. The sterility percentage of spikelets is given by a function of cooling degree-day (Uchijima, 1976) during sensitive period of spikelets to cool temperature ($0.75 \leq DVI \leq 1.2$).

### Incorporation of $CO_2$ and high temperature effects into the model

In order to make SIMRIW applicable to predictions of the effects of anticipated global environment change (elevated $CO_2$ and warming) on rice yield, two important processes need to be incorporated into the model: the process to determine the $CO_2$ effect on the growth and yield, and one to determine high temperature effect on the reproductive organs. These two processes were modeled on the basis of experimental results with TGT shown in the previous section, and incorporated into SIMRIW as follows:

The effects of $CO_2$ concentration on photosynthesis was incorporated into SIMRIW simply as the enhancement on radiation conversion efficiency by $CO_2$. By analyzing rice canopy photosynthesis-$CO_2$ relationship data by Baker et al. (1990b), Horie et al. (in preparation) found that the following rectangular hyperbola fitted well to the relative response to $CO_2$ (R) in the radiation conversion efficiency of $CO_2$ acclimated rice:

$$R = \frac{Rm(Ca-330)}{(C_a-330) + Kc} + 1 \qquad (2)$$

where Rm is the asymptotic response limit of R-1, Ca is the $CO_2$ concentration in ppm and Kc the value of Ca at which (R-1) = 0.5Rm. Eq. (2) is identical to one which was obtained by Allen et al. (1987) for the response of soybean seed and biomass yield to $CO_2$.

The experimental results with TGT in the foregoing section indicated that the relative enhancement rate of radiation conversion efficiency (R) by nearly doubled $CO_2$ (690ppm) is 1.24 for rice over a wide range of temperature. This suggests that best estimates of parameters in Eq. (2) are Rm= 1.54 and Kc= 1787ppm. Eq. (2) was incorporated into SIMRIW together with these values for the parameters.

Eq. (1) was incorporated into SIMRIW to simulate high temperature-induced sterility percentage (100-$\delta$) of spikelets. The sensitive period of rice spikelets to high temperature was represented in terms of the crop developmental index as $0.96 \leq DVI \leq 1.2$.

**Model validation**

To examine the effectiveness of SIMRIW for simulating year-to-year variations of rice yields at different locations in Japan, three prefectures were adopted: Hokkaido, Gunma and Miyazaki as representatives of the northern, central and southern Japan, respectively. For each prefecture, weather data (daily maximum and minimum temperatures, and daily solar radiation) at one station were used for the period 1979 to 1990 to simulate the yields.

Since SIMRIW gives a climatically potential yield, simulated yields were much higher than the actual. It was recognized that the difference between the simulated and the actual yields decreae with the progress of year, indicating an increasing trend in the actual yield due to advancement of rice production technologies. By assuming a linear increase in rice production technologies with year, the simulated yield (Yp) may be converted to actual yield (Ya) by

$$Ya = \{b_0 + b_1 (i—1)\} Yp \quad (3)$$

where i stands for year number from 1979, and $b_0$ and $b_1$ are coefficients. A multiple regresssion analysis was made between the actual yield (Ya) and simulated yield (Yp) by using Eq. (3) for each prefecture, and values of 1.3, 1.7 and 0.9% were obtained as rates of yearly yield increases due to technological advancement in Hokkaido, Gunma and Miyazaki, respectively.

A close linear relationship was obtained between the actual yields and simulated yields, converted to the level of current farmers' in the three prefectures examined (Fig. 6). The relation shown in Fig. 6 suggests that the model explains fairly well the weather-induced yearly variations of rice yield.

**Prediction of the effects of global environment change on rice yield in Japan**

Effects of predicted global environmental change, i.e., elevated $CO_2$ and the anticipated greenhouse effect climate, on rice yield in Japan were simulated by SIMRIW modified as explained above. For the future environmental conditions, we adopted the doubled $CO_2$ concentration in the atmosphere and temperature rise predicted by GISS general circulation model (Hansen et al., 1984) under the doubled $CO_2$ concentration. The three prefectures of Hokkaido, Gunma and Miyazaki were chosen for this study. Simulations were made for three cases in each prefecture: the present climate, the present climate and doubled $CO_2$, and the GISS model-predicted temperature climate under doubled $CO_2$. For the present climate, we used actual daily maximum and minimum temperatures, and daily solar radiation data for 1979-1990 period, observed at Sapporo (43.0 , 141.20E) in Hokkaido, Maebashi (36.24 , 139.04E) in Gunma and Miyazaki (31.55 , 131.25E) in Miyazaki prefecture. For doubled $CO_2$ climate, we simply added monthly mean temperature rise predicted by GISS model to the actual daily maximum and minimum temperatures at each location. The monthly mean temperature rises during rice growing season, predicted by GISS model at Sapporo, Maebashi and Miyazaki, were 3.0-4.0, 2.8-31. and 2.9-3.1°C, respectively.

