農業気象 (*J. Agric. Meteorol.*) 51 (3): 245–257, 1995

Predicting Responses to Climatic Change of the Potential Vegetation Distribution in China

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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 of mean annual temperature and a 20% increase of annual precipitation; Scenario B, a 4-degree increase of mean annual temperature and a 20% increase of annual precipitation. It was predicted that (1) the conifer forest distributed in northeast China at the present time may be deprived of its suitable habitat within the boundary of China, (2) the broadleaf 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, Climatic change, Statistical model, Impact assessment, China.

1. Introduction

How does global climatic change effect the vegetation distribution in China? 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.

What is global climatic change?

The amounts of some trace gases in the atmosphere, notably 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. All of these gases are transparent to incoming short-wave radiation from space, but they absorb and emit long-wave radiation and are thus able to influence the Earth's climate. This is 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 of 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 have 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

Received on March 14, 1995.
Accepted on June 26, 1995.

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 more favorable regions, and thus many plant and animal species may become extinct (IPCC, 1990b).

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.

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 (Frederick, 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, com 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 socioecomic 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 (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.

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, Zabinski and Davis (1988) for the Great Lakes region of the United States of America, and Tsunekawa *et al.* (1993) for Japan.

This method analyzes the current distributions of vegetation types and its bioclimatology 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

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.

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 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_i the mean of x_i and x_j, the Mahalanobis distance can be written as

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

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

$\sigma = (\sigma^{ij})$ and $\bar{\mu}_i = (\mu_i^{(1)} + \mu_i^{(2)})/2$,

then

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

The linear discriminant function z is

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

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.

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 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

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

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 of 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 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 1).

We used two climatic variables; mean annual 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.

2.3 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.*,

Table 1 Vegetation classification and their characteristics.

Vegetation code	Physiognomy of vegetation	Dominant plant species	Climatic type by Köppen classification	Distribution	Mean annual 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/Broadleaf 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	Broadleaf deciduous forest/ Three crops for two years or two crops annually	*Quercus spp., Acer spp., Ulumus 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	Broadleaf 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	Broadleaf evergreen forest/ Double-cropping rice annually	*Vatica astrotricha, Dipterocarpus davidiana*	Cfa	South China (Guangdong)/ Southwest China (Yunnan)	19.8 ± 2.0	1588 ± 382

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 x 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 of 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 of precipitation, and Scenario B involving a warming of 4 degrees and a 20% increase of precipitation.

3. Results

3.1 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 (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%).

3.2 Estimation by Logit Model

The parameters of the logit model are shown in Table 2. For example, the probability that one grid cell with a mean annual temperature of T℃ and annual precipitation of P mm is assigned to vegetation (a) is;

$$P(\mathrm{a}) = \{\exp(T \times (-0.292 \times 10) + P \times (-0.145 \times 10^{-1}) + 0.459 \times 10^{2})\} / \{\exp(T \times (-0.292 \times 10) + P \times (-0.145 \times 10^{-1}) + 0.459 \times 10^{2}) + \exp(T \times (-0.263 \times 10) + P \times (-0.059 \times 10^{-1}) + 0.429 \times 10^{2}) + \cdots + \exp(T \times (0.0) + P \times (0.0) + 0.0)\}$$

Table 2 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: Mean annual temperature (℃), PREC: Annual precipitation (mm), Const.: Constant.

The estimated vegetation classification can be determined vegetation 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% (Table 2). 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 (Fig. 2) and the actual vegetation map (Fig. 1) 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.

3.3 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.

3.4 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 of mean annual temperature and a 20% increase of 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% (Table 3). 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 (Fig. 3), the conifer forest distributed in northeast China at the present time may be deprived of its suitable 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.

3.5 Prediction of Potential Vegetation Distribution using the Logit Model under Scenario B

Next, Scenario B involving a 4-degree increase of mean annual temperature and a 20% increase of annual precipitation was used. As a result, it was indicated that the proportion of grid cells

Table 3 Prediction of vegetation classification under Scenario A, a 2-degree increase of mean annual temperature and a 20% increase of annual precipitation.

