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EFFECTS OF ELEVATED CO_2 AND GLOBAL CLIMATE CHANGE ON RICE YIELD IN JAPAN

Takeshi Horie[1], Tsutomu Matsui[1], Hiroshi Nakagawa[1] and Kenji Omasa[2]

ABSTRACT: Long-term CO_2 x temperature experiments on rice using Temperature Gradient Chambers (TGCs) revealed that nearly doubled CO_2 concentration in the atmosphere increases crop dry matter production by 24 % through the enhancement of radiation conversion efficiency to biomass, but not through the promotion of radiation interception rate. Although temperature gave a negligibly small influence on the CO_2 effect on biomass production, it significantly affected the grain yield through spikelet fertility. High temperatures were most damaging rice spikelets at the moment of their flowering and made them sterile. The temperature (T_{mh}) at which 50 % spikelets are sterile was 38.2°C for a high temperature-tolerant genotype 'Koshihikari', and 36.6°C for a sensitive genotype 'Akihikari'. Those findings from TGC experiments were parametrized and incorporated into rice growth simulation model SIMRIW.

Impact assessments of elevated CO_2 concentration and global climate change on regional rice yield in Japan were made by using SIMRIW under various climate scenarios. The model predicted that a 100 μmol mol^{-1} increase in CO_2 concentration alone increases rice yield in Japan by 7 - 8 %, and that a 2°C temperature rise significantly reduces this CO_2 effect in the most part of Japan. Then, the effects of 2 x CO_2 climates on regional rice yield were predicted for high temperature-sensitive and tolerant genotypes by using 2 x CO_2 climate scenarios generated by GFDL, GISS and UKMO general circulation models. It was found out that the 1.6°C difference in the spikelet sensitivity to high temperature damage between those two genotypes gives significantly large effects on the predicted rice yield in central-south (Tokai and South Kanto districts) and south-western Japan under 2 x CO_2 climates. Even with the high temperature-tolerant genotype, rice yield in those regions was predicted to decrease by 0 - 10 % than the present under 2 x CO_2 climates except for GISS, while that in northern Japan was predicted to increase by 10 - 25 % depending on climate scenarios. The model also predicted that 2 x CO_2 climates significantly increase yearly yield variability in the central-south and south-western Japan, while they stabilize the yield fluctuation in the northern Japan. Alternations of phenological development genotypes and cropping seasons furthermore promoted the positive effects of 2 x CO_2 climates in the northern Japan, but did not significantly mitigate the negative effects in the southern

[1] Faculty of Agriculture, Kyoto University, Kyoto 606, Japan.
[2] National Institute for Environmental Studies, Tsukuba, Ibaraki 305, Japan.

Japan. For mitigating the predicted negative effects of 2 x CO_2 climates in the southern Japan, explorations for high temperature-resistant genotypes are necessary.

KEY WORDS: rice, elevated CO_2, temperature gradient chamber(TGC), simulation model for rice-weather (SIMRIW), Japan

1. INTRODUCTION

Although Japan relies on imported grains from abroad for two-thirds of the total consumption, its staple food rice is the only crop that it self-supplies. Rice production in Japan is under the control of the government to produce approximately 10 million tons annually which just meet the national demand. This production plan of rice, however, is occasionally disturbed by climatic variations : over production in favorable climate years and shortage in adverse climate years. Except for typhoons which occasionally attack some district of Japan, variations in temperature and solar radiation during rice growing seasons are the major factors that bring yearly variations of Japanese rice production (Yoshino *et al.*, 1988). The cool summer in 1993, for instance, caused 26 percent reduction of Japanese rice production and forced Japan to import more than two million tons of rice, resulting in abrupt highering of rice price in the international market. However, unlike most other countries in the world, water plays a negligible roles as a yield reducing factor in Japanese rice production, because almost all rice fields in Japan are fully irrigated.

Since Japanese rice production is so sensitive to temperature and solar radiation, it is requested to assess the impacts of elevated CO_2 concentration in the atmosphere and anticipated global warming (Hansen *et al.*, 1984) on regional rice production in Japan. To answer this, we have been conducting various experiments on CO_2 x temperature effects on rice by using a Temperature Gradient Chamber (TGC) newly developed (Horie *et al.*, 1991; Kim *et al.*, 1992). The data from TGC experiments were parametrized and incorporated into SIMRIW or SImulation Model for RIce-Weather relationship to simulate rice growth and yield in relation to CO_2 concentration, temperature and solar radiation conditions (Horie, 1993). By applying SIMRIW for Japan with doubled CO_2 climate data predicted by general circulation models for dynamics of earth's atmosphere (GCMs), Horie *et al.* (1995b) predicted that doubled CO_2 concentration and global warming will increase rice yield in northern Japan by 10-30 %, but decrease it in south-western Japan by 10-40 % depending on climate scenarios. Similar results have also been predicted for rice yields in Asia under a doubled CO_2 climate by Matthews *et al.* (1995) by using their rice model ORYZA 1.

These predictions, however, had two major limitions. First, current cultivars and cropping seasons were assumed for predicting rice yield under changed climates, though these are likely to change under doubled CO_2 climates. Second, a value derived from experiments only on 'Akihikari' rice in the TGC was utilized for a crop parameter related to high temperature-induced sterility of rice spikelets, despite this parameter may give a significant effect on the predicted yield under a 2 x CO_2 climate. Furthermore, it was found that a cultivar difference exists in the value of this parameter (Matsui and Horie, 1992). The objectives of this simulation study are three folds. The first is to clarify the effect of the genetical difference in spikelet sensitivity to high temperature damage on regional rice yield in Japan under doubled CO_2 climate. The second is to predict to what extent alternations of cultivars and cropping season can mitigate or promote negative or positive effects of doubled CO_2 climate on regional rice production. On the basis of these analyses, the third is to predict most probable effects of doubled CO_2 concentration and anticipated global climate change on regional rice yield in Japan.

This paper briefly describes the model SIMRIW, experimental derivations of its parameters, and the model performance, and then represents the simulation results on the effects of elevated CO_2 and predicted climate change on regional rice yields in Japan.

2. BASIC STRUCTURE OF THE MODEL SIMRIW

Since the details of SIMRIW, the rice model applied for this study have already been reported (Horie, 1987; Horie *et al.*, 1992, 1995a), only a brief description is made here about the basic structure of SIMRIW.

SIMRIW consists of three major parts that describe the processes of ontogenetic crop development, biomass accumulation and yield formation. The ontogenetic development process of rice from emergence to heading is represented in SIMRIW by a continuous variable, the developmental index (DVI), the value of which is defined to be zero at emergence, 1.0 at heading and 2.0 at maturity. The value of DVI at any given 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 the rice crop is simulated using the idea that crop dry weight at any moment is proportional to the absorbed solar radiation accumulated up to that moment (Monteith, 1977). This process of biomass accumulation is characterized by only one crop parameter, the solar radiation conversion efficiency (Cs). The Cs is assumed to be constant up to heading (DVI=1), and thereafter is given by a decreasing function with respect to DVI to simulate the maturation or senescence process. The leaf area growth rate which governs the radiation absorption rate is modeled as a unique function of temperature. This is in contrast to the traditional approach in which leaf area growth is calculated from its weight growth through 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 the largely independent nature of each to the other, as described by Horie *et al.* (1979).

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

SIMRIW gives a climatically potential yield of a given cultivar of irrigated rice under optimal cultivation technologies. Horie (1987) showed that a close linear relationship existed between the simulated potential yield (Yp) and actual yield (Ya) across respective locations in Japan and in the USA. The relationship could be represented by,

$$Ya = KYp \quad (1)$$

in which K is regarded as an index of the overall technology level of rice cultivation converted into the farmers' yield at the present day.

3. EXPERIMENT AND PARAMETRIZATION ON CO_2 AND HIGH TEMPERATURE EFFECTS ON RICE

For the application of SIMRIW for impact prediction of doubled CO_2 climate on rice yield, parametrizations of the effects of CO_2 concentration and high temperature on rice are indispensable. However, information about this effect based on long-term CO_2 x temperature treatments on rice is very limited to those of Imai *et al.* (1985) and Baker *et al.* (1990a, b). For this reason, we conducted long-term CO_2 x temperature treatment experiments on rice, using a newly developed temperature gradient chamber (TGC) (Horie *et al.*, 1995c). The TGC is a 25 m-long plastic-covered tunnel in which the air flows from one end to the other at a given rate to create a temperature gradient along its longitudinal axis by solar energy in daytime (Fig.1). At night time, the direction of the air was reversed, and heated air by an oil-heater at the daytime exhaust end was led into TGC to create a temperature gradient along the long-axis of TGC due to natural cooling. Two TGCs, one with and one without CO_2 enrichment capability were constructed. Rates of airflow and CO_2 release were controlled by a computer to maintain the temperature difference between the two ends of TGC at 5°C and CO_2 concentration in TGC at 700 μmol mol^{-1}. This system enabled long-term CO_2 x temperature treatments on rice under field-like conditions.

A result of a long-term CO_2 x temperature experiment in the TGC is represented in Fig.2 in which dry weights of crop and panicle of 'Akihikari' rice grown under ambient (350 μmol mol^{-1}) and elevated CO_2 (700 μmol mol^{-1}) concentrations are given as a function of average temperature over the growth period. The doubled CO_2 concentration increased total dry weight of rice by 25 % on average over the entire temperature range (27-32°C). No consistent temperature effect could be seen on the total dry weight in the temperature range of this experiment. However, temperature gave a significant effect on the panicle dry weight both under the elevated and ambient CO_2 conditions : the panicle dry weight decreased sharply as the average temperature exceeded 29°C irrespective of CO_2 concentrations. This sharp decline in the panicle weight at the higher temperature was due to high temperature-induced sterility of rice spikelets. A similar result was also obtained

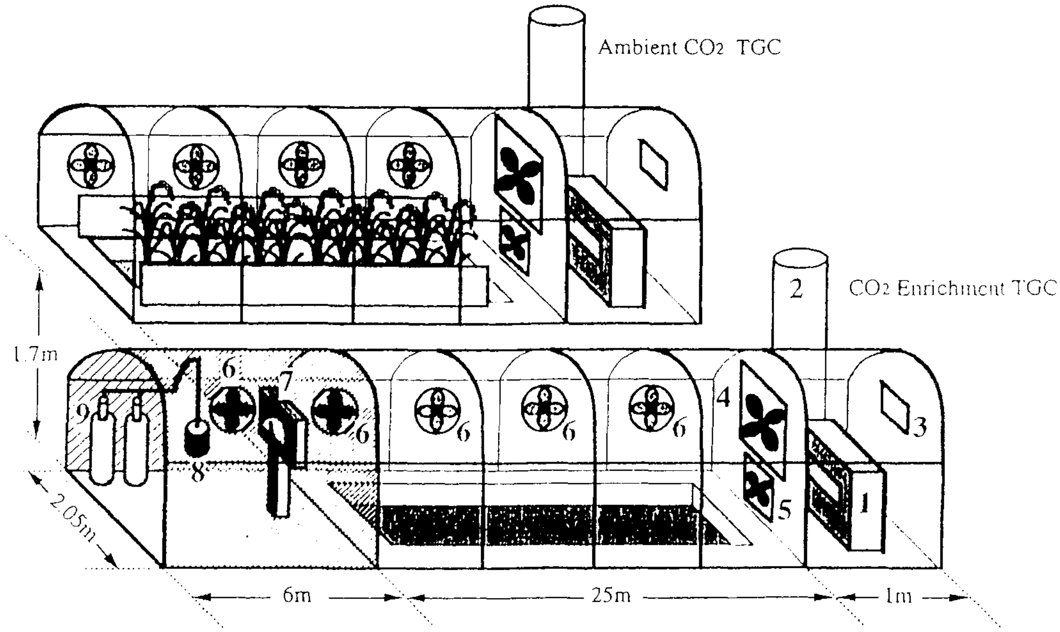

Fig. 1. Schematic drawing of Temperature Gradient Chamber (TGC) of CO_2 enrichment type (bottom) and ambient CO_2 type (top) for the study of temperature x CO_2 effect on rice (Horie *et al.*, 1995c). The numbers on the figure show, 1 : oil heater, 2 : stovepipe of oil heater, 3 : air exhaust window, 4 : variable speed exhaust fan, 5 : reversible exhaust fan, 6 : oscillating fan, 7 : CO_2 controller, 8 : CO_2 injection pipe, and 9 : liquid CO_2 tanks, respectively.

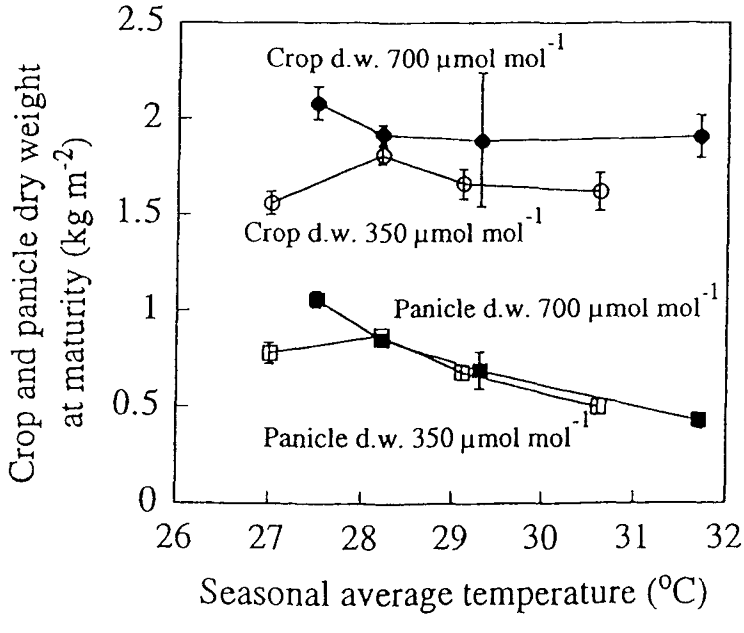

Fig. 2. Total crop and panicle dry weights of rice at maturity grown under elevated (700 μmol mol^{-1}) and ambient (350 μmol mol^{-1}) CO_2 concentrations in the TGC as a function of seasonal mean temperature (Horie *et al.*, 1995c).

for rice by Baker *et al.* (1990a).

Based on experimental results in the TGC and also on information from other researchers (Imai *et al.*, 1985 ; *Baker et al.*, 1990a), it was concluded that doubled CO_2 enhances crop dry matter production of rice by 24 % than that under ambient CO_2, and that this enhancement rate is fairly constant over a wide range of temperature. This finding together with the fact that doubled CO_2 gives only a negligibly small effect on rice leaf area development (Imai *et al.*, 1985 ; Baker *et al.*, 1990a ; Kim *et al.*, 1992) indicates that the enhancement of dry matter production of rice by elevated CO_2 concentration is through the increase in the radiation conversion efficiency, and that doubled CO_2 increases the radiation conversion efficiency of rice by 24 %. Based on this, the CO_2 effect on rice dry matter production was simply parametrized in SIMRIW by giving the radiation conversion efficiency as a function of CO_2 concentration (Horie, 1993).

Among rice organs, high temperature is most damaging to spikelets at anthesis. When the temperature at flowering period exceeds about 35°C, failure in pollination results in spikelet sterility (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. Fertility percentage (100-sterility percentage) of spikelets was plotted against average daily maximum temperature over 10 day-period around the heading stage for 'Akihikari' rice grown under the elevated and ambient CO_2 conditions in TGC (Fig. 3). The results indicate that CO_2 concentration has no effect on the temperature and fertility relationship. The relation was approximated by (Horie, 1993)

$$F = \frac{100}{1 + \exp\{0.853(T_m - T_{mh})\}} \qquad (2)$$

where F is the fertility percentage, T_m is the average daily maximum temperature during the flowering period, and T_{mh} is a parameter to give the value of T_m at which F becomes 50 %.