Simulations were made for the 12-year period for the three scenarios at each location. All the simulated yields were converted by Eq. (3) to the yields at rice production technology level in 1990. The simulation results for Hokkaido and Miyazaki are shown in Figs. 7, as cumulative probability of yield.

In Hokkaido, climatically induced yield variability under the present climate ranged 3.4 to 6.0 t/ha, and thus production is very unstable. Doubling $CO_2$ alone is predicted to increase the yield by 24% with unchanging variability. Doubling $CO_2$ and the temperature rise is predicted to increase the average yield by 22% and to reduce the yield variability. The reduction in yield variability under the doubled $CO_2$ climate is for the following reasons. Namely, poor yield years in Hokkaido are associated with cool summer damage of rice, and doubled $CO_2$ climate almost clears this damage. Good yield years are associated with warm summer and further temperature rise shortens the growth period of rice, and hence reduce the yield in Hokkaido.

In Miyazaki, climatically induced yield variability under the present climate ranged 4.0-5.2 t/ha, and thus the production is very stable. Doubling $CO_2$ alone will increase the yield by 24% with unchanging the variability. Doubled $CO_2$ and temperature rise will increase the average yield by 14%, but also increase the variability by approximately 2 times the present. The increase of yield variability under doubled $CO_2$ climate in Miyazaki is ascribed to increase in steriled rice spikelets due to higher temperature during flowering period in warm summer years.

It may be concluded from the simulation analysis that:

i. The global environment change (doubling $CO_2$ and associated global warming) will increase the average yield of irrigated rice in the northern Japan by about 20% with reducing the yearly variability.

ii. In the southern Japan, it will increase the average yield by about 10% with about 2 times increase in the yearly variability.

iii. The effect on the yield in central Japan will be in between those in the northern and the southern Japan.

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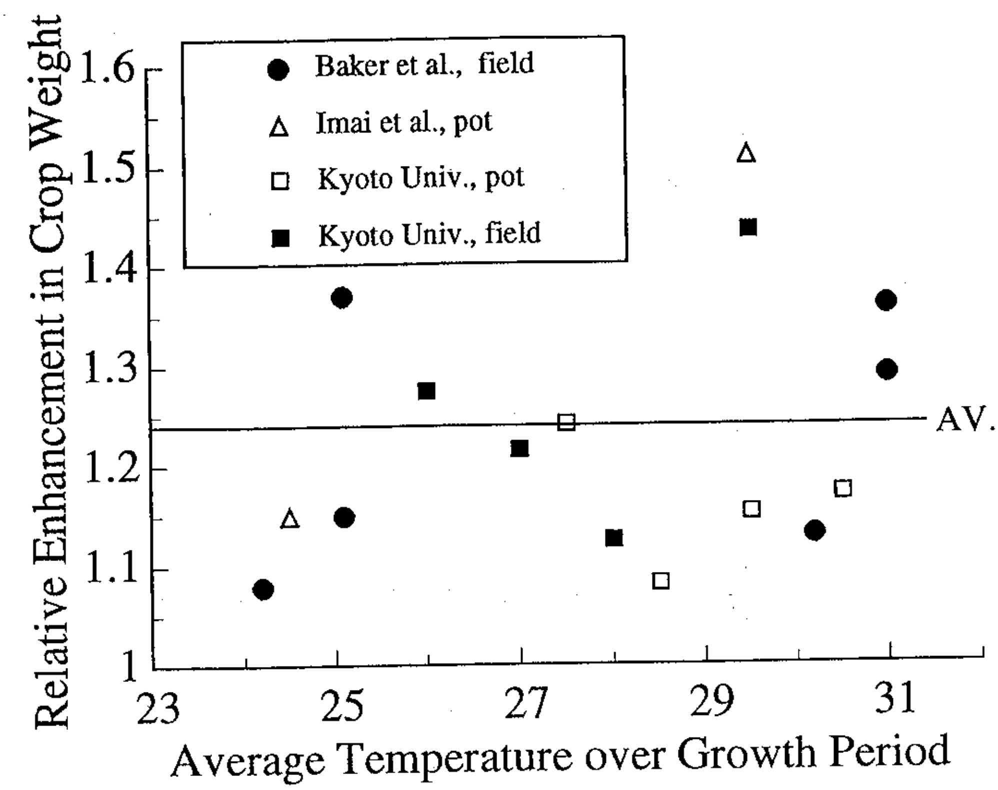



Fig. 1. Relative responses in crop dry weight of rice to nearly doubled $CO_2$ concentrations as a function of temperature (Horie, 1993). Source: Imai et al. (1985), Baker et al. (1990c) and data from TGT experiments in Kyoto.