		Estimated vegetation classification under Scenario A									
		a	b	c	d	e	f	g	h	i	Total
Estimated Actual Vegetation	a	25,590	22,539	3,961	95	0	0	0	0	0	52,185
	(%)	49.0	43.2	7.6	0.2	0.0	0.0	0.0	0.0	0.0	15.8
	b	0	52,089	0	3,862	0	7,575	0	0	0	63,526
	(%)	0.0	82.0	0.0	6.1	0.0	11.9	0.0	0.0	0.0	19.2
	c	0	0	17,372	4,116	8,223	0	0	0	0	29,711
	(%)	0.0	0.0	58.5	13.9	27.7	0.0	0.0	0.0	0.0	9.0
	d	0	0	0	9,903	0	11,171	0	0	0	21,074
	(%)	0.0	0.0	0.0	47.0	0.0	53.0	0.0	0.0	0.0	6.4
	e	0	0	0	79	44,683	0	0	0	0	44,762
	(%)	0.0	0.0	0.0	0.2	99.8	0.0	0.0	0.0	0.0	13.5
	f	0	0	0	0	0	21,008	15,200	58	0	36,266
	(%)	0.0	0.0	0.0	0.0	0.0	57.9	41.9	0.2	0.0	10.9
	g	0	0	0	0	0	0	26,655	14,132	7,178	47,965
	(%)	0.0	0.0	0.0	0.0	0.0	0.0	55.6	29.5	15.0	14.5
	h	0	0	0	0	0	0	0	5,425	11,473	16,898
	(%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.1	67.9	5.1
	i	0	0	0	0	0	0	0	0	18,915	18,915
	(%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	5.7
	Total	25,590	74,628	21,333	18,055	52,906	39,754	41,855	19,615	37,566	331,302
	(%)	7.7	22.5	6.4	5.4	16.0	12.0	12.6	5.9	11.3	100.0

Upper row; the frequency of grid-cells (approx. 5km x 5km). Lower row; its ratio in each row(%).

Table 4 Prediction of vegetation classification under Scenario B, a 4-degree increase of mean annual temperature and a 20% increase of annual precipitation.

		Estimated vegetation classification under Scenario B									
		a	b	c	d	e	f	g	h	i	Total
Estimated Actual Vegetation	a	16,927	21,717	10,817	2,724	0	0	0	0	0	52,185
	(%)	32.4	41.6	20.7	5.2	0.0	0.0	0.0	0.0	0.0	15.8
	b	0	36,503	0	10,050	0	16,973	0	0	0	63,526
	(%)	0.0	57.5	0.0	15.8	0.0	26.7	0.0	0.0	0.0	19.2
	c	0	0	6,891	5,269	17,549	2	0	0	0	29,711
	(%)	0.0	0.0	23.2	17.7	59.1	0.0	0.0	0.0	0.0	9.0
	d	0	0	0	2,345	76	18,653	0	0	0	21,074
	(%)	0.0	0.0	0.0	11.1	0.4	88.5	0.0	0.0	0.0	6.4
	e	0	0	0	0	44,762	0	0	0	0	44,762
	(%)	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	13.5
	f	0	0	0	0	0	11,378	24,789	99	0	36,266
	(%)	0.0	0.0	0.0	0.0	0.0	31.4	68.4	0.3	0.0	10.9
	g	0	0	0	0	0	0	16,072	1,650	30,243	47,965
	(%)	0.0	0.0	0.0	0.0	0.0	0.0	33.5	3.4	63.1	14.5
	h	0	0	0	0	0	0	0	315	16,583	16,898
	(%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	98.1	5.1
	i	0	0	0	0	0	0	0	0	18,915	18,915
	(%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	5.7
	Total	16,927	58,220	17,708	20,388	62,387	47,006	40,861	2,064	65,741	331,302
	(%)	5.1	17.6	5.3	6.2	18.8	14.2	12.3	0.6	19.8	100.0

Upper row; the frequency of grid-cells (approx. 5km x 5km). Lower row; its ratio in each row(%).

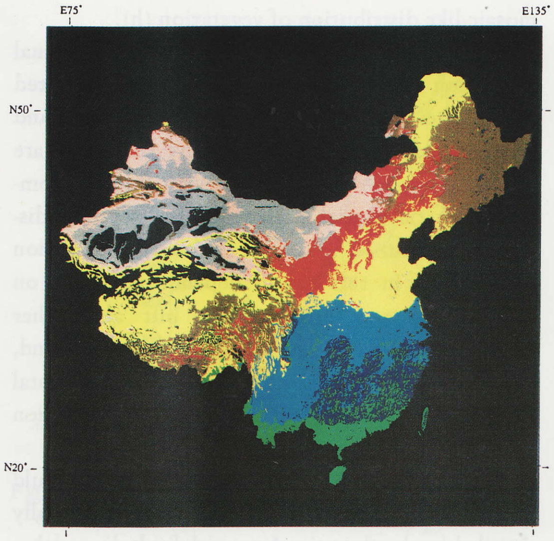

Fig. 1. Actual vegetation distribution of China. The raster-type data were digitized from the "Actual vegetation map of China (scale 1: 4,000,000)" made in 1979 by the Institute of Botany, Academia Sinica.