From a further investigation on high temperature-induced spikelet sterility by using a phytotron under fixed day and night temperature conditions, it revealed that a relatively large cultivar difference exists in the sensitivity of rice spikelets to high temperature (Fig. 4). 'Akihikari' subjected for the TGC experiment (Fig. 3) was found to be more sensitive to high temperature at flowering peiod than 'Koshihikari'. The value of T_{mh} of 'Akihikari' rice was estimated to be 36.6°C from the result shown in Fig. 4, which is very close to the value estimated from Fig. 3. On the other hand, the T_{mh} value of 'Koshihikari' was estimated to be 38.2°C from Fig. 4, indicating that 'Koshihikari' spikelets are more tolerant to high temperature stress during the flowering period than 'Akihikari'. Based on this, the impact assessments of elevated CO_2 and climate change on rice yield by SIMRIW were made for two genotypes of high temperature-sensitive (T_{mh} = 36.6°C) and tolerant one (T_{mh} = 38.2°C).

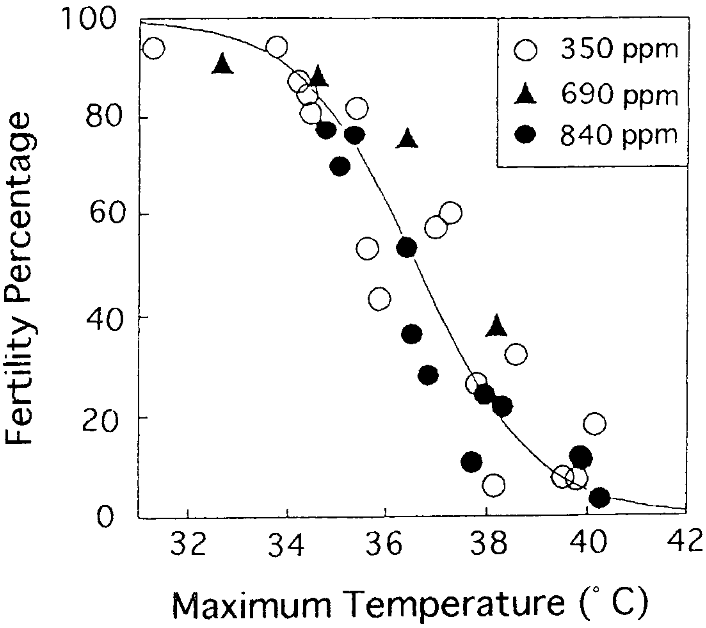

Fig. 3. Relation between average daily maximum temperature during the flowering period and spikelet fertility in the variety Akihikari acclimated to different CO_2 concentrations (Horie, 1993).

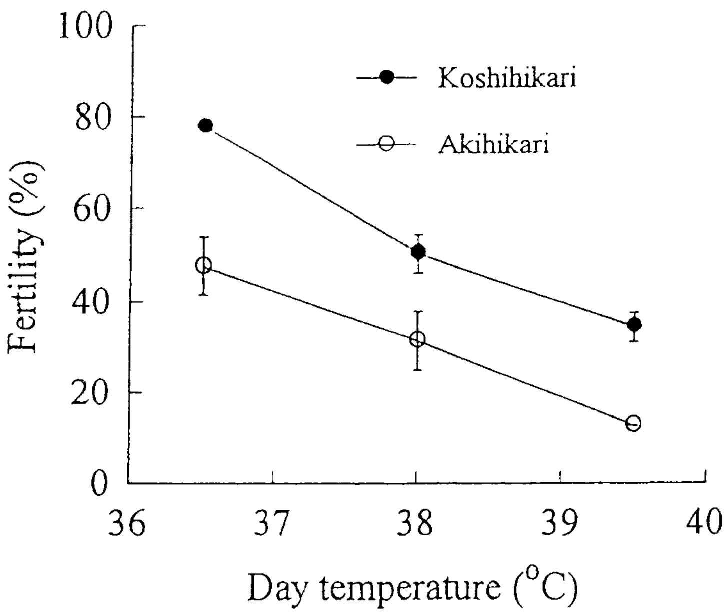

Fig. 4. Spikelet fertility percentages of rice cultivar 'Koshihikari' and 'Akihikari' as affected by day temperature during the flowering period (Matsui *et al.*, unpublished). Plants were subjected to constant day and night temperatures during flowering period.

4. MODEL PERFORMANCE

Figure 5 demonstrates SIMRIW outputs of rice yield as a function of input daily mean temperature, solar radiation and atmosphere CO_2 concentration conditions. In this sensitivity analysis, those environmental conditions were set at constant and diurnal temperature range at 8°C over the entire growth season. As crop parameters for the phenological development, the values obtained for 'Nipponbare' rice were used with *Tmh* value of 36.6°C. Under the constant environmental conditions, the optimum mean temperature for simulated yield was 22-23°C. The sharp decrease of the yield below 22°C reflects the increase of sterile spikelets from cool temperature damage. As temperature increased above the optimum, yield declined more or less linearly up to about 30°C, which results from shortened total growth duration. Sharp decline of yield above 30°C results from spikelet sterility caused by high temperature damage. It should be noted that this threshold temperature for high-temperature damage depends on *Tmh* value, and that the *Tmh* value employed in this simulation is from high temperature-sensitive genotype. The overall temperature response pattern of simulated rice yield agrees fairly well with the results of Munakata (1976).

The model predicts that rice yields are proportional to solar radiation over the entire temperature range and that doubled CO_2 in the atmosphere alone increases rice yield by 24 % under each temperature and radiation condition. These responses resulted from the model hypotheses described in the foregoing sections.

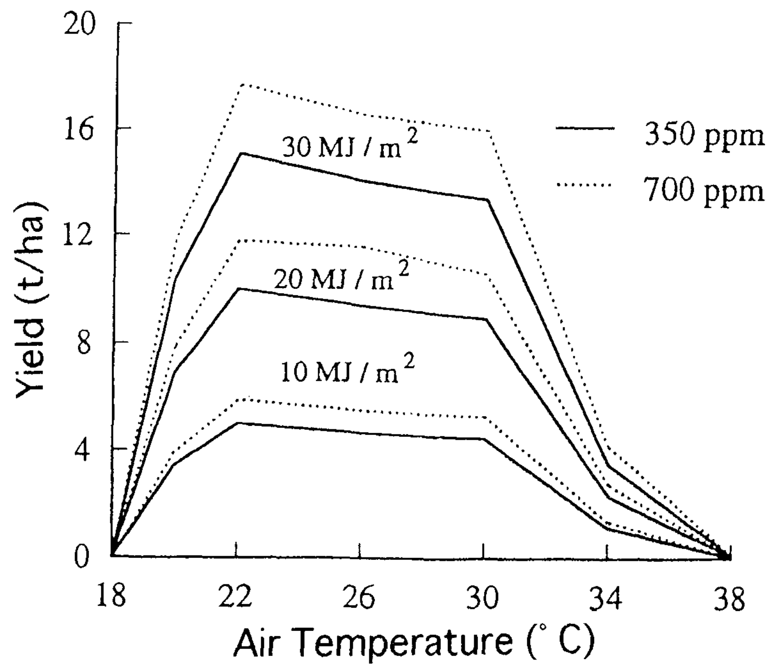

Fig. 5. Simulated yield responses of the cultivar Nipponbare to daily mean temperature, solar radiation, and CO_2 concentration, under constant environmental conditions (Horie *et al.*, 1995a). Day length and diurnal temperature range were set at 12 h and 8°C in each case, respectively.

Validations of SIMRIW were made by using rice growth and yield data obtained at International Rice Research Institute in Philippines and regional farmers' yield data over Japan. Those validations indicated that the model satisfactorily explained difference in rice yield among locations and cropping seasons based on difference in environments (Horie *et al.*, 1995a, b).

5. EFFECTS OF ELEVATED CO_2 AND CLIMATE CHANGE ON REGIONAL RICE YIELD

5.1 Input data

For the assessment of impact of global environment change (elevated CO_2 and climate change) on Japanese rice production, Japan islands were divided into fourteen agro-ecological zones (AEZs) according to Ozawa (1962). Daily weather data for the twelve years from 1979 to 1990 in nine weather stations were selected. The covering AEZs of those weather stations are given in Table 1. Since weather data were not specified for AEZs X and XIII, the climate change effects on rice yield in those AEZs were estimated by interpolation of the predicted yields in the surrounding AEZs.

Table 1 Weather stations, their representing agro-ecological zones (AEZs), and cultivars adopted for the prediction of rice yield under global environment change scenarios in each AEZ.

Site ID	Weather station	Latitude	Longitude	Representing AEZs	Cultivars adopted
1	Sapporo	43° 03'N	141° 20'E	I,II,III,IV	Ishikari
2	Akita	39° 43'N	140° 06'E	VI	Sasanishiki
3	Sendai	38° 16'N	140° 54'E	V	Sasanishiki
4	Maebashi	36° 24'N	139° 04'E	VII,VIII	Koshihikari
5	Toyama	36° 42'N	137° 12'E	IX	Koshihikari
6	Nagoya	35° 10'N	136° 58'E	XI	Nipponbare
7	Hiroshima	34° 22'N	132° 26'E	XII	Nipponbare
8	Kohchi	33° 33'N	133° 32'E	XIV	Nipponbare
9	Miyazaki	31° 55'N	131° 25'E	XIV	Mizuho

From the twelve-year weather data, the 'average' climate for each location was synthesized by averaging daily weather values over the twelve years for each location. This average climate was then used as the baseline to evaluate the effects of climate change on rice yields. Five future climate scenarios were examined : 450 μmol mol^{-1} CO_2 concentration with no change in climate, 450 μmol mol^{-1} CO_2 with a 2°C temperature rise and the 2 x CO_2 climate predicted by the GFDL, GISS and UKMO General Circulation Models (GCMs) of the earth's atmosphere. Those GCMs predicted climate data were supplied by the Data Support Section within the Scientific Computing Division of the National Center for Atmospheric Research through US EPA (Bachelet *et al.*, 1995). The future climate conditions were created by adding the monthly temperature changes in each scenario to the current daily maximum and minimum temperatures of the same month, and by multiplying relative changes in monthly solar radiation by current daily solar radiation values.

As crop parameters for phenological development of rice, the values derived from cultivars listed up in Table 1 were used for each AEZ. Although some of those cultivars are no longer the predominant cultivars in some AEZs at present, those cultivar were adopted for the simulation by assuming that phenological development traits of the present predominant cultivars in each AEZ are not very different from those. Rice yields under the various climate scenarios were simulated in each AEZ for two cases of the crop parameter (T_{mh}) that represents the spikelet sensitivity to high temperature damage at flowering : T_{mh} = 36.6°C for sensitive and 38.2°C for tolerant genotypes to the high temperature damage.

The potential rice yields that SIMRIW simulated were converted into actual farmers' yield at the present day, by multiplying the simulated yields by the technological coefficient (K in Eq. (1)). Since regional farmers' yield in most AEZs in Japan are increasing owing to technological advancements, the coefficient K in each region is a function of time. Based on multiple regression analysis between the reported actual yield and simulated potential yield for twelve year period in each region, the technological coefficient (K) at the present day was determined for each region (Horie *et al.*, 1995b).

5.2 Climate change effects on regional rice yield for high temperature-sensitive and tolerant genotypes

Table 2 shows the predicted change in rice yield under each climate scenario from that of the base (current average) climate for high temperature-sensitive and tolerant

Table 2. Predicted change in potential rice yields from the current values at various locations under different CO_2 and climate conditions.

Climate		Sapporo	Akita	Sendai	Maebashi	Toyama	Nagoya	Hiroshima	Kohchi	Miyazaki
CO_2		**High Temperature Sensitive Genotype**								
ppm										
450	+0°C	+6.7%	+8.0	+7.8	+7.7	+7.7	+7.7	+7.7	+7.7	+7.8
450	+2°C	+0.7%	+6.2	+3.8	+5.2	+2.4	-6.8	+1.9	+3.1	+7.3
640	GFDL	-2.8%	+12.5	+7.3	+7.1	-10.5	-33.9	-21.1	-15.3	+3.7
640	GISS	+13.3%	+26.3	+19.9	+22.3	+18.5	-2.2	-17.4	-29.0	+1.2
640	UKMO	+8.4%	+24.0	+17.7	+13.5	+13.6	-40.9	-47.1	-36.7	-10.0
		High Temperature Tolerant Genotype								
ppm										
450	+0°C	+6.7%	+8.0	+7.8	+7.7	+7.7	+7.7	+7.7	+7.7	+7.8
450	+2°C	+0.8%	+6.2	+3.8	+5.3	+3.0	+4.5	+3.9	+5.7	+7.3
640	GFDL	-2.8%	+12.4	+7.3	+8.5	-9.4	-9.1	-5.1	+0.2	+6.0
640	GISS	+13.3%	+26.3	+19.8	+21.9	+18.5	+18.8	+9.9	+12.5	+22.0
640	UKMO	+8.4%	+24.0	+17.7	+23.2	+13.5	-1.2	-7.8	-2.1	+13.2

genotypes in the nine locations investigated. The results shown in Table 2 were obtained by assuming current cultivars and cropping seasons for all climate conditions. Irrespective of rice genotypes, the model predicted that a 100 μmol mol^{-1} increase in CO_2 concentration over the present level will increase rice yield by 7-8 % at all locations. In conditions where a 2°C temperature rise was added to the 100 μmol mol^{-1} CO_2 elevation, the positive effect of the elevated CO_2 decreased in all the locations, with largest reductions for high temperature-sensitive genotype in southern Japan. The negative effects of the 2°C temperature rise resulted from the facts that higher temperature accelerates rice phenological development and shortens growth duration, and, in southern Japan, causes spikelet sterility for the high temperature-sensitive genotype.

The predicted relative changes of rice yield for the respective locations under 640 μmol mol^{-1} CO_2 and GFDL, GISS and UKMO climate conditions were plotted on the map for high temperature-sensitive (Fig. 6) and tolerant (Fig. 7) genotypes. The predicted effects of 2 x CO_2 climates on rice yield in Japan depend significantly on climate scenarios, adopted rice genotypes and regions. Positive effects of 2 x CO_2 climates, ranging from ca. 10 % (GFDL) to ca. 25 % (GISS and UKMO) yield increase, were predicted in northern Japan, irrespective of rice genotypes adopted. The predicted effects of 2 x CO_2 climates on rice yield in the central-south(AEZ XI) and south-western Japan strongly depend on adopted rice genotypes. For the high temperature sensitive genotypes, severe yield reductions by ca. 10 % (GFDL), 20 % (GISS) and ca. 40 % (UKMO) from the present were predicted in those regions. When the high temperature-tolerant genotype was adopted, those negative effects of 2 x CO_2 climates in the central-south (AEZ XI) and south-western Japan decreased to less than 10 % (GFDL and UKMO) or were reversed into positive (GISS). Note that the temperature (T_{mh}) at which 50 % of spikelets are sterile differed only 1.6°C between the two genotypes. It turned out that the small difference in the spikelet sensitivity to high temperature damage gives significantly large effects on the predicted Japanese rice production under 2 x CO_2 climates.

Since it is very likely that, under a 2 x CO_2 climate, rice cultivars in southern Japan will be endowed with tolerance to high temperature damage of spikelets at flowering, the prediction for the high temperature-tolerant genotype would be a better estimate of probable effects of future climates. Based on this, the predicted rice yield change in Japan under each 2 x CO_2 climate scenario may be summarized as follows : doubled CO_2 with GISS climate will increase rice yield in most regions in Japan by 10 - 25 % ; that with GFDL climate will increase the yield by approximately 10 % in the northern Japan and reduce it by 5 - 10 % in the southern Japan ; that with UKMO climate will increase the yield by approximately 20 % in the northern Japan and reduce it by 5 % in the southern Japan. The largest positive effect in GISS scenario resulted from the fact that GISS model predicts the smallest temperature rise and an increase of solar radiation under doubled CO_2 conditions in Japan, while the smallest positive effect in GFDL scenario resulted from GFDL model predicting a reduction in solar radiation in most part of Japan.