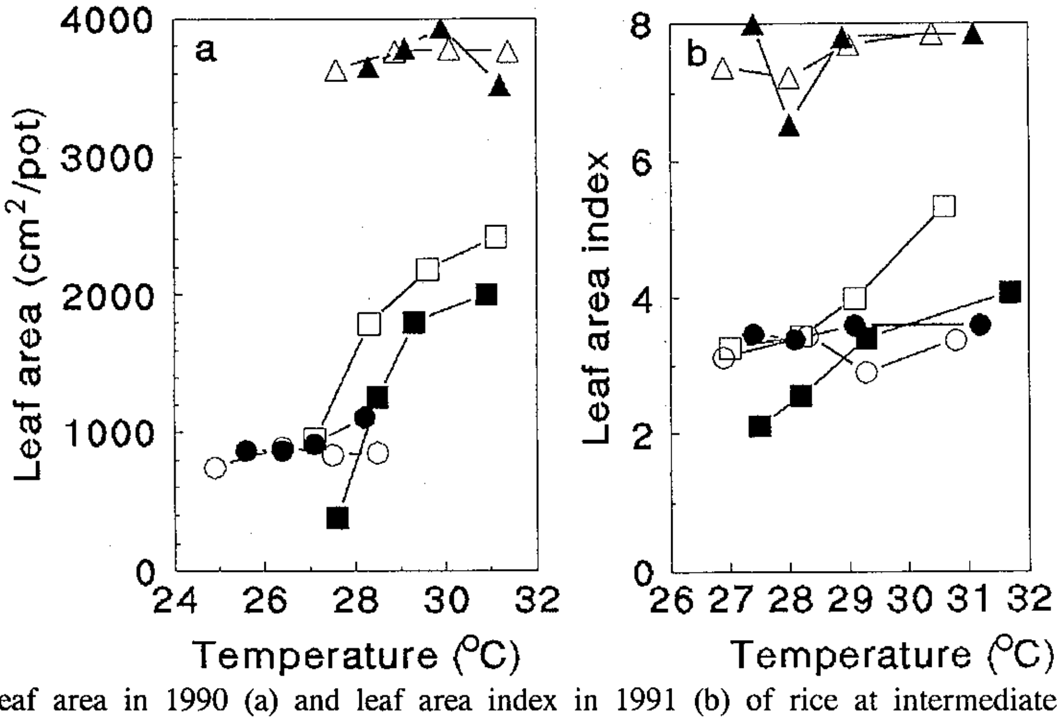



Fig. 2. Leaf area in 1990 (a) and leaf area index in 1991 (b) of rice at intermediate N application at panicle initiation (○, ●), heading (△, ▲), and maturity (□, ■) as a function of temperature and $CO_2$ levels. (Nakagawa et al., 1993). Open and closed symbols denote ambient and nearly doubled $CO_2$ levels, respectively.