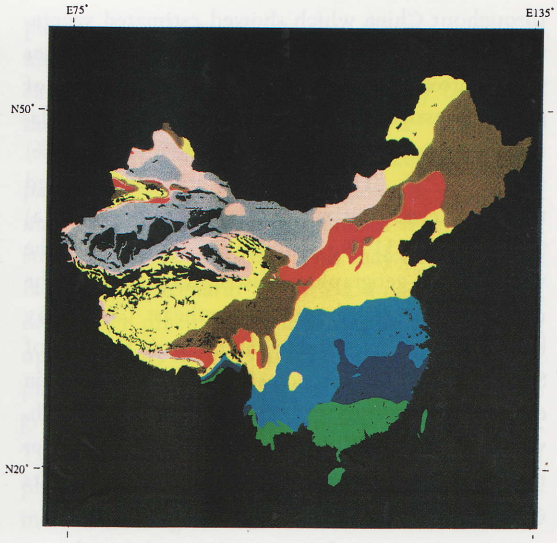

Fig. 2. Modelled vegetation distribution. Here, the linear multinomial logit model was applied to explain the relationship between vegetation classification and climatic conditions.

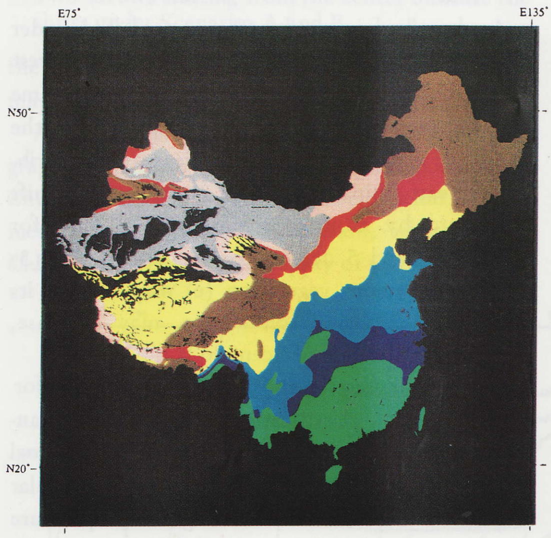

Fig. 3. Potential vegetation distribution predicted by the logit model under Scenario-A involving a 2-degree increase of mean annual temperature and a 20% increase of annual precipitation.

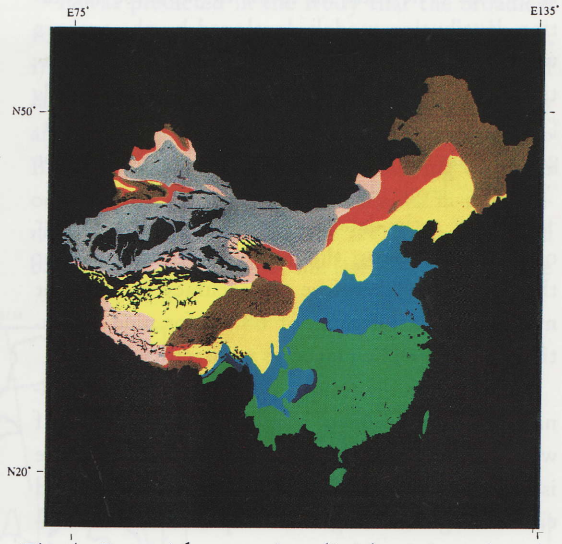

Fig. 4. Potential vegetation distribution predicted by the logit model under Scenario-B involving a 4-degree increase of mean annual temperature and a 20% increase of annual precipitation.

Legend

	Vegetation code	Physiognomy of vegetation
	a	Conifers/Steppes
	b	Meadows/Broadleaf deciduous forests
	c	Steppes/Deserts
	d	Steppes/Scrubs
	e	Deserts
	f	Broadleaf deciduous forests/Three crops for two years or two crops annually
	g	Evergreen and deciduous scrubs/Two crops containing upland and rice annually
	h	Broadleaf evergreen forests/Evergreen conifers/One or double cropping rice
	i	Broadleaf evergreen forests/ Double-cropping rice annually

throughout China which showed estimated vegetation classifications different from the present ones was approx. 53% (Table 4). 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 (Fig. 4), the conifer forest distributed in northeast China may be deprived of its suitable habitat, as in the case of Scenario A. The broadleaf 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.

4. Discussion

4.1 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 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 Fig. 1 and Fig. 2, 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.