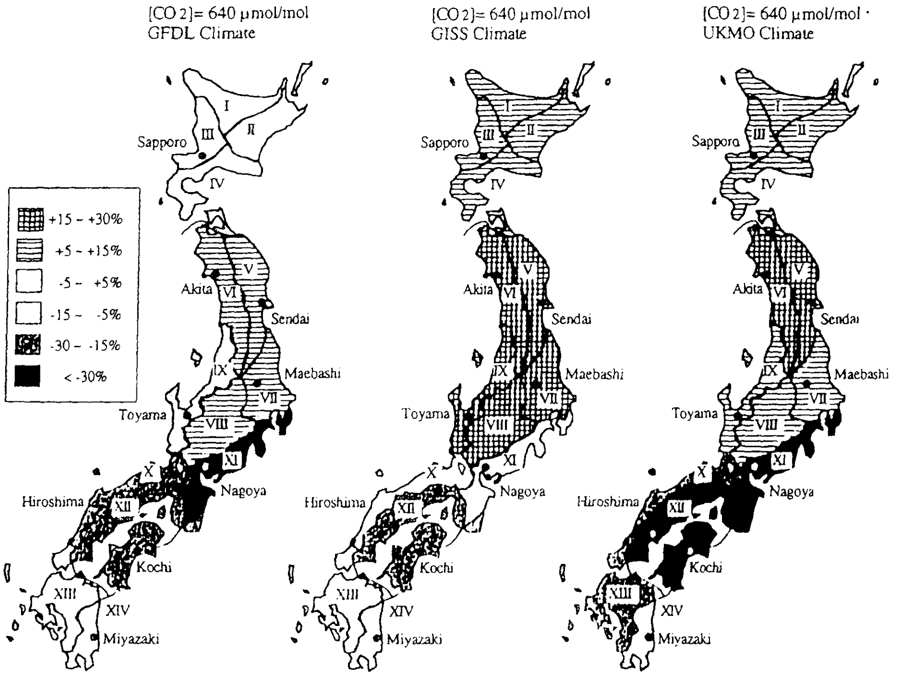

Fig. 6. Effects of 2 x CO_2 and associated climate change predicted by three GCMs on regional rice yield in Japan (prediction by SIMRIW for high temperature-sensitive genotype) (adapted from Horie *et al.*, 1995b).

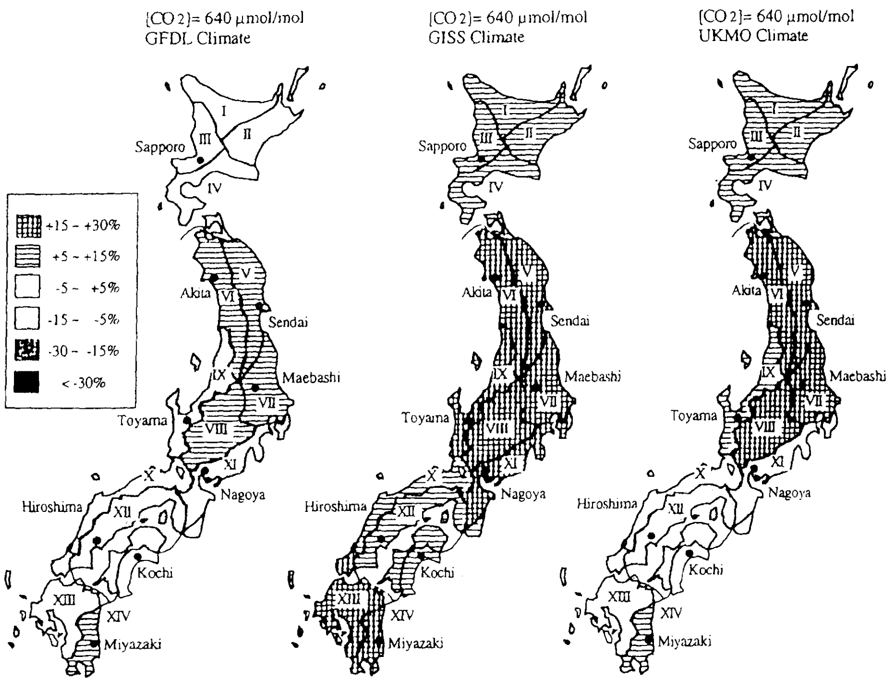

Fig. 7. Effects of 2 x CO_2 and associated climate change predicted by three GCMs on regional rice yield in Japan (prediction by SIMRIW for high temperature-tolerant genotype).

5.3 Probability analysis on effects of GCM climates on rice yield

Probability analyses were made on effects of doubled CO_2 and climate change on rice yield for representative locations, by using daily weather data in the 1979 - 1990 period at Sapporo (AEZ I to IV), Sendai (AEZ V), Nagoya (AEZ XI) and Miyazaki (AEZ XIV) as base climates, and climate change scenarios by GFDL, GISS and UKMO GCMs. Rice genotype with tolerance to high temperature damage of spikelets was adopted for the probability analysis at each location. Figure 8 gives the results of the probability analysis by SIMRIW where the simulated rice yield in each of twelve years under the three different climate scenarios was plotted as cumulative probability distributions.

At Sapporo in Hokkaido (AEZ I to IV), the average predicted yield under the current climate was 5.27 t/ha with a coefficient of variation (CV) of 9.7 %. Yield increases of +4.6 %, + 21.5 % and + 17.5 % were predicted for the 2 x CO_2 climate of the GFDL, GISS and UKMO, respectively. The GISS gave the largest yields of the three GCMs due to the smallest temperature rise and to increased solar radiation levels. Since cool summer damages of rice, which cause a large year-to-year variation of rice yield in Hokkaido, hardly occurred under the 2 x CO_2 climates, significant reductions of the yield variability were predicted there.

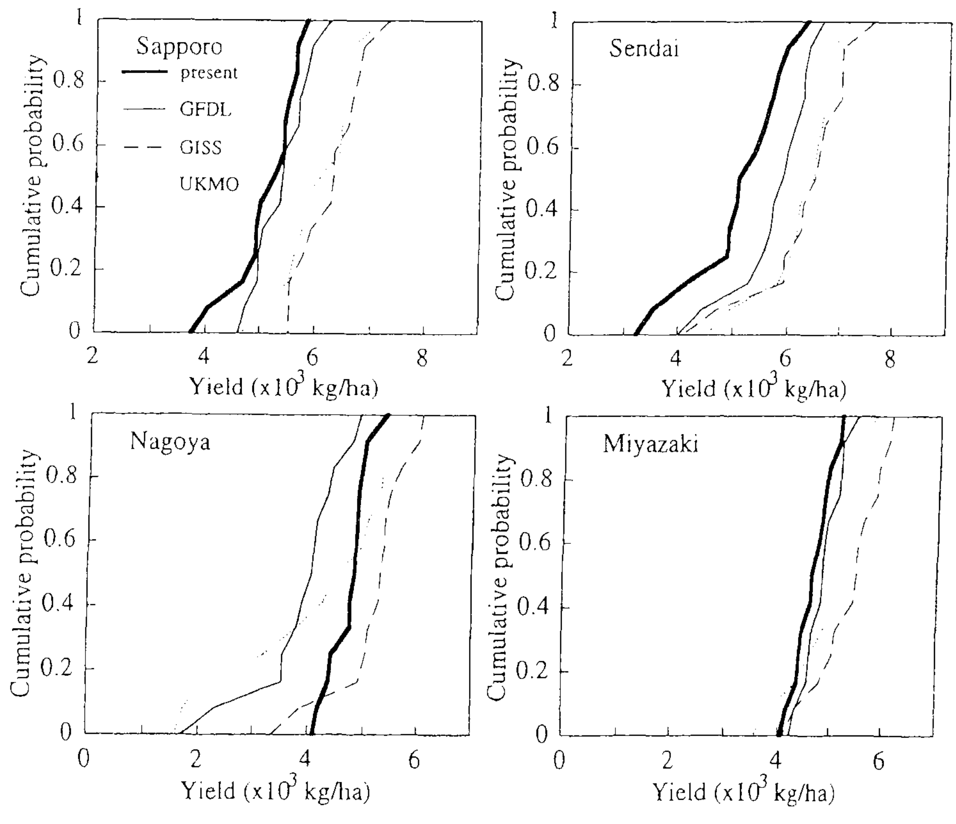

Fig. 8. Cumulative distribution functions for rice yield at four representative locations in Japan under 2 x CO_2 and three scenarios of global climate change (prediction by SIMRIW for high temperature-tolerant genotype).

The largest positive effect of 2 x CO_2 climates was predicted in Tohoku district (AEZ V and VI). At Sendai, the 2 x CO_2 climates not only increased the average yield by 12.5 % to 24.3 %, depending on GCMs, it also reduced the yield variability from the current 15 % to less than 11%.

The largest negative effect of a 2 x CO_2 climate was predicted at Nagoya in Aichi (AEZ XI), where changes in the average yield were - 16.6 %, + 10.4 % and - 9.9 % for GFDL, GISS and UKMO climates. The yield variability was also predicted to significantly increase from the current CV of 7 % to between 11 % and 32 %. These negative effects are due to Nagoya having the highest daily maximum temperature during current conditions of all the locations investigated, so that, further warming in years with hot summer increases the possibility of high temperature-induced spikelet sterility.

At Miyazaki in Miyazaki prefecture (AEZ XIV), between + 3.8 % and + 15.8 % increase of average yield was predicted. However, yield variability was predicted to slightly increase there under 2 x CO_2 climates. The average yield and its variability predicted for Nagoya and Miyazaki are not so catastrophic as those reported in the previous report (Horie *et al.*, 1995b). This is due to the previous report employing the high temperature-sensitive genotype for the prediction, while the present analysis employing the tolerant genotype. Again, it shows that only 1.6°C difference in the T_{mh} value of cultivar gives significant influence on the predicted rice yield in Japan under 2 x CO_2 climates.

5.4 Effect of cultivar and cropping season alternations on rice yield under doubled CO_2 climate

It is realistic to assume that, under a 2 x CO_2 climate, rice production technologies will be adapted to changed climate. Of the technological adaptation, alternations of cultivars and cropping seasons are most likely to occur under a climate change. Apart from the tolerance to high temperature damage of spikelets, rice cultivar adaptation will be made mainly through changes in phenological development traits. The objective of this section is to predict the effects of change in phenological development parameters of cultivars and in cropping seasons on rice yield at selected locations under a 2 x CO_2 climate.

Figure 9 shows the simulated rice yields as a function of transplanting date for current and adapted cultivars under current and GFDL climate condition at Sapporo, Sendai and Nagoya. The 'average' daily climate over twelve-year period was used for this analysis at each location. At Sapporo, phenological development parameters from 'Koshihikari' and 'Ishikari' were used for the adapted and current cultivars, respectively. Since Sapporo is close to northern limit of rice cultivation in Japan, its current climate provides potential transplanting period of only one month for 'Ishikari', a very short season rice, and none for 'Koshihikari', a medium maturing cultivar. The predicted GFDL climate will extend the potential transplanting season of 'Ishikari' to three month, and increase the yield by about 20 % by its one-month earlier transplanting. When the medium maturing cultivar 'Koshihikari' is adopted with one month earlier transplanting under GFDL climate, a 50 % increase in potential rice yield is predicted by SIMRIW. Similarly it is predicted for Sendai that GFDL climate will enable a half month earlier transplanting of 'Nipponbare', a later maturing cultivar than the current 'Sasanishiki', with 13 % increase in the potential yield.

At Nagoya where a negative effect of GFDL climate was predicted, it is predicted that alternation of cropping season will not mitigate the negative effect, despite the climate change significantly extends the cropping season. Replacement of the current cultivar 'Nipponbare' with 'IR 36', an indica type rice, will increase the yield both under the current and GFDL climate conditions, but not mitigate the negative effect of GFDL climate on rice yield there.

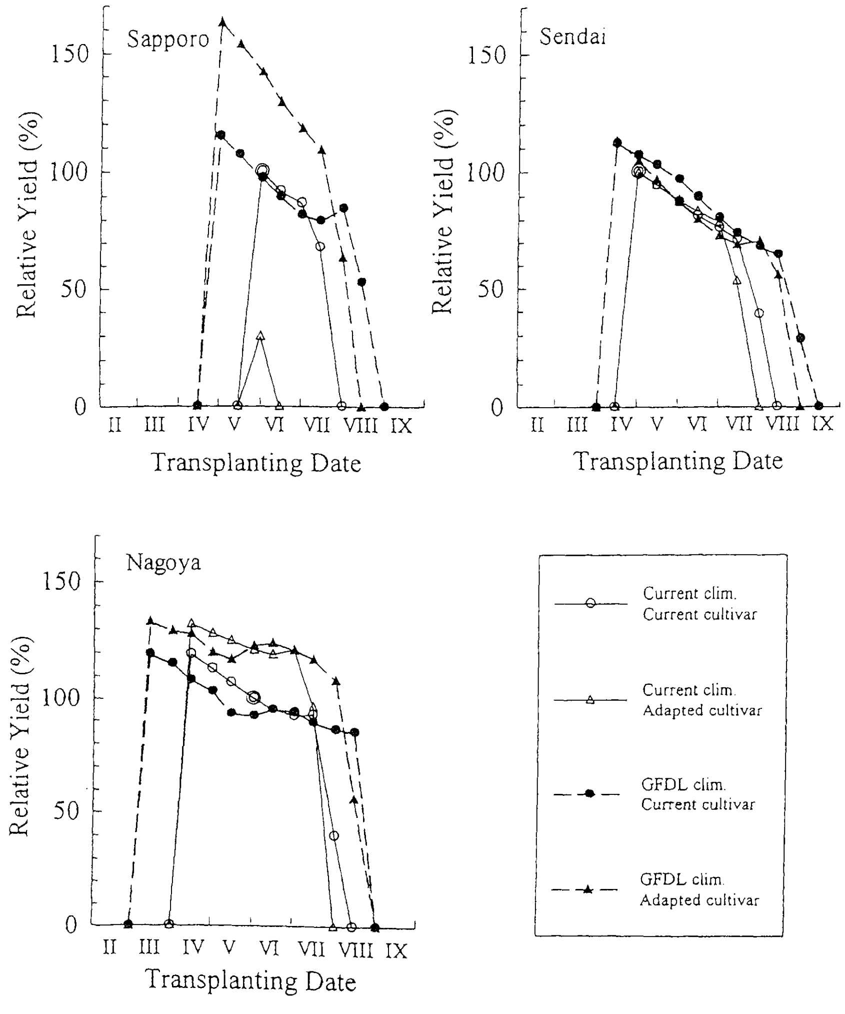

Fig. 9. Relative yield change as a function of transplanting date for current and phenologically adapted rice cultivars under current and GFDL 2 x CO_2 climate conditions for three representative locations (prediction by SIMRIW). The current cultivars used for simulations were 'Ishikari', 'Sasanishiki' and 'Nipponbare' for Sapporo, Sendai and Nagoya, respectively, and the phenologically adapted cultivars were 'Koshihikari', 'Nipponbare' and 'IR 36' for Sapporo, Sendai and Nagoya, respectively. All the cultivars used were assumed to have the same tolerance to high temperature damage of spikelets at flowering as that of 'Koshihikari'. The double circle on the figure denotes the current transplanting date.

The above analysis suggests that adoption of adapted cultivars in phenology and alternation of cropping seasons will furthermore increase rice yield in those regions where a positive effect of 2 x CO_2 is predicted for current cultivation conditions, but will not significantly mitigate rice yield in those regions where negative effects are predicted. In hotter regions where a negative effect of 2 x CO_2 climate is predicted on rice, the only way to mitigate it would be adoption of much resistant genotypes to high temperature-induced spikelet sterility, either with higher tolerance to high temperature at flowering time or with capability to flower early in the morning before temperature rise as reported by Imaki *et al.* (1987).