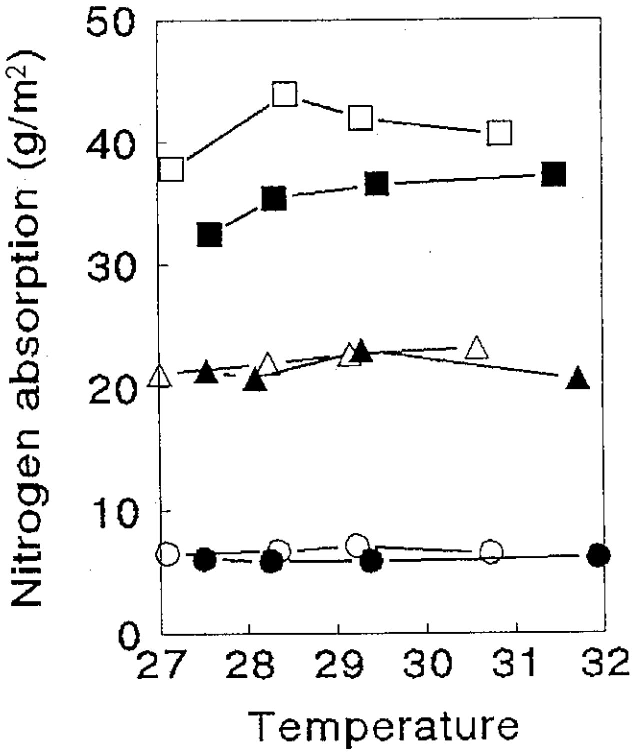



Fig. 3. Amount of N absorption at maturity of rice grown under different temperature conditions in the ambient (open symbols) and nearly doubled (closed symbols) $CO_2$ levels (Kim et al., 1992). ○, △ and □ denote the low (6g/m$^2$), intermediate (24g/m$^2$) and high (48g/m$^2$) N applications, respectively.

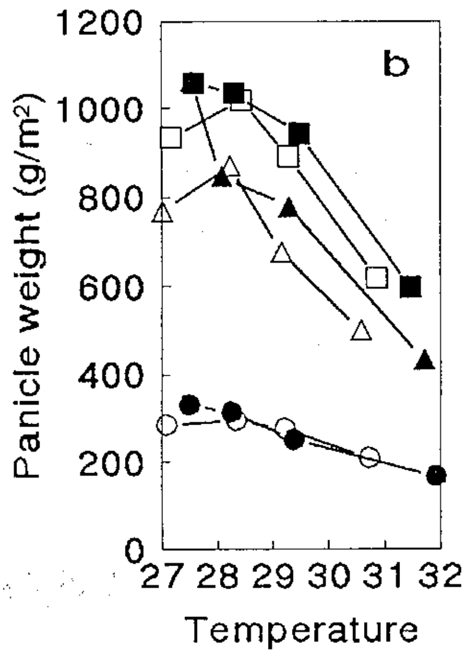



Fig. 4. Panicle dry weight as a function of temperature and N application conditions for rice grown under the ambient (open symbols) nearly doubled $CO_2$ levels (Kim et al., 1992). ○, △ and □ denote the low, intermediate and high N applications, respectively.

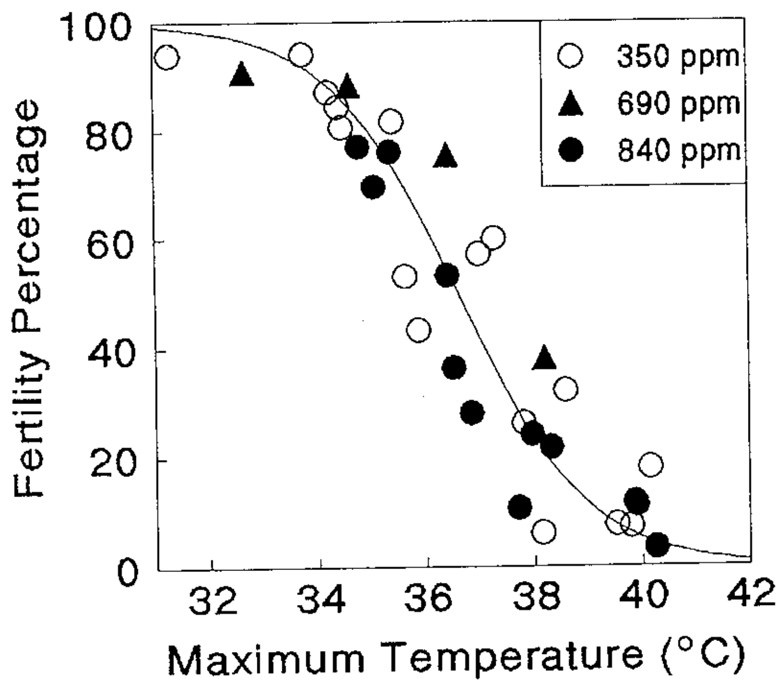



Fig. 5. Relationship between average daily maximum temperature during flowering period and fertility percentage of spikelets for rice acclimated to different $CO_2$ concentrations (Horie, 1993).

