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Modeling distribution changes of vegetation in China under future climate change

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Climatic change will result in great changes in vegetation. In this paper, a biogeographical model, the BIOME1, was used to predict potential vegetation distribution in China under climate change. Firstly, the BIOME1 was validated according to the climate–vegetation relationships in China. Kappa statistics showed that the validated BIOME1 was able to capture the geographical patterns of vegetation more accurately. Then, the validated BIOME1 was used to predict the distribution of vegetation of China under two climatic scenarios produced by a Regional Circulation Model, RegCM2/CN. The simulation results showed obvious northward shifts of the boreal, temperate deciduous and evergreen and tropical forests, a large expansion of tropical dry forest/savanna and reduction of tundra on the Tibetan Plateau. Three vulnerable regions sensitive to climate changes are pointed out, i.e., Northern China, the Tibetan Plateau and Southwestern China (mainly Hengduan Mountains in Yunnan Province and west of Sichuan Province). In recent decades, China has experienced dramatic industrialization and population growth, which exert strong pressure on the environment of China. The consequences of climate changes warrant more attention for maintaining a sustainable environment for China.

Keywords: BIOME1 model, plant functional types, chinese vegetation, climate change

1. Introduction

Large scale vegetation distribution is largely controlled by climate [1]. Many studies indicate global climate change occurs as a result of anthropogenic greenhouse gases (GHG) [2–4]. The global average temperature increased by 0.5°C over the past century [2], and it is expected to continue increasing by an additional 1.4°C to 5.8°C by the end of 21st century [4]. China also experienced a trend of climate warming, with precipitation increasing since 1950 [5]. Climate change will result in changes in vegetation distributions, and then affect the environment of humans. It is important to assess possible responses of vegetation distribution to climate change.

The common approaches in assessing vegetation distribution changes caused by climate change are bioclimatic classification schemes [6,7]. Holdridge Scheme [8,9] is probably the most popular one, but it does not lend itself to biological interpretation in terms of plant life forms and attributes [10]. Recently, the dynamic vegetation models [11–13] integrated into vegetation succession processes and physiological responses to transient climate change provided us an opportunity to evaluate vegetation response to transient and long-term climate change. But these models require more data or physiological parameters, and are limited by knowledge on vegetation dynamics, responses of plants to elevated CO_2 and other physiological processes [14]. In addition, many basic issues about vegetation distribution under the monsoon climate of Eastern-Asia and the effects of the Tibetan Plateau remain unclear due to the lack of relevant studies in China [15–17]. Therefore, much research is needed in running a dynamic vegetation model in China.

The BIOME1 [18], the first one of the BIOME models [18–20], is considered a landmark in the development of global vegetation models. It has been used widely, such as in paleo-vegetation and climate reconstruction [21], climate change and vegetation feedback to climate [22–25]. It is a biogeographical model and uses plant functional types (PFTs) as basic vegetation types. PFTs can be defined as a set of plants exhibiting similar response to environmental conditions and having similar effects on the dominant ecosystem processes [26], which greatly reduce the complexity and often uncharted characteristics of species diversity in nature [27]. Introducing PFTs into BIOME1 pioneered the use of PFTs in the development of the BIOME model series (i.e., BIOME3 [19] and BIOME4 [20]) and the dynamic global vegetation models (DGVMs) [11–13]. The PFTs in the BIOME1 are concise and appropriate for representing global vegetation. The environmental constraints in the model have clear physiological interpretations in limiting the distributions of these PFTs. Therefore, the PFTs and environmental constraints in the BIOME1 are widely used by subsequent vegetation models, such as BIOME3 [19], IBIS [11], LPJ–DGVM [12] and LSM–DGVM [13].

The wide use of the PFTs and environmental constraints in the BIOME1 makes it important to test these PFTs and

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Table 1
Environmental constraints for each plant functional type in the BIOME1 model.

	T_{min}		GDD_0	GDD_5	T_{max}	α		
Plant functional types	Min	Max	Min	Min	Min	Min	Max	D
Trees								
1 Tropical evergreen	15.5	–	–	–	–	0.80	–	1
2 Tropical raingreen	15.5	–	–	–	–	0.45	0.95	1
3 Warm-temperate evergreen	5.0	–	–	–	–	0.65	–	2
4 Temperate summergreen	−15.0	15.5	–	1200	–	0.65	–	3
5 Cool-temperate conifer	−19.0	5.0	–	900	–	0.65	–	3
6 Boreal evergreen conifer	−35.0	−2.0	–	350	–	0.75	–	3
7 Boreal summergreen	–	5.0	–	350	–	0.65	–	3
Non-trees								
8 Sclerophyll/succulent	5.0	–	–	–	–	0.28	–	4
9 Warm grass/shrub	–	–	–	–	22.0	0.18	–	5
10 Cool grass/shrub	–	–	–	500	–	0.33	–	6
11 Cold grass/shrub	–	–	100	–	–	0.33	–	6
12 Hot desert shrub	–	–	–	–	22.0	–	–	7
13 Cold desert shrub	–	–	100	–	–	–	–	8
No plants (Dummy type)	–	–	–	–	–	–	–	

T_{min}: mean temperature of the coldest month; GDD_0: growing degree-days on 0°C base; GDD_5: growing degree-days on 5°C base; T_{max}: mean temperature of the warmest month; α: AET/PET, Priestley–Taylor coefficient of annual moisture availability; D: Dominancy hierarchy.

their climatic constraints according to the relationships between climate and vegetation of a given region. Insufficient work has been done in analyzing the relationships between PFTs and climate of China, and there is little knowledge for running a PFTs-based model to simulate the vegetation–climate interactions in China, where the vegetation distribution is strongly affected by the monsoon climate and the Tibetan Plateau. So, the BIOME1 model is a good choice under these situations for evaluating the effects of climate change on Chinese vegetation for its moderate number of PFTs and the concise environmental constraints that can be easily validated according to the relationship between climate and vegetation of China.

Several researches were carried out studying the responses of vegetation to climatic changes over China. Chen et al. [28] modeled possible response of life zone in China by the Holdridge life zone Scheme. Ni et al. [29] simulated the vegetation distribution and net primary production (NPP) of China by the BIOME3. Zhao et al. [30] simulated the distribution of vegetation in China by the MAPSS model. They pointed out possible changes of Chinese vegetation in the future, but all of these works lack detailed discussions on the use of PFTs and thorough examination in relationships between climate and vegetation in China. Because of the strong influence of monsoon climate and the Tibetan Plateau on the distribution and the traits of vegetation in China [31], the studies on classification of PFTs and on the climate–vegetation relationships are needed.

In this paper, we predicted the possible changes of vegetation distribution after a thorough validation of the BIOME1 according to the relationship between climate and vegetation in China, and assessed the vulnerable areas in which the biomes would be changed greatly. The aims of our research were to predict potential vegetation distribution under changed climate and to explore the relationship between vegetation and climate in China by the concept of PFTs. We also discussed the problems of the PFTs in the BIOME1 when it was applied in China.

2. Materials and methods

2.1. Description of the BIOME1 model

In the BIOME1 model, 14 plant functional types are defined and are assigned climate constraints in