6. CONCLUSIONS

Probable effects of elevated CO_2 concentration in the atmosphere and anticipated global climate change on regional rice yield in Japan were predicted by using the rice growth simulation model SIMRIW in which experimental data from long-term CO_2 x temperature treatments on rice were incorporated. Important conclusions derived from this study may be summarized as follows:

1. A 100 μmol mol^{-1} increase in CO_2 concentration alone will increase rice yield in Japan by 7 - 8%, and that a 2° C temperature rise will significantly reduce this CO_2 effects in most Japan.
2. Effects of 2 x CO_2 climate on regional rice yield depend significantly on regions, cultivars adopted and on climate change scenarios.
3. The most sensitive crop parameter that gives significant effects on predicted rice yield under 2 x CO_2 climate scenarios is the spikelet sensitivity to high temperature damage at flowering period. For a high temperature-sensitive genotype, severe yield reductions in the southern Japan by ca. 10%, 20 % and ca. 40 % from the present were predicted under 2 x CO_2 climates from GFDL, GISS and UKMO general circulation models, respectively, while, for a high temperature-tolerant genotype, the yield reduction in the southern Japan was less than 10%. In the northern Japan, positive effects of 2 x CO_2 climates, ranging from ca. 10 % (GFDL) to ca. 25 % (GISS and UKMO) yield increase were predicted, irrespective of cultivar sensitivity to high temperature damage.
4. The 2 x CO_2 climates will significantly increase yearly yield variability in the southern Japan, while they stabilize the variability in the northern Japan.
5. Alternations of phenological development genotypes and cropping seasons will furthermore promote the positive effects of 2 x CO_2 climates in the northern Japan, but will not significantly mitigate the negative effects in the southern Japan.
6. For mitigating the predicted negative effects of 2 x CO_2 climates in the southern Japan, explorations for more resistant rice genotypes to the high temperature damage at flowering are necessary.

REFERENCES

Bachelet, D., King, G.A. and Chaney J., 1995. Climate change scenarios. In: *Modelling the Impact of Climate Change on Rice Production in Asia.* (ed by

R.B. Matthews, M.J. Kropff, D. Bachelet and H.H. van Laar), 67-83, Cab International, Oxon, UK.

Baker, J.T., Allen, L.H., Jr., Boote, K.J., Rowland-Bamford, A.J., Waschmann, R.S., Jones, J.W., Jones, P.H. and Bowes, G., 1990a. Temperature effects on rice at elevated CO_2 concentration. *1989 Progress Report of Response of Vegetation to Carbon Dioxide, No.060.* Plant Stress and Protection Research Unit, USDA-ARS, University of Florida, Gainesville, 70 pp.

Baker, J.T., Allen, L.H., Jr. and Boote, K.J., 1990b. Growth and yield responses of rice to carbon dioxide concentration. *J. Agr. Sci.*, **115**, 313-320.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R. and Lerner, J., 1984. Climate sensitivity: analysis of feedback mechanisms. In: *Climate Processes and Climate Sensitivity* (ed by J. Hansen and T. Takahashi), Maurice Ewing Series, 5, 130-163. American Geophysical Union, Washington, D.C.

Horie, T., 1987. A model for evaluating climatic productivity and water balance of irrigated rice and its application to Southeast Asia. *Southeast Asian Studies,* **25**, 62-74.

Horie, T., 1993. Predicting the effects of climatic variation and effect of CO_2 on rice yield in Japan. *J. Agr. Meteorol.*, **48**, 567-574.

Horie, T. and Nakagawa, H., 1990. Modeling and prediction of development process in rice. I. Structure and method of parameter estimation of a model for simulating developmental process toward heading. *Jpn. J. Crop Sci.*, **59**, 687-695.

Horie, T., Nakagawa, H., Centeno, H.G.S. and Kropff, M.J., 1995a. The rice crop simulation model SIMRIW and its testing. In: *Modelling the Impact of Climate Change on Rice in Asia* (ed by R.B. Matthews, M.J. Kropff, D. Bachelet and H.H. van Laar), 51-66, Cab International, Oxon, UK.

Horie, T., Nakagawa, H. and Ohnishi, M., 1995b. Rice production in Japan under current and future climates. In: *Modelling the Impact of Climate Change on Rice in Asia* (ed by R.B. Matthews, M.J. Kropff, D. Bachelet and H.H. van Laar), 143-164, Cab International, Oxon, UK.

Horie, T., Nakagawa, H., Nakano, J., Hamotani, K. and Kim, H.Y., 1995c. Temperature gradient chamber for research on global environment change. II. A system designed for rice in Kyoto, Japan. *Plant, Cell Environ.*, **18**,1064-1069.

Horie, T., Nakano, J., Nakagawa, H., Wada, K., Kim H.Y. and Seo, T., 1991. Effects of elevated CO_2 and high temperature on growth and yield of rice. 1. Development of temperature gradient tunnels. *Jpn. J. Crop Sci.*, **60** (Extra issue. 2), 127- 128.

Horie, T., de Wit, C.T., Goudriaan, J. and Bensink, J., 1979. A formal template for the development of cucumber in its vegetative stage. *Proc. KNAW, Ser. C*, **82**, 433-479.

Horie, T., Yajima, M. and Nakagawa, H., 1992. Yield forecasting. *Agr. Syst.*, **40**, 211-236.

Imai, K., Colman, D.F. and Yanagisawa, T., 1985. Increase of atmospheric partial pressure of carbon dioxide and growth and yield of rice (*Oryza sativa* L.) *Jpn. J. Crop Sci.*, **54**, 413-418.

Imaki, T., Tokunaga, S. and Obara, S., 1987. High temperature-induced spikelet sterility of rice in relation to flowering time. *Jpn. J. Crop Sci.*, **56** (extra issue 1), 209-210 (in Japanese).

Kim, H.Y., Horie, T., Nakagawa, H., Wada, K. and Seo, T., 1992. Effects of elevated CO_2 concentration and high temperature on growth and nitrogen use efficiency of rice. *Proc. of the First Asian Crop Science Conference: Crop Production and Improvement Technology in Asia.* Korean Society of Crop Science, 205-212.

Matsui, T. and Horie, T., 1992. Effects of elevated CO_2 and high temperature on growth and yield of rice. 2. Sensitive period and pollen germination rate in high temperature sterility of rice spikelets at flowering. *Jpn. J. Crop Sci.*, **61**(extra issue 1), 148-149

Matthews, R.B., Horie, T., Kropff, M.J., Bachelet, D., Centeno, H.G., Shin, J.C., Mohandass, S., Singh, S., Zhu Defeng and Moon Hee Lee, 1995. A regional evaluation of the effect of future climate change on rice production in Asia. In: *Modelling the Impact of Climate Change on Rice in Asia* (ed by R.B. Matthews, M.J. Kropff, D. Bachelet and H.H. van Laar.), 95-139, Cab International, Oxon, UK.

Monteith, J.L., 1977. Climate and efficiency of crop production in Britain. *Philos. T. Roy. Soc. Lon. B*, **281**, 277-294.

Munakata, K., 1976. Effects of temperature and light on the reproductive growth and ripening of rice. *Proc. of the Symp. on Climate and Rice.*, 187-210, IRRI, Philippines.

Ozawa, Y., 1962. Climatic zoning of Japan for land use. *Chiri*, 7, Kokinshoin, Tokyo, 300-364 and 432-438 (in Japanese).

Satake, T. and Yoshida, S., 1978. High temperature-induced sterility in Indica rice at flowering. *Jpn. J. Crop Sci.*, **47**, 6-17.

Uchijima, T., 1976: Some aspects of relation between low air temperature and sterile spikelets in rice plants. *J. Agr. Meteorol.*, **31**, 199-202.

Yoshino, M., Horie, T., Seino, H., Tsujii, H., Uchijima, T. and Uchijima, Z., 1988. The effects of climatic variations on agriculture in Japan. In: *The Impact of Climatic Variations on Agriculture, Vol. 1. Assessments in Cool Temperature and Cold Regions* (ed by M.L. Parry, T.R. Carter and N.T. Konijn), 725-865, Kluwer Academic Publishers, Dordrecht.

PREDICTION OF JAPANESE POTENTIAL VEGETATION DISTRIBUTION IN RESPONSE TO CLIMATIC CHANGE

Atsushi Tsunekawa[1], Hitoshi Ikeguchi[2] and Kenji Omasa[1]

ABSTRACT Potential shift of natural vegetation in Japan caused by global climatic change was predicted by the direct transfer function approach. Two types of vegetation distribution model, fuzzy model and multinomial logit model, were applied to explain the relationship between vegetation classification of remaining natural vegetation and climatic conditions. The logit model indicated a more successful result than the fuzzy model. Then, the effects of increase in mean annual temperature were predicted using the logit model. It was indicated that the percentage of grid-cells in all of Japan which showed different predicted vegetation classifications from the present ones are approximately 23% for a 1-degree increase, 44% for a 2-degree increase, and 62% for a 3-degree increase.
KEY WORDS global climatic change, natural vegetation, potential shift, direct transfer function approach, vegetation distribution model

1. INTRODUCTION

How does global climatic change affect the vegetation distribution in Japan? Our goal is to answer this question. For this purpose, we have developed statistical models for prediction of the potential vegetation distribution by the direct transfer function approach. Two types of vegetation distribution model, fuzzy model and multinomial logit model, were examined.

What is global climatic change?

The amounts of some trace gases in the atmosphere, especially carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons (CFCs) and tropospheric ozone (O_3), have been increasing due to human activities such as the massive consumption of fossil fuels, exhaust emissions from factories and automobiles, agricultural activities, and so on (Japan Environment Agency, 1993). All of these gases are transparent to incoming short-wave radiation from the sun, but they absorb and emit long-wave radiation and are thus able to influence the Earth's climate. This is

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[1] National Institute for Environmental Studies, Tsukuba, Ibaraki 305, Japan
[2] Museum of Nature and Human Activities, Sanda, Hyogo, 669-13, Japan
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called 'global climatic change' or 'global warming' and trace gases which cause this 'greenhouse effect' are called 'greenhouse gases.'

Increased concentrations of CO_2 and other greenhouse gases lead to a warming of the Earth's surface and the lower atmosphere. As a result of the increasing concentrations of greenhouse gases, it is now believed that in the first half of the next century a rise in global mean temperature could occur which will exceed any in man's history (Bolin *et al.*, 1986).

According to the assessment by Working Group I of the Intergovernmental Panel on Climate Change, as a result of the "business as usual" scenario, the average global temperature might have increased by approximately one degree by the year 2025 and by three degrees by the end of the next century. The sea level might rise approximately 20 cm by the year 2030 and 65 cm by the end of the next century (IPCC, 1990a).

Why should we assess the impact on vegetation?

'Global warming' would not only be greater than recent natural fluctuations, but it would occur 15 to 40 times faster than past natural changes (Schneider, 1989). It has been stated by many scientists that such a rate of change may exceed the ability of many species to adapt or disperse into new regions, and thus many plant and animal species may become extinct (IPCC, 1990b). Thus, researches on the impact assessment of climatic change on ecosystems are being promoted all over the world (Goudriaan *et al.*, 1990; Pan, 1993; Peters and Lovejoy, 1992; Rotmans, 1990; Solomon and Shugart, 1993; UK Climate Change Impacts Review Group, 1991).

Dale and Rauscher (1994) summarized the major information needed for forest management.

1. Predictions of expected changes in land use.
2. Compilations of maps of forest type distribution.
3. Compilations of maps of species composition changes.
4. Estimates of changes in forest resource productivity.
5. Estimates of expected changes in forest health.
6. Estimates of potential effect on biological diversity.
7. Predictions of effects on wildlife habitat.

Our target corresponds to the second item; 'Compilations of maps of forest type distribution. Where and when will forest type distributions be altered in response to climate change?'. Strictly speaking, our target may be 'compilations of vegetation type maps of potential distribution in response to climate change.' This is expected to be of critical importance for policy makers and land managers.

Previous studies on Japanese vegetation

Generally speaking, the most important factors limiting vegetation distribution are thermal and moisture conditions. However, because the Japanese islands have abundant precipitation of approximately 1,500 mm/year, thermal conditions limit vegetation more strongly than moisture (Kira, 1974, Yamanaka, 1979). Consequently, plant ecologists have always maintained that Japanese vegetation shows ordination from north to south horizontally, and from high to low altitudinally, according to thermal conditions (Honda, 1922).

To interpret the distribution of Japanese vegetation zones, which is clearly related to thermal conditions, Kira (1949) devised two effective indices, 'the warmth index' (WI) which indicates the positive influence of warmth and the negative influence of excessive heat, and 'the coldness index' (CI) which indicates the negative influence of low temperature. The formulation of these indices is as follows:

$$WI = \Sigma\ (t-5) \text{ for months } t > 5\ ^{\circ}C$$
$$CI = \Sigma\ (5-t) \text{ for months } t < 5\ ^{\circ}C$$

where t is the monthly mean temperature.

Using the warmth index, Uchijima *et al.* (1992) examined which tree species in Japan would be most sensitive to a probable climatic warming.

Why adopt the direct transfer function approach?

The IPCC Working Group II classified the methodologies used for impact studies on ecosystems into four approaches; (1) the direct transfer function approach, (2) the palaeoreconstruction approach, (3) simulation modeling of ecosystems at the stand level, and (4) reasoning from ecological or ecophysiological knowledge (IPCC, 1990b).

We take the first approach; the direct transfer function approach, which has been used by many scientists in impact assessment studies, for example, Emanuel *et al.* (1985a, 1985b) on a global scale, and Zabinski and Davis (1988) for the Great Lakes region of the United States of America.

This method analyzes the current distributions of vegetation types and its bioclimatology (Box, 1981; Desjardins *et al.*, 1992) and predicts their possible future distributions as climatic patterns using the suggested climate change scenarios. As a result of the analysis, it can show areas where current vegetation might be replaced by another type of vegetation in response to climatic change. In these areas it can be considered that the climate is no longer optimal for the current vegetation type. These areas, therefore, are those which would be most vulnerable to disruption as a result of projected climatic changes. As such, considerable care should be given to development of management strategies for these areas (IPCC, 1990b).

2. MATERIALS AND METHODS

2.1 Models

2.1.1 Fuzzy model

The fuzzy model expresses the relationship between vegetation classification and climatic conditions by fuzzy rules with certainty measures. Each rule for estimation of vegetation classification can be described as:

Rule *r*: if *Xr* then *Ari* with *Cr*,

where *Xr* is a fuzzy set of climatic conditions such as annual mean temperature, etc., *Ari* is a subset of vegetation classification, and *Cr* is a certainty measure of each rule.

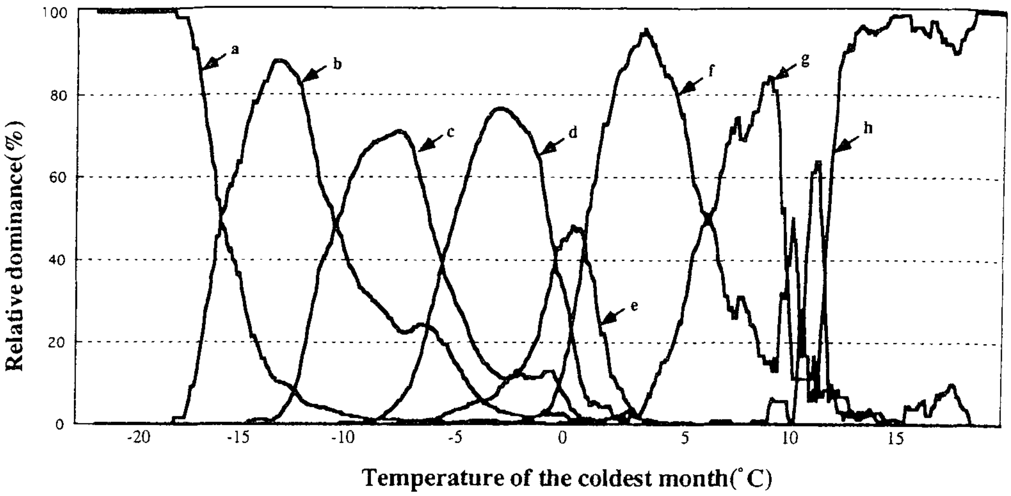

Fig.1. Temperature of the coldest month and relative dominance of each vegetation classification.