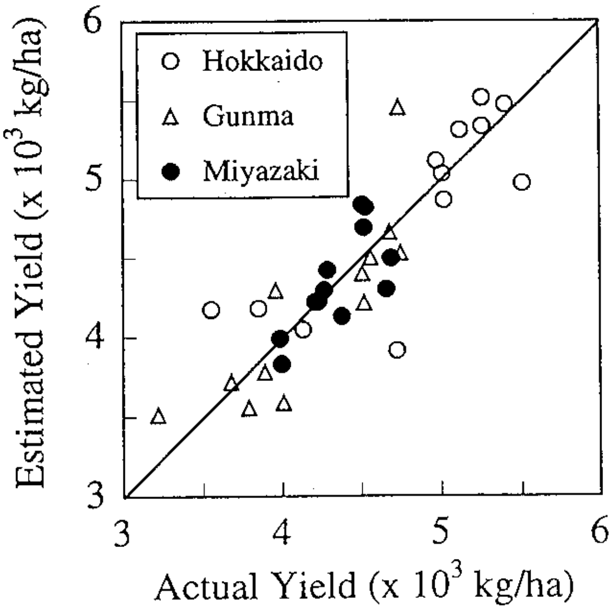
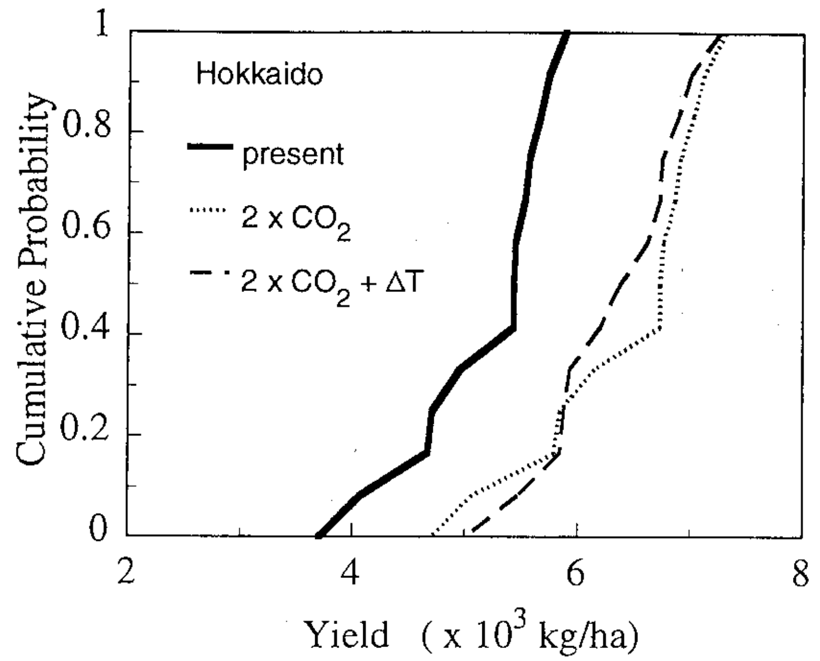



Fig. 6. Comparison between actual yield and simulated yield adjusted by technology trend for 12 year-period in three different prefectures in Japan (Horie, 1993).



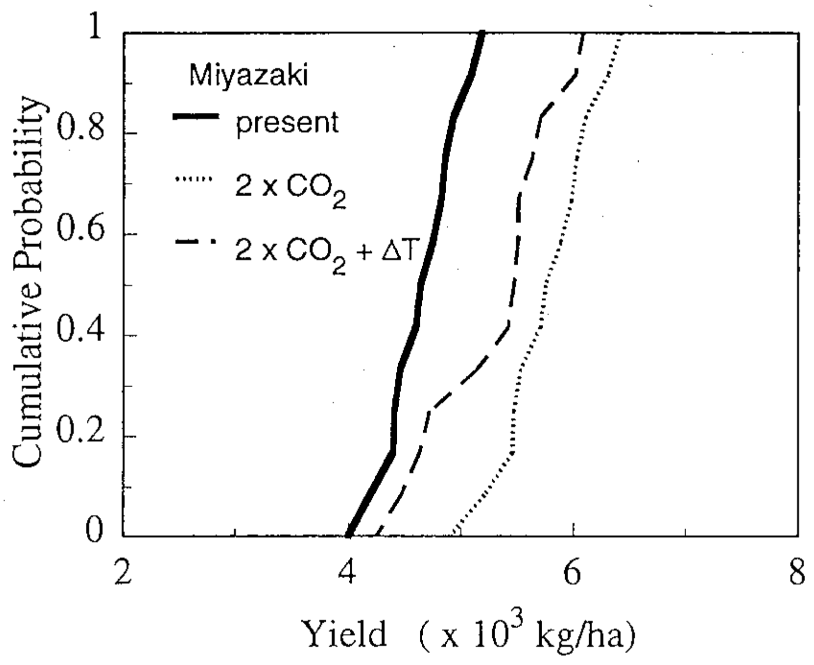




Fig. 7. Cumulative distribution functions for rice yield in Hokkaido (upper) and Miyazaki (lower) for three scenarios of global environmental change: simulation by modified SIMRIW (Horie, 1993).