4.2 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 suitable habitat within the boundary of China, (2) the broadleaf 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 5 illustrates the climatic conditions for each vegetation classification taking the mean annual 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 smaller standard deviation for precipitation and the latter a relatively smaller 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

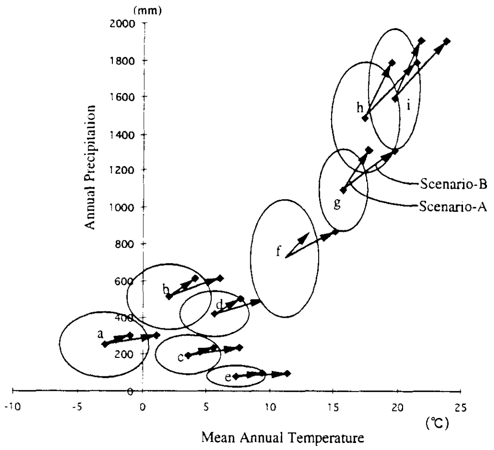

Fig. 5. Climatic conditions for each vegetation classification. The mean annual temperature is taken as the horizontal axis and annual precipitation as the vertical axis. Each rectangular ellipse has its center at the average of temperature and precipitation for each vegetation and the radiuses represent their standard deviations. Two arrows starting from the center indicate the shifts under Scenarios A and B.

the distribution of broadleaf forest in east China may move more than that of other vegetation.

As shown in Fig. 6, 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 of 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 of temperature and a 20% increase of precipitation may have a negative effect on plants through drying up.

4.3 Speed of Shift

It was predicted in the study that the broadleaf 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

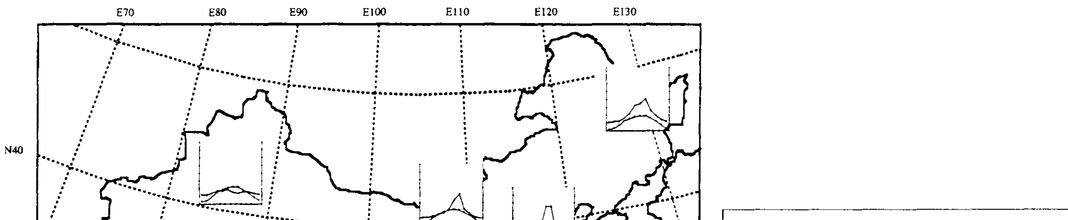

Fig. 6. Climate diagram of China using Global Historical Climatology Network data compiled by Vose *et al.* (1992), which is a digital database including long-term climatological data on monthly temperature, precipitation and so on.

speed of shift of suitable 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):

Quercue (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 suitable 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.

4.4 Limitations of the Prediction

From the results of this analysis, it was indicated that a climate change under Scenario A, a 2-degree increase of mean annual temperature and a 20% increase of 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 of mean annual temperature and a 20% increase of 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 may not be accurate due to the discriminant errors of the model.

Next, as for 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 suitable 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 suitable 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 suitable 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.

5. Conclusions and next steps

As we described in the introduction, our final goal is to answer the question 'How does global climatic change effect 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) As a result of comparison between the discriminant analysis model and the multinomial logit model to explain the actual vegetation distribution in China by mean annual 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.

(2) The total hit ratio for logit model was 68.7%, which indicates that for nine classes of Chinese vegetation, around 70% of it can be explained by mean annual 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.

(3) 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 of temperature and a 20% increase of precipitation, and Scenario B, a 4-degree increase of temperature and a 20% increase of 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

suitable habitat within the boundary of China, (2) the broadleaf 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 suitable 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 of albedo, reduction of soil moisture and evapotranspiration, and decrease of 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.

Acknowledgment

This research was supported by Global Environment Research Program Budget, set aside by the Japan Environment Agency for the promotion of comprehensive research on the global environment.

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気候変化が中国の植生分布に及ぼす影響の予測

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要　約

二酸化炭素等のいわゆる温室効果ガスの大気中の濃度が人間活動により上昇し，地表面気温の上昇等の地球規模の気候変化がもたらされるのではないかと憂慮されている。本研究では，このような地球規模の気候変化によって引き起こされる中国における植生分布のシフトを直接転移関数法アプローチによって予測した。植生分布と気候条件との関係を説明するために，2種類の統計モデル（判別分析モデルおよび多項ロジットモデル）を試みた。その結果，ロジットモデルの方が判別分析モデルよりも良い結果を示した。そこで植生の分布シフトをロボックら（1993）によって提唱された気候変化シナリオにもとづき，このロジットモデルを用いて推定した。

ロボックらのシナリオは，大気中の等価二酸化炭素濃度が産業革命前の2倍の水準になる時期の地域的な気候条件を2種類の状況で考えるもので，シナリオＡは年平均気温2度上昇，降水量20％増加，シナリオＢは年平均気温4度上昇，降水量20％増加となっている。

その結果，以下のことが予測された。(1) 中国東北部に分布する針葉樹林域は，最適生息地が北方に移動するのにともない，中国内では大幅に減少する，(2) 東部に分布する広葉樹林域はシナリオＡで約3度，シナリオＢで約5度，北方にシフトする，(3) 西部に分布する砂漠地域が拡大し，ステップおよびサバンナが減少する。とくにシナリオＢのとき，このことが顕著である。

キーワード：潜在的植生分布，気候変化，統計モデル，影響評価，中国