Table 1 Examples of fuzzy rules.

If 'Temperature of the coldest month is extremely low' then 'Vegetation classification is a ' with '1.0'.
If 'Temperature of the coldest month is very low' then 'Vegetation classification is b ' with '0.8'
If 'Temperature of the coldest month is low' then 'Vegetation classification is c ' with '0.8'
If 'Warmth index extremely low' then 'Vegetation classification is a ' with '0.8'
If 'Warmth index is very low' then 'Vegetation classification is b ' with '0.8'

The combination of each rule is computed using the probability-theory of Dempster and Shafer (Kainuma *et al.*, 1991).

Figure 1 shows the relative dominance of each vegetation classification for the temperature of the coldest month. *Cr* was determined using such relative dominances. Fuzzy rules could be described as shown in Table 1. Figure 2 shows the structure of rules to estimate vegetation classification.

2.1.2 Linear multinomial logit model

The multinomial logit model is one of several random utility models, which assumes that the doer selects an alternative that has the highest utility and that the utility itself is not constant, but random (Sugiura, 1989). Generally speaking, the relationship between a land and the vegetation on it includes some uncertainty, since the formation process of a plant community involves uncertain elements, for example, competition at the individual level, seed dispersal etc. and also there are some environmental

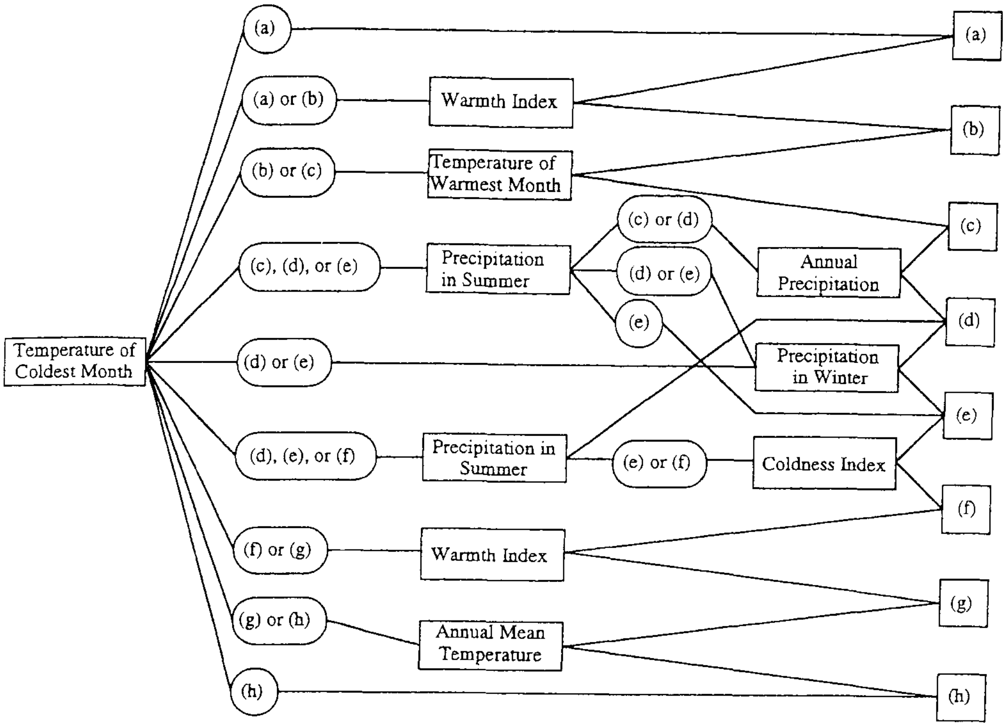

Fig.2. Structure of fuzzy rules for vegetation classification.

conditions which are too difficult to measure or too complex to be included in the analysis. Therefore the random utility model, which assumes the existence of an unknown part for the analysts, would be applicable.

In the case of the linear multinomial logit model, the probability of selecting an alternative is explained to be in proportion to the exponential of the linear combination of the explanatory variables (Ikeguchi *et al.*, 1991).

The multinomial logit model can be shown as

$$P(i)=\left\{\exp\left(\sum_{j=1}^{J}\left(A_{ij}\times V_j\right)+C_i\right)\right\}\Bigg/\left\{\sum_{i=1}^{I}\exp\left(\sum_{j=1}^{J}\left(A_{ij}\times V_i\right)+C_i\right)\right\} \qquad (1)$$

where $P(i)$: probability of the i-th vegetation classification, V_j: the j-th explanatory variable, A_{ij}: parameter of the j-th explanatory variable of the i-th vegetation classification, C_i: constant of the i-th vegetation.

The study computed the selection probability under each condition from data on vegetation classification and climatic conditions, and then computed the parameters of linear function by the maximum likelihood method.

2.2 Data

Data are arranged in the form of a $1km^2$ grid system covering the whole of Japan.

Vegetation data were provided by the Japan Environment Agency. Natural communities were selected and reordered into 8 groups corresponding to "order" or "alliance" level (Miyawaki, 1983, Table 2). Climatic data were merged into a database from datafiles supplied by the Meteorological Agency. The database contains 386,950 grid cells, and among them, 59,786 grid cells are those of remaining natural vegetation and the rest are those of substitution vegetation and value-missing (Color Plate 16). The study made a model using data on remaining natural vegetation and then predicted vegetation classification for the whole of Japan using the model.

Table 2 Natural vegetation classification and the number of grid-cells.

Code	Phytosociological classification	Characteristics	No. of grid-cells
a	*Vaccino-Pinetalia pumilae*	Alpine grassland, etc.	1, 158
b	*Abieti-Piceetalia Jezoensis*	Subalpine conifer forest	15, 345
c	*Saso-Fagion crenatae* (1)	Cool-temperate vegetation typical in Hokaido	24, 541
d	*Saso-Fagion crenatae* (2)	Cool-temperate vegetation typical in the Japan Sea side	13, 542
e	*Sasomoropho-Fagion crenatae*	Cool-temperate vegetation typical in the Pacific side	1, 920
f	*Illicio-Quercetalia acutae*	Warm-temperate vegetation typical on hills	1, 726
g	*Maeso japonicae-Castanopsion Sieboldii*	Warm-temperate vegetation typical on lowlands	657
h	*Psychotrio-Castanopsion Sieboldii*	Subtropical vegetation	897

3. RESULTS

3.1 Estimation by fuzzy model

The hit ratio of the fuzzy model was approx. 70.3% (42,002/59,786). The hit ratios of each vegetation classification were a) 17.7%, b) 49.7%, c) 82.5%, d) 78.2%, e) 39.4%, f) 73.5%, g) 65.9%, h) 99.4%, and their average was 63.2%. The hit ratios of h) and c) were relatively high and those of a) and e) was relatively low. Comparison of the estimated natural vegetation map by the fuzzy model (Color Plate 17) and the actual vegetation map (Color Plate 16) showed that the boundary between cool-temperate vegetation and warm-temperate vegetation of the estimated map was located southward to that of the actual map.

3.2 Estimation by logit model

The hit ratio of the logit model was approx. 75.8% (45,320 /59,786). The hit ratios of each vegetation classification were a) 28.8%, b) 61.7%, c) 78.6%, d) 91.4%, e) 77.2%, f) 83.1%, g) 69.6%, h) 54.4%, and their average was 68.1%. The hit ratios of d) and f) were relatively high and those of a) and h) were relatively low. Comparison of the estimated natural vegetation map by the logit model (Color Plate 18) and the actual vegetation map showed that cool-temperate vegetation of the Pacific side was underestimated.

3.3 Comparison of fuzzy model and logit model

Comparison of the fuzzy model and the logit model showed that both total hit ratio and average hit ratio of the logit model were higher than those of the fuzzy model. From the viewpoint of geographical distribution, those of the logit model were superior to those of the fuzzy model, especially for the discrimination of the Pacific side vegetation and the Japan Sea side vegetation for cool-temperate vegetation.

3.4 Prediction of potential shift using the logit model

By varying the climatic parameters of the logit model, potential shift under the warmed climate was predicted. Three scenarios of 1-degree, 2-degree, and 3-degree increases in annual mean temperature were used. As a result, it was indicated that the percentage of grid-cells in all of Japan which showed different predicted vegetation classifications from the present classifications were approx. 23% for a 1 degree increase, 44% for a 2 degree increase, and 62% for a 3 degree increase. Moreover, the alpine and subalpine vegetation which is distributed separately in the mountainous regions at the present time may be deprived of its suitable habitat (Color Plate19-21).

4. DISCUSSION

From the results of the analysis, it is indicated that even only a 1 degree increase in annual mean temperature might cause potential shift to another vegetation classification for approx. 23% of the total grid-cells (approximately 1km x 1km) in Japan.

What does the potential shift indicated by the study mean? First, as for the accuracy, since the hit ratio of the model is approx. 76%, it must be noted that a corresponding error may be included. Next, as for the ecological meaning of the potential shift, as many ecologists have pointed out, the shifting speed of plant species may be slower than that of a habitat by global warming. Besides, it differs depending on each species. Therefore, it cannot be considered that all plant communities shift to habitats with the same species composition and the same forest structure.

In the regions where shifting of plant species cannot catch up with that of the habitat, some change might be caused in the ecosystem. However, the methodology used in the study has limitations in predicting whether the change might be "competitive displacement" or "catastrophic decline" (Neilson and King, 1991).

Moreover, the model doesn't include all environmental changes in the future. Especially, fertilization effects caused directly by an increase of atmospheric CO_2

might change plant response to temperature, precipitation, and other climatic conditions.

REFERENCES

Bolin, B., Döös, B.R., Jäger J. and Warrick, R.A. (eds.), 1986. *The Greenhouse Effect Climatic Change and Ecosystems.* John Wiley & Sons, Chichester, 541 pp.

Box, E.O., 1981. *Macroclimate and Plant Forms: An Introduction to Predictive Modeling in Phytogeography.* Dr W. Junk Publishers, The Hague, Netherlands, 258 pp.

Dale, V.H. and Rauscher, H.M., 1994. Assessing impacts of climate change on forests: the state of biological modeling. *Clim. Change,* **28**, 65-90.

Desjardins, R.L., Gifford, R.M., Nilson, T. and Greenwood, E.A.N., 1992. *Advances in Bioclimatology.* Springer-Verlag, Berlin, 157 pp.

Emanuel, W.R., Shugart, H.H. and Stevenson, M.P., 1985a. Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. *Clim. Change,* **7**, 29-43.

Emanuel, W.R., Shugart, H.H. and Stevenson, M.P., 1985b. Response to comment: climatic change and the broad-scale distribution of terrestrial ecosystem complexes. *Clim. Change*, **7**, 457-460.

Goudriaan, J., Keulen, H. van, and Laar, H.H. van (eds), 1990. *TheGreenhouse Effect and Primary Productivity in European Aagro-ecosystems.* Pudoc, Wageningen, 90 pp.

Honda, S., 1922. *Studies on Forest Zones in Japan.* Tokyo (in Japanese).

Ikeguchi, H., Takeuchi, K. and Tsunekawa, A., 1991. Potential natural vegetation mapping of Japan by means of GIS: *Environmental Change and GIS. Vol.1* (ed. by I. Ota), 26-33.

Intergovernmental Panel on Climate Change (IPCC), 1990a. *Climate Change, the IPCC Scientific Assessment.* (ed by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums) University Press, Cambridge, 365 pp.

Intergovernmental Panel on Climate Change (IPCC), 1990b. *Climate Change, the IPCC Impacts Assessment.* (ed by W.J. McG. Tegart, G.W. Sheldon and D.C. Griffiths), Australian Government Publishing Service, Canberra, 278pp.

Japan Environment Agency (Global Environment Department), 1993. *Dictionary for Global Environment.* Chuou-Houki, Tokyo, 175 pp. (in Japanese),.

Kainuma, M., Nakamori, Y., Morita, T., Kai, K. and Tsunekawa, A., 1991. Estimation of Japanese vegetation zones using fuzzy modeling. *Proc. 7th Fuzzy System Symposium* (Nagoya, Jun. 12-14, 1991), 561-562 (in Japanese with English abstract).

Kira, T., 1949. *Forest Zones in Japan. Ringyo Kaisetsu Series, 17,* Nippon Ringyo Gijutsu Kyokai, Tokyo (in Japanese).

Kira, T., 1974. A climatological interpretation of Japanese vegetation zones. In: *Vegetation science and environmental protection,* (ed by A. Miyawaki and R. Tuexen), 21-30, Maruzen, Tokyo.

Miyawaki, A.(ed.), 1983. *Handbook of Japanese vegetation* (revised edition), Shibundo, Tokyo, 872 pp. (in Japanese).

Neilson, R.P. and King, G.A., 1991, *Continental Scale Biome Responses to Climatic Change.* The EPA Environmental Research Laboratory in Corvallis, Oregon, 31pp.

Pan, T., 1993. The climate change space influences agricultural production in northeast China. *J. Agr. Meteorol.* **48**, 767-770.

Peters, R.L., Lovejoy, T.E. (eds),1992. *Global Warming and Biological Diversity.* Yale University Press, New Haven & London, 386 pp.

Rotmans, J., 1990. *IMAGE - An Integrated Model to Asses the Greenhouse Effect.* Kluwer Academic Publishers, Dordrecht, 289 pp.

Schneider, S.H., 1989. The greenhouse effect, science and policy. *Science,* 243, 771-781.

Solomon, A.M. and Shugart, H.H. (eds), 1993: *Vegetation dynamics &Global Change.* Champman & Hall, New York, 338 pp.

Sugiura, Y., 1989. *Location and spatial behavior.* Kokon Shoin, Tokyo, 207 pp. (in Japanese).

Tsunekawa, A., Ikeguchi, H., Kainuma, M., Tobe, K. and Omasa, K., 1993. Effects of climatic change on the vegetation distribution in Japan. *J. Agr. Meteorol.,* **48**, 867-870.

Uchijima, Z., Seino, H. and Nogami, M., 1992. Probable shifts of natural vegetation in Japan due to CO_2-climatic warming. *NIAES Series No. 1 (Ecological Processes in Agro-ecosystems),* Natl. Inst. Agro-Environ. Sci., 189-201.

United Kingdom Climate Change Impacts Review Group, 1991. *The Potential Effects of Climate Change in the United Kingdom.* HMSO, London, 124 pp.

Yamanaka, T., 1979. *Japanese forest vegetation.* Tsukiji-shokan, Tokyo, 223 pp. (in Japanese).

Zabinski, C. and Davis, M. B., 1988. Hard times ahead for Great Lakes forests - A climate threshold model predicts responses to CO2-induced climate change -. In: *The Potential Effects of Global Climate Change on the United States,* (ed. by US EPA), 2, 5-1~5-19.

CLIMATIC CHANGE AND ITS IMPACTS ON THE VEGETATION DISTRIBUTION IN CHINA

Atsushi Tsunekawa[1], Xinshi Zhang[2], Guangsheng Zhou[2] and Kenji Omasa[1]

ABSTRACT: The potential vegetation distribution shift in China caused by global climatic change was predicted by the direct transfer function approach. Two types of statistical model, the discriminant analysis model and the multinomial logit model, were applied to explain the relationship between vegetation classification and climatic conditions. The logit model resulted in a more successful result than the discriminant analysis model. Thus, the effects of global climatic change were estimated using the logit model under two climatic change scenarios proposed by Robock *et al.* (1993): Scenario A, a 2-degree increase in annual mean temperature and a 20% increase in annual precipitation; Scenario B, a 4-degree increase in annual mean temperature and a 20% increase in annual precipitation. It was predicted that (1) the conifer forest distributed in northeast China at the present time may be deprived of its habitat within the boundary of China, (2) the broadleaved forest distributed in east China may shift northward by around 3 degrees of latitude for Scenario A and 5 degrees for Scenario B, and (3) the desert region in west China may expand and steppe and savanna may decrease, especially in the case of Scenario B.
KEY WORDS: potential vegetation distribution, climate change, statistical model, impact assessment, China.

1. INTRODUCTION

It is necessary to carry out studies from a variety of approaches to examine the effects of global climatic change on ecosystems. One such approach is to model the relationship between current climatic conditions and actual vegetation and use it to predict potential vegetation distribution resulting from a change in climatic parameters. This kind of approach is called the 'direct transfer function approach', and in the previous section we used it to predict the Japanese potential vegetation. In this section, we attempt the same approach, this time focusing on Chinese vegetation. Here, two types of model, a discriminant analysis model and a linear multinomial logit model, are examined.

[1] National Institute for Environmental Studies, Tsukuba, Ibaraki 305, Japan.
[2] Institute of Botany, Chinese Academy of Science, 141 Xizhimenwai Avenue, Beijing, P.R. China.
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Why focus on China?

There are some spatial scales for understanding the impact of climate change on vegetation. The implications of the impacts and methodologies for assessing them differ according to the spatial scale to be considered (Frederic, 1994).

Graham *et al.* (1990) divided spatial scales into four categories; biosphere, biome, ecosystem and tree level. The biosphere's responses to climate change involve alterations in the energy, carbon, or water fluxes of vegetation (Henderson-Sellers, 1993; Solomon and Shugart, 1993; MacDonald and Sertorio, 1989). At the biome level, species respond to climate change through evolution, migration, extinction, or adaptation to new disturbance regimes. The ecosystem's responses to climate change take years to centuries and occur via nutrient cycling, production, water use, succession, competition, and response to changes in disturbance regimes (Parton *et al.*, 1994). The response of individual trees to climate change occurs through phenological, reproductive, and physiological processes on time scales ranging from minutes to decades and spatial scales ranging from cells to that of a large tree.

The spatial scale of our study corresponds to the biome level in Graham's classification. Its response to climatic changes take years to millennia, and the human activities on this scale relate to plant breeding, land management and conservation.

We have chosen China because it is the largest country in Asia, with an area of approximately 9.6 million km^2 It consists of a wide variety of climatic zones; tropical, sub-tropical, warm-temperate, cool-temperate, alpine, sub-alpine, arid and semi-arid, and the vegetation is also diversified according to environmental conditions (Editorial Committee of Vegetation of China, 1980). Furthermore, China has a human population of approximately 1.2 billion, the largest in the world, and thus its socioeconomic impact is very important.

Previous studies on impact assessment of Chinese vegetation

Ohta *et al.* (1993) simulated changes in the net primary productivity (NPP) of the natural vegetation of monsoon East Asia including China under three, doubled CO_2-climate scenarios (GISS, GFDL and UKMO). The gridded climatic data were used together with the Chikugo model developed by Uchijima and Seino (1985) to assess NPP under baseline and CO_2-doubling climates.

Chang and Yang (1993) analyzed climate-vegetation interaction in China. The distribution and NPP of vegetation zones show a close relationship with a series of climatological indices. Multivariate analysis for climate and vegetation zones in China provides a quantitative environmental interpretation for two significant ecological gradients. The first gradient is mainly a thermal gradient, which can be displayed by latitude, altitude, biotemperature, and annual mean temperature. The second gradient is basically a moisture gradient, and is correlated highly with longitude and potential evapotranspiration.

Chang (1993) related vegetation types and their distribution patterns with certain climatic types in a series of mathematical forms by means of quantitative analysis of vegetation-climate interaction or digitized diagrams of bioclimatology. He applied Holdridge's life zone system in order to relate vegetation and climate and predicted the changing pattern of vegetation under doubled CO_2 conditions.

Our study has some similarity to that of Chang (1993) in that both studies predict impacts caused by climate change with reference to vegetation types in China. Chang (1993) used the Holdridge life zone classification which was originally developed to explain the global vegetation distribution, and the result showed some differences from the actual vegetation distribution. So we attempted to apply statistical prediction models focusing on the Chinese vegetation to improve the accuracy.

This study attempts to answer the question 'How does global climatic change effect the vegetation distribution in China?'. For this purpose, we have developed statistical models for predicting the potential vegetation distribution by the transfer function approach. In Section 2, we examine the climatic trends in China during this century. Then, using the data and methods described in Section 3, the results of model development and prediction are presented in Section 4. An overall discussion follows in Section 5, and finally the conclusions and future steps are described in Section 6.

2. CLIMATIC TRENDS IN CHINA DURING THE 20TH CENTURY

2.1 Data and methods

We analyzed climatic trends in China during the 20th century using 'Global Historical Climatology Network (GHCN) data' compiled by Vose *et al.*, which is a digital database including long-term climatological data on monthly temperature, precipitation, station level air pressure and sea level air pressure (Vose *et al.*, 1992).

We analyzed the data as follows.

1) We extracted temperature and precipitation data for all of China using the country code for China (230). The number of stations was 477 for temperature and 251 for precipitation. Among them, the number of stations for which both temperature and precipitation data were available was 202. To calculate the average values between 1961 and 1990, we searched stations for which both temperature and precipitation data for this period were available. The number of these was 123.

2) By referring to 'Vegetation of China (1980)' etc., we selected 11 representative stations among these 123, and calculated the monthly mean values for temperature and precipitation. The results were shown as a climate-diagram map.

3) Next, we searched stations for which older data were available. We were able to find 17 stations for which both temperature and precipitation data were available since 1911 at the latest, and among these 4 stations had data dating back to 1901. Unfortunately, as shown in Fig. 1, these observation stations were concentrated in eastern China. Therefore, the results of the following analysis should be taken as representative of the climatic trends for eastern China.

We calculated the annual mean temperature and total annual precipitation in each year for each station. However, years in which stations were lacking data, even for one month, were processed as missing years.

4) We subjected the temperature and precipitation data for each station by linear regression analysis and then calculated the fluctuations of temperature and precipitation for each decade.

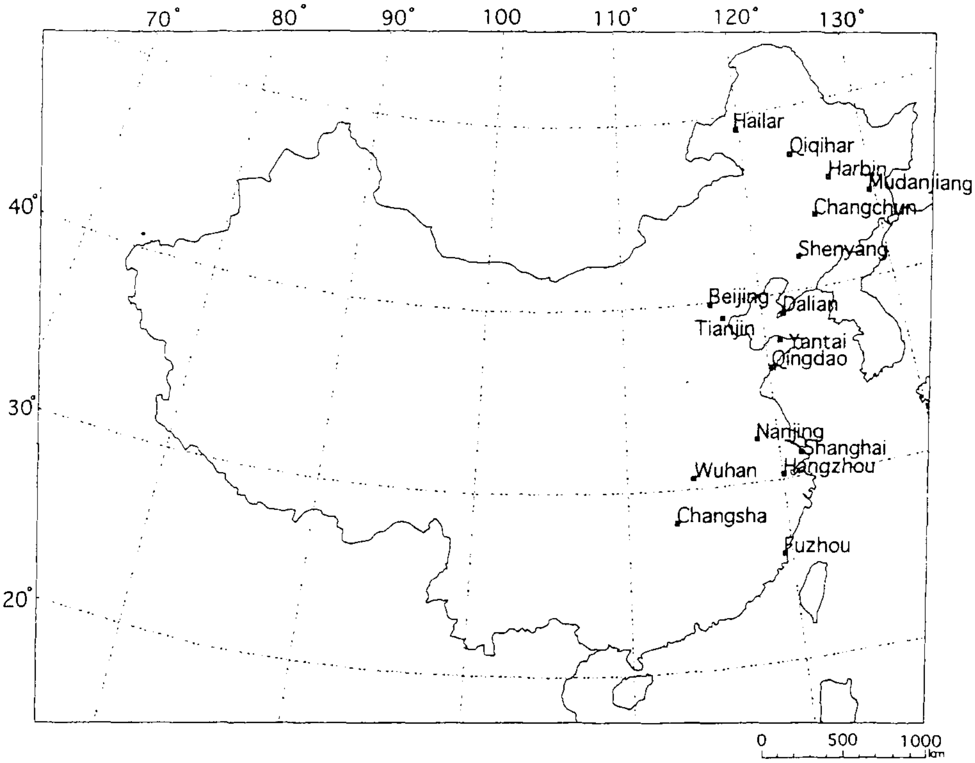

Fig. 1. The distribution of observation stations for which long-term climatological data are available.

2.2 Climate diagram

For understanding the climatic conditions affecting plants at a glance, it is convenient to use a climate diagram developed by Walter *et al.* (Walter and Lieth, 1960-67; Walter *et al.*, 1975). In the diagram, the horizontal axis is changed according to whether the data are for the northern or southern hemisphere, in order to let the center of the figure correspond to the summer. On the vertical axis, the scale of temperature and precipitation is adjusted to let 10°C correspond to 20 mm. The period when the precipitation curve lies below the temperature curve is considered to be a relative dry period.

Among 11 stations representing a variety of Chinese climatic zones, the lowest of annual mean temperature was 2.7 °C at Suihenfe (44.38° N, 131.15° E) and the highest was 21.8 °C at Guangzhou (23.13° N, 113.32° E). The highest annual precipitation was 1700 mm at Guangzhou and the lowest was 235 mm at Urumqi (43.78° N, 87.62° E).

Taking a general view of Fig. 2, we can see a north to south tendency for temperature (north is cold, south is warm) and an east to west tendency for precipitation (east is moist, west is arid).

2.3 Temperature trends

As shown in Table 1, stations which had an inclination of the regression line of more than 0.01, indicating more than a 1°C increase per hundred years and a significance level of more than 5% were Mudanjiang (2.3.°C/century), Shenyang (1.9 °C/c), Hailar

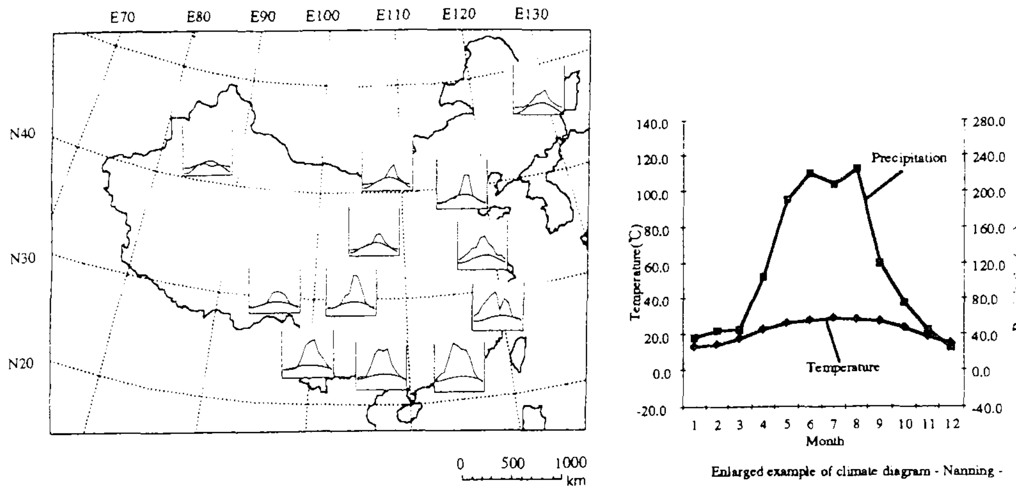

Fig. 2. Climate-diagrams map of China.

Table 1 Climatic trends in the eastern China during the 20th century.

	Latitude (N)	Longitude (E)	Temperature			Precipitation		
			Average (°C)	Trend (°C/ century)	Significance level	Average (mm)	Trend (mm/ century)	Significance level
Hailar	49.22	119.75	-2.1	1.4	0.000	315	37	0.318
Qiqihar	47.38	123.92	3.3	0.2	0.608	370	130	0.070
Harbin	45.75	126.77	3.5	1.1	0.000	555	-45	0.396
Mudanjiang	44.57	129.60	3.2	2.3	0.000	516	-3	0.955
Changchun	43.90	125.22	4.8	1.0	0.001	631	-128	0.045
Shenyang	41.77	123.43	7.6	1.9	0.000	685	70	0.333
Beijing	39.93	116.28	11.8	-0.0	0.827	606	18	0.876
Tianjin	39.10	117.17	12.4	-0.0	0.935	527	103	0.154
Dalian	38.90	121.63	10.3	0.4	0.084	592	45	0.598
Yantai	37.53	121.40	12.4	0.6	0.004	661	121	0.088
Qingdao	36.07	120.33	12.1	0.3	0.205	701	171	0.130
Nanjing	32.00	118.80	15.4	-0.0	0.702	1003	70	0.547
Shanghai	31.17	121.43	15.5	0.9	0.000	1158	-29	0.745
Wuhan	30.62	114.13	16.6	-0.8	0.000	1194	88	0.464
Hangzhou	30.23	120.17	16.3	-0.1	0.589	1458	-191	0.118
Changsha	28.23	112.87	17.3	-0.9	0.000	1356	-67	0.613
Fuzhou	26.08	119.28	20.0	-1.5	0.000	1409	-361	0.018

(1.4 °C/c), Harbin (1.1 °C/c) and Changchun (1.0 °C/c).

The only station which had an inclination of the regression line of less than -0.01, indicating more than a 1 °C decrease per hundred years, and a significance level of more than 5% was Fuzhou (-1.5 °C/century).

The increasing tendency was remarkable in northern China, whereas southern China had a decreasing tendency (Table 1).

Figure 3 shows the trends of temperature and precipitation for each decade, in which overall temperature increased during 1911-1940, then dropped around 1941-1950, and again increased from 1951.

2.4 Precipitation trends

As shown in Table 1, there were only two stations which had more than a 5% significance level: Fuzhou (-361 mm/century) and Changchun (-128 mm/c).

Figure 3 shows more complex trends than those of temperature. A drop during 1921-1930 and a peak during 1951-1960 can be seen.

3. DATA AND METHODS

3.1 Models

3.1.1 Discriminant analysis model

Discriminant analysis is a multivariate statistical method, which classifies observations whose group is unknown into one or more groups (nominally measured variables) on the basis of one or more numeric variables (Dillon and Goldstein, 1984).

For the sake of simplicity, if we wish to discriminate a new sample (*e.g.*, each grid cell in the case of this study) into one of two groups (*e.g.*, vegetation classification), G1

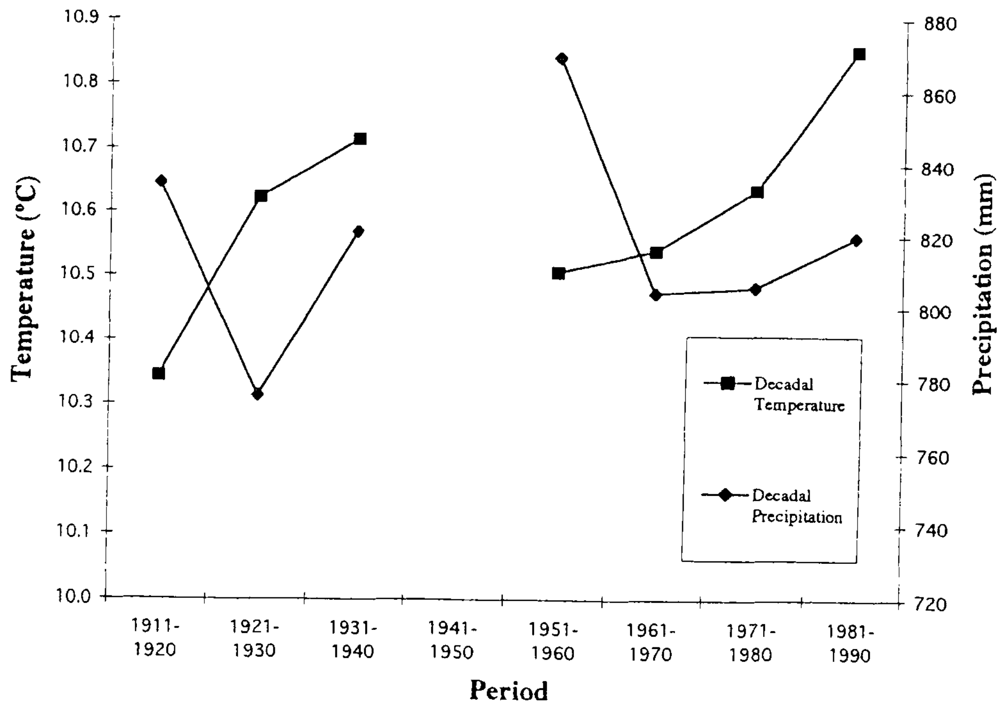

Fig. 3. Decadal fluctuaitons of temperature and precipitation.

and G2, and if we can assume that p independent variables have a multivariate normal distribution and the $p \times p$ variance-covariance matrix of the independent variables in each of the two groups are the same, then letting x_p be the p-th variable (*e.g.*, climatic parameter), σ^{ij} the variance-covariance matrix, and μ_i and μ_j the mean of x_i and x_j, the Mahalanobis distance can be written as

$$D^2 = \sum_{i=1}^{p} \sum_{j=1}^{p} \sigma^{ij}(x_i - \mu_i)(x_j - \mu_j) \tag{1}$$

If the variance-covariance matrix of G1 and G2 is the same and we may define

$$\sigma = (\sigma^{ij}) \text{ and } \bar{\mu} = (\mu_i^{(1)} + \mu_j^{(2)})/2 \tag{2}$$

then

$$D_2^2 - D_1^2 = 2\{a_1(x_1 - \bar{\mu}_1) + a_2(x_2 - \bar{\mu}_2) + \cdots\cdots a_p(x_p - \bar{\mu}_p)\}. \tag{3}$$

The linear discriminant function z is

$$z = a_1(x_1 - \bar{\mu}_1) + a_2(x_2 - \bar{\mu}_2) + \cdots\cdots + a_p(x_p - \bar{\mu}_p) \tag{4}$$

If $z>0$, then we can assign the sample to G1, and if $z < 0$ then we can assign it to G2.

The study used the DISCRIM procedure of "Statistical Analysis System" (SAS release 5.18 at Tokyo University). A likelihood ratio test of the homogeneity of the within-group covariance matrices was performed, and if the test statistic was significant, the within-group matrix was used; otherwise the pooled covariance matrix was used.

3.1.2 Linear multinomial logit model

The multinomial logit model is often used in the field of econometrics to relate environmental conditions to the purchasing behavior of consumers. In the case of the linear multinomial logit model, probability to select an alternative is explained to be in proportion to the exponential of linear combination of the explanatory variables (Ikeguchi *et al.*, 1991). The study computed selection probability under each condition from data on vegetation classification and climatic conditions, and then computed parameters of linear function by the maximum likelihood method.

3.2 Data

Data are arranged in the form of a grid system covering the whole of China in the area of north latitude 18° to 52° and east longitude 73° to 135°. Each grid cell is 150 min for the latitudinal direction and 225 min for the longitudinal direction, corresponding to approximately 5 km x 5 km around central China.

All the data were developed by the Institute of Botany, Academia Sinica. The vegetation data were digitized from the "Actual vegetation map of China (scale 1 : 4,000,000)" made in 1979 by the Institute of Botany. Plant communities were selected and reordered into nine groups corresponding to physiognomy level (Table 2).

We used two climatic variables; annual mean temperature and annual precipitation, which were derived from averages from the period 1951 to 1980 and interpolated from station data (point data) to area data.

The database contains around 370,000 grid cells, among which 331,302 grid cells were used, since the rest had values missing for one or more variables.

3.3 Doubled CO_2-climate scenarios

In studies on climate impact assessment, the output from general circulation models (GCMs) of the climate system is often used. However, the use of GCM output for regional level impact assessment has two serious problems (Robock *et al.*, 1993);

(1) Because current state-of-the-art GCMs are unable to simulate accurately even the current seasonal cycle of climate on a regional basis, the reliability of GCM output is not high.

(2) The spatial resolution of GCMs (typical grid spacing of 500 × 500 km) is too coarse for regional level studies.

Therefore, Robock *et al.* (1993) have developed a new procedure for combining GCM output with climatic information in order to produce scenarios. They provided three regional scenarios as case studies; China, Sub-Saharan Africa and Venezuela. They showed in the Chinese case study that a warming of 2-4 degrees and an increase in precipitation of about 20% would seem the most likely result of an equivalent doubling of CO_2.

On the basis of their results, we assume two scenarios, Scenario A involving a warming of 2 degrees and a 20% increase in precipitation, and Scenario B involving a warming of 4 degrees and a 20% increase in precipitation.

4. RESULTS

4.1 Estimation by discriminant analysis model

The hit ratio of the discriminant analysis model was approx. 66.1%. The hit ratios of each vegetation classification were, respectively, (a) 77.7%, (b) 54.1%, (c) 64.5%, (d) 55.4%, (e) 79.6%, (f) 66.9%, (g) 69.4%, (h) 45.3% and (i) 67.1%. The hit ratios of (e) and (a) were relatively high and that of (h) was relatively low. Comparison of the estimated natural vegetation map by the discriminant analysis model and the actual vegetation map showed that the vegetation of (b) was underestimated (number of estimated grid cells / actual grid cells = 74%), and the vegetation of (c) overestimated (estimated / actual = 158%).

4.2 Estimation by logit model

The parameters of the logit model are shown in Table 3. For example, the probability that one grid cell with an annual mean temperature of T ℃ and annual precipitation of P mm is assigned to vegetation (a) is;

Table 2 Vegetation classification and their characteristics.

Vegetation code	Physiognomy of vegetation	Dominant plant species	Climatic type by Köppen classification	Distribution	Annual mean temperature (°C)	Annual precipitation (mm)
a	Conifer/Steppe	*Larix* spp., *Pinus* spp., *Arenaria musiformis*	Dw/H	Northeast China (Daxinganling) / Xizang(Tibet)	-2.9 ± 3.4	248 ± 179
b	Meadow/ Broadleaved deciduous forest	*Carex* spp., *Kobresia* spp.	Dw/H	Xizang(Tibet)/ Northeast China (Heilongjiang)	2.1 ± 3.3	510 ± 180
c	Steppe/Desert	*Stipa* spp., *Carex* spp.	BS	Nei Mongol (Chilin, Heilongjiang) /Xinjiang	3.6 ± 2.6	193 ± 106
d	Steppe/Scrub	*Corylus heterophylla*, *Ostryopsis davidiana*, *Vitex negundo* var. *heterophylla*, *Tamarix* spp.	BS	North China (Gansu, Hebei)	5.7 ± 2.7	415 ± 126
e	Desert	*Sympegma regelii*, *Anabasis salsa*	BW	Xinjiang (Takelamagan Desert)	7.4 ± 2.3	77 ± 58
f	Broadleaved deciduous forest/ Three crops for two years or two crops annually	*Quercus* spp., *Acer* spp., *Ulmus* spp.	Cw	North China (Shandong)/ Central China (Anhui, Henan)	11.2 ± 2.7	720 ± 322
g	Evergreen and deciduous scrub/ Two crops containing upland and rice annually	*Rhododendron* spp., *Melastoma* spp., *Pinus* spp.	Cfa	Central China (Hubei)/ Southwest China (Guizhou)	15.8 ± 1.9	1090 ± 227
h	Broadleaved evergreen forest/ Evergreen conifer/ One or double cropping rice	*Cyclobalanopsis* spp., *Castanopsis* spp., *Lauraceae* spp.	Cfa	South China (Fujian)/ Central China (Jiangxi)	17.5 ± 2.7	1486 ± 299
i	Broadleaved evergreen forest/ Double-cropping rice annually	*Vatica astrotricha*, *Dipterocarpus davidiana*	Cfa	South China (Guangdong)/ Southwest China (Yunnan)	19.8 ± 2.0	1588 ± 382

Table 3 Parameters and hit ratios of multinomial logit model.

Vegetation Code	TEMP	PREC	Const.	Hit/Original grid-cells	Hit ratio(%)
a	-0.292×10	-0.145×10^{-1}	0.459×10^{2}	37,463/51,420	72.9
b	-0.263×10	-0.059×10^{-1}	0.429×10^{2}	41,896/60,520	69.2
c	-0.227×10	-0.221×10^{-1}	0.469×10^{2}	16,811/30,598	54.9
d	-0.214×10	-0.133×10^{-1}	0.436×10^{2}	11,798/27,369	43.1
e	-0.174×10	-0.336×10^{-1}	0.456×10^{2}	36,149/42,092	85.9
f	-0.172×10	-0.068×10^{-1}	0.367×10^{2}	25,971/36,999	70.2
g	-0.102×10	-0.042×10^{-1}	0.249×10^{2}	35,164/42,995	81.8
h	-0.079×10	-0.001×10^{-1}	0.152×10^{2}	9,725/20,686	47.0
i	0	0	0	12,570/18,623	67.5
Total				227,547/331,302	68.7

TEMP: Annual mean temperature(℃), PREC:Annual mean precipitation (mm), Const.: constant.

$$P(a) = \left\{\exp\left(T\times(-0.292\times10)+P\times(-0.145\times10^{-1})+0.459\times10^{2}\right)\right\} \Big/ \left\{\begin{array}{l}\exp\left(T\times(-0.292\times10)+P\times(-0.145\times10^{-1})+0.459\times10^{2}\right)\\ +\exp\left(T\times(-0.263\times10)+P\times(-0.059\times10^{-1})+0.429\times10^{2}\right)\\ +\cdots\cdots+\exp\left(T\times(0.0)+P\times(0.0)+0.0\right)\end{array}\right\} \tag{5}$$

The estimated vegetation classification can be determined as (x) which has the highest probability among $P(a)$ to $P(i)$.

The hit ratio of the logit model was approx. 68.7% (227,547 /331,302). The hit ratios of each vegetation classification were (a) 72.9%, (b) 69.2%, (c) 54.9%, (d) 43.1%, (e) 85.9%, (f) 70.2%, (g) 81.8%, (h) 47.0% and (i) 67.5%, respectively. The hit ratios of (e) and (g) were relatively high and those of (d) and (h) were relatively low. Comparison of the estimated natural vegetation map by the logit model (Color Plate 23) and the actual vegetation map (Color Plate 22) showed that the boundary between (a) and (b) in the estimated map was greatly simplified in the south-east area of the Tibetan plateau where many valleys run, compared to the actual vegetation map which shows a very complicated distribution resembling a mosaic. Vegetation (d) was underestimated, and especially the distribution around west Tashinganling could not be estimated.

4.3 Comparison of discriminant analysis model and logit model

Comparison of the discriminant analysis model and the logit model showed that the total hit ratio of the latter was higher than that of the former. From the viewpoint of geographical distribution, those of the logit model were superior to those of the discriminant analysis model, especially for the discrimination of (a) and (b) around the south-eastern part of the Tibetan Plateau. Therefore, the logit model was selected for use in the following predictions.

4.4 Prediction of potential vegetation distribution using the logit model under Scenario A

By varying the climatic parameters of the logit model, the potential shift under the changed climate was predicted. First, Scenario A involving a 2-degree increase in annual mean temperature and a 20% increase in annual precipitation was used. As a result, it was indicated that the proportion of grid cells in all of China which showed estimated vegetation classifications different from the present ones was approx. 33%. The percentage of grid cells assigned to classifications other than present one was relatively high in vegetation (h)(68%), (d)(53%) and (a) (51%). The number of grid cells assigned to other classifications is high in vegetation (a)(26,595), (g)(21,310) and (f)(15,258). From the viewpoint of geographical distribution (Color Plate 24), the conifer forest distributed in northeast China at the present time may be deprived of its habitat within the boundary of China. The broadleaf forest distributed in east China (vegetation f, g, h, i) may shift northward by around 3 degrees of latitude.

4.5 Prediction of potential vegetation distribution using the logit model under Scenario B

Next, Scenario B involving a 4-degree increase in annual mean temperature and a 20% increase in annual precipitation was used. As a result, it was indicated that the proportion of grid cells throughout China which showed estimated vegetation classifications different from the present ones was approx. 53%. The percentage of grid-cells assigned to other classifications is relatively high in vegetation (h)(98%), (d)(89%) and (c)(77%). The number of grid cells assigned to other classifications is high in vegetation (a)(35,258), (g)(31,893) and (b)(27,023). From the viewpoint of geographical distribution (Color Plate 25), the broadleaved forest distributed in east China (vegetation f, g, h, i) may shift northward by around 5 degrees of latitude. Moreover the desert region, vegetation (e), may expand its area, and vegetation (c), steppe, may decrease.

5. DISCUSSION

5.1 Climatological trends in China during the 20th century

The tendency for climatic trends shown in Section 2, *i.e.*, a tendency for temperature to be increased in the north and decreased in the south, and an unclear linear tendency for precipitation, is consistent with the results of previous studies (*e.g.*, Chen *et al.*, 1992; Yatagai and Yasunari, 1994).

Our analysis indicates that the temperature inclination during this century has been between -1.5 and 2.3 °C/century at the 5% significance level, depending on the region. The predicted global warming rate is approximately 3 °C/century. Therefore the rate of past warming in China is less than that for predicted global warming, and it should be noted that the region where temperature has been increasing does not cover all of

China.

Therefore, there is a possibility that in the next century when the temperature increase of 3 °C is expected , the ecosystem in China may change more than that in the past century.

5.2 Modeling of vegetation distribution

As a result of the logit model, the total hit ratio is 68.7%. The total hit ratios of Japanese vegetation distribution models developed by the authors were, respectively, 85.4% in the case of the four-group classification corresponding to vegetation zone levels (Takeuchi *et al.*, 1991) and 75.8% for the eight-group classification corresponding to "order" or "alliance" levels (Tsunekawa *et al.*, 1993).

The hit ratio depends strongly on the number of classified groups: the more classified, the lower the hit ratio. Therefore the accuracy of the logit model, with a hit ratio of 68.7% for nine vegetation groups, can be judged as satisfactory.

As shown in the results, there are many discrimination errors between vegetation (a) and (b). If we compare Color Plate 22 and Color Plate 23, it is found that there is a big difference in distribution pattern around east Xizang. This region corresponds to the southwest part of the Tibetan Plateau, which is severely dissected by the Jinsha Jiang River, Lancang Jiang River (Mekong River) and Nu Jiang River (Salween River). Because the vegetation is affected by the elevation and the direction of slope, the vegetation distributions of (a) and (b) are spatially mixed like a mosaic.

Also, the estimated distribution of vegetation (h) is rather simplified in comparison with that of the actual vegetation. In the regions where vegetation (h) is distributed, low mountains, hills, valleys and plains are spatially mixed, thus creating a mosaic-like distribution of vegetation (h).

There are two main reasons why the actual vegetation of these regions could not be estimated well. The first is that the spatial resolution and accuracy of climatic data used by the study are not good enough to reflect the very fine and complex climatic spatial pattern of the severely dissected Plateau. The second is that the vegetation distribution in this region depends not only on temperature and precipitation, but also other environmental factors such as solar radiation, wind, snow and soil properties. However, environmental factors other than temperature and precipitation were not included in the model.

Therefore it is expected that the model could be improved greatly by using more spatially detailed and accurate data and including other environmental factors such as solar radiation, wind, snow and soil properties.

5.3 Prediction of potential vegetation distribution

As described in results, it was predicted under climatic change scenarios that (1) the conifer forest distributed in northeast China at the present time may be deprived of its habitat within the boundary of China, (2) the broadleaved forest distributed in east China (vegetation f, g, h, i) may shift northward by around 3 degrees of latitude for Scenario A and 5 degrees for Scenario B, and (3) the desert region, vegetation (e) may expand its area, and vegetation (c), steppe, may decrease, especially in the case of Scenario B.

Figure 4 illustrates the climatic conditions for each vegetation classification taking the annual mean temperature as the horizontal axis and annual precipitation as the vertical axis. Each rectangular ellipse has its center at the average of temperature and precipitation for each vegetation, and the radiuses represent their standard deviations. Two arrows starting from the center indicate the shifts under Scenarios A and B. Vegetation (a), (b), (c), (d) and (e) have rectangular ellipses and vegetation (f), (g), (h) and (i) have oblong ellipses, indicating that the former vegetation has a relatively small standard deviation for precipitation and the latter a relatively small standard deviation for temperature. This may indicate that the temperature increase affects the latter vegetation more than the former vegetation, and may be the reason why the distribution of broadleaved forest in east China may move more than that of other vegetation.

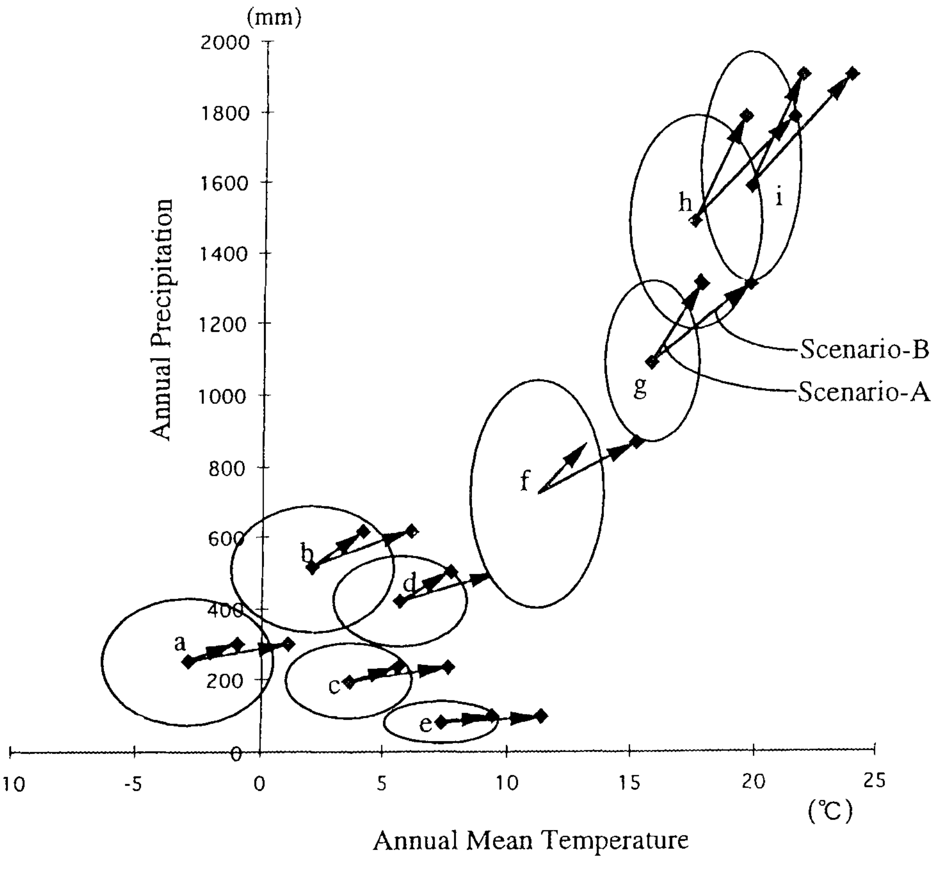

Fig. 4. Climatic conditions for each vegetation classification. The annual mean temperature is taken as the horizontal axis and annual precipitation as the vertical axis. Each rectangular ellipse has its center at the average of temperature and precipitation for each vegetation and the radiuses represent their standard deviations. Two arrows starting from the center indicate the shifts under Scenario A, B.

As shown in Fig. 2, which illustrates the geographical pattern of climate diagrams, southeast China seems to have enough precipitation in summer due to monsoon circulation, whereas west China has a very limited supply of water useful for plants. This fact suggests that thermal condition may be more important for plant growth in the east, whereas moisture conditions may be important in the west.

The most distinctive feature of Scenario B compared to A is that the desert region, vegetation (e), may expand its area, and the area of vegetation (c), steppe, may be reduced. This may be due to the fact that in Scenario B, with a 4-degree increase, even if the precipitation increases by 20%, "drying up" of plants may occur. From the viewpoint of plant physiology, the biggest factors limiting the growth of plants are low temperature and dryness. The increase in temperature is related to both phenomena, but has a positive effect on the former, and a negative one on the latter. It is estimated a 4-degree increase in temperature and a 20% increase in precipitation may have a negative effect on plants through drying up.

5.4 Speed of shift

It was predicted in the study that the broadleaved forest distributed in east China (vegetation f, g, h, i) might shift northward by around 3 degrees of latitude (around 350 km) under Scenario A and by around 5 degrees (around 600 km) under Scenario B. If we can assume that CO_2 doubling will have occurred by the year 2030, as shown in the business as usual scenario by the IPCC, then this will be 50 years from now at the latest. Therefore, the speed of shift of habitats would be 7 km/year under Scenario A and 12 km/year under Scenario B.

On the other hand, maps based on fossil pollen data for Europe 0 - 13,000 years ago show the following migration rates of major tree species (Huntley and Birks, 1983):

Quercus (deciduous)	0.075 - 0.5 km/year
Acer	0.5 - 1.0 km/year
Pinus	1.5 km/year
Ulmus	0.1 - 1.0 km/year

Therefore, if we take the deciduous genus *Quercus* as a main tree species in east China, the speed of shift of habitats would be 14 times and 24 times faster than the migration speed recorded over the past 13,000 years in Europe under Scenarios A and B respectively. At the same time, we should also pay attention to the fact that the speed of shift would differ among species.

5.5 Limitations of the prediction

From the results of this analysis, it was indicated that a climate change under Scenario A, a 2-degree increase in annual mean temperature and a 20% increase in annual precipitation, might cause a potential shift to other vegetation classifications in approx. 33% of the total grid cells in China, and that under Scenario B, a 4-degree increase in annual mean temperature and a 20% increase in annual precipitation, a potential shift to other vegetation classifications for approx. 53% of total grid cells would occur.

What does the potential shift indicated by our study mean?

First, with respect to accuracy, since the hit ratio of the model is approx. 69%, it must be noted that a corresponding error may be included. In particular, the prediction for east Xizang (south-east area of the Tibetan plateau) may not be accurate due to the discriminant errors of the model.

Next, as for the ecological significance of the potential shift, as pointed out above, the actual speed of shift of plant species may be slower than that for a habitat due to climate change. Furthermore, it would differ according to the plant species. Therefore, it appears that all plant communities would not be able to shift to habitats with the same species composition and the same forest structure. In regions where the shift of plant species cannot catch up with that of the habitat, some change would occur in the ecosystem. However, the methodology used in this study has limitations in predicting whether the change might be "competitive displacement" or "catastrophic decline" (Neilson and King, 1991).

Moreover, the model does not include all environmental changes in the future. Especially, fertilization effects caused directly by an increase of atmospheric CO_2 might change the plant responses to temperature, precipitation, and other climatic conditions.

6. CONCLUSIONS AND NEXT STEPS

As we described in the introduction, our final goal is to answer the question 'How does global climatic change affect the vegetation distribution in China?' through compilations of maps of vegetation type distribution. In this study, we were able to identify regions where climatic change might have a serious impact on the actual vegetation. We can summarize the results of the study as follows.

(1) There is a possibility that the ecosystem in China may change in the next century when the temperature increase of 3 °C is estimated more than that in the this century.

(2) As a result of comparison between the discriminant analysis model and the multinomial logit model to explain the actual vegetation distribution in China by annual mean temperature and annual precipitation, the logit model proved superior to the discriminant analysis model in terms of the hit ratios and geographical distribution of estimated actual vegetation.

(3) The total hit ratio for the logit model was 68.7%, which indicates that for nine classes of Chinese vegetation, around 70% of it can be explained by annual mean temperature and annual precipitation. The residuals are thought to be caused by the spatial accuracy of the climatic data used in the study, and the vegetation distribution is considered to depend partially on other environmental factors such as solar radiation, wind, snow, soil properties, and slope gradient.

(4) The potential vegetation under the climatic change was estimated using the logit model. Two scenarios proposed by Robock *et al.* (1993) were applied: Scenario A, a 2-degree increase in temperature and a 20% increase in precipitation, and Scenario B, a 4-degree increase in temperature and a 20% increase in precipitation. As a result, it was predicted under the climatic change scenarios that (1) the conifer forest distributed in northeast China at the present time may be deprived of its habitat within the boundary of China, (2) the broadleaved forest distributed in east China may shift northward by around 3 degrees of latitude for Scenario A and 5 degrees for Scenario B, and (3) the desert region may expand its area, and steppe and savanna may decrease, especially in the case of Scenario B.

If we summarize the impact of climatic change on Chinese vegetation, the habitat for forests might shift rapidly toward the north in east China, and steppe and meadow might be replaced by desert through drying up in west China. Therefore, future research should take into account these results and place priority on the following two points.

(1) In east China, the forest zone might shift in a northerly direction. However, because of the very large population concentration in this region and the predominant use of land in this region for paddy or wheat fields, the majority of forests are isolated geographically. For the forest's smooth shift, flexible dispersal of plant seeds is necessary However, geographical isolation may prevent the forest from shifting smoothly. Therefore it is urgent priority to develop a 'landscape transition model' based on spatial rules or neighborhood interactions, which can examine the potential for shifting in the face of changing landscape patterns for the purpose of appropriate forest management (Dale and Rauscher, 1994).

(2) In west China, especially the areas surrounding deserts, the change in moisture conditions due to increasing temperature and drying-up may cause 'desertification' of steppe and savanna. Then desertification accompanied by reduction of vegetation may accelerate the climatic change through an increase in albedo, reduction in soil moisture and evapotranspiration, and decrease in surface roughness, *i.e.*, a positive feedback of climatic change. Therefore it is necessary to develop a 'grassland model' that can simulate the regional patterns of ecosystem properties including plant production and soil properties., taking account of fertilization effects by increased CO_2 , extreme events such as drought and severe heat, and livestock management for appropriate grassland management so as not to cause desertification (Conner, 1994). The CENTURY model (Parton *et al.*, 1987) or EPIC model (Williams *et al.*, 1984) may be instructive for development of such a model.

REFERENCES

Chang, H., 1993. A vegetation-climate classification system for global change studies in China. *Q. Sci.*, **2**, 157- 173. (in Chinese with English abstract).

Chang, H. and Yang, D., 1993. Study on climate-vegetation interaction in China. *J. Environ. Sci.*, **5**, 130-149.

Chen, L.-X., Dong, M. and Shao, Y.N., 1992. The characteristics of interannual variations of the East Asian Monsoon. *J. Meteorol. Soc. Jpn.*, **70**, 397-421.

Conner, J.R., 1994. Assessing the socioeconomic impacts of climate change on grazinglands. *Clim. Change*, **28**, 143-157.

Dale, V.H. and Rauscher, H.M., 1994. Assessing impacts of climate change on forests: the state of biological modeling. *Clim. Change*, **28**, 65-90.

Dillon, W.R. and Goldstein, M., 1984. *Multivariate Analysis - Methods and Applications.* John Wiley & Sons, New York, 587 pp.

Editorial Committee of Vegetation of China, 1980. *Vegetation of China.* Science Press, Beijing, 1375 pp. (in Chinese).

Frederick, K.D., 1994. Integrated assessments of the impacts of climate change on natural resources. *Clim. Change*, **28**, 1-14.

Graham, R.L., Turner, M.G. and Dale, V.H., 1990. How increasing atmospheric CO_2 and climate change affect forests. *BioScience*, **40**, 575-587.

Henderson-Sellers. A., 1993. Continental vegetation as a dynamic component of a global climate model. a preliminary assessment. *Clim. Change*, **23**, 337-377.

Huntley, B. and Birks, H.J.B., 1983. *An Atlas of Past and Present Pollen Maps for Europe: 0-13000 Years Ago*. Cambridge University Press, Cambridge, 667pp.

Ikeguchi, H., Takeuchi, K. and Tsunekawa, A., 1991. Potential natural vegetation mapping of Japan by means of GIS. In: *Environmental Change and GIS. Vol.1* (ed. by I. Ota), 26-33.

MacDonald, G. and Sertorio, L. (eds.), 1989. *Global Climate and Ecosystem Change*. Plenum Press, New York, 252 pp.

Neilson, R.P. and King, G.A., 1991. *Continental Scale Biome Responses to Climatic Change*. The EPA Environmental Research Laboratory in Corvallis, Oregon, USA, 31 pp.

Ohta, S., Uchijima, Z. and Oshima, Y., 1993. Probable effects of CO_2-induced climatic changes on net primary productivity of terrestrial vegetation in East Asia. *Ecol. Res.*, **8**, 199-213.

Parton, W.J., Schimen, D.S., Cole, C.V and Ojima, D.S., 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Sci. Soc. Am. J.*, **51**, 1173-1179.

Parton, W.J., Ojima, D.S. and Schimel, D.S., 1994. Environmental change in grasslands: assessment using models. *Clim. Change*, **28**, 111-141.

Robock, A., Turco, R.P., Harwell, M.A., Ackerman, T.P., Andressen, R., Chang, H.-S. and Sivakumar, M.V.K., 1993. Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Clim. Change*, **23**, 293-335.

Solomon, A.M. and Shugart, H.H. (eds.), 1993. *Vegetation Dynamics & Global Change*. Champman & Hall, New York, 338 pp.

Takeuohi, K., Ikeguchi, H. and Tsunekawa, A., 1991. Estimation of Japanese vegetation zones using GIS. *Reports for Scinece Research Budget of the Ministry of Education, Science and Culture, F.Y. 1990, GIS for Environmental Change by Modernization*, 13-20. (in Japanese with English abstract).

Tsunekawa, A., Ikeguchi, H., Kainuma, M., Tobe, K. and Omasa, K., 1993. Effects of climatic change on the vegetation distribution in Japan. *J. Agr. Meteorol.*, **48**, 867-870.

Tsunekawa, A., Zhang, X., Zhou, G. and Omasa, K., 1995. Predicting responses to climatic change of the potential vegetation distribution in China. *J. Agr. Meteorol.*, **51**, 245-257

Uchijima, Z. and Seino, H., 1985. Agroclimatic evaluation of net primary productivity of natural vegetation. (1) Chikugo model for evaluating net primary productivity. *J. Agr. Meteorol.*, **40**, 343-352.

Vose, R.S., Heim, R., Schmoyer, R.L., Karl, T.R., Steurer, P.M., Eischeid, J.K. and Peterson, T.C., 1992. *The Global Historical Climatology Network - Long-term Monthly Temperature, Precipitation, Sea Level Pressure and Station Level*

Pressure Data. Oak Ridge National Laboratory, Oak Ridge, USA, 311 pp.
Walter, H. and Lieth, H., 1960-67. *Klimadiagramm - Weltatlas* (in 3 Lief.), G. Fischer, Jena.
Walter, H., Harnickell, E. and Mueller-Dombois, D., 1975. *Climate Diagram Maps*, Springer-Verlag, Berlin, 36pp.
Williams, J.R., Jones, C.A. and Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. Am. Soc. Agr. Eng.*, **27**, 129-144.
Yatagai, A. and Yasunari, T., 1994. Trends and decadal-scale fluctuations of surface air temperature and precipitation over China and Mongolia during the recent 40 year period (1951-1990). *J. Meteorol. Soc. Jpn.*, **72**, 937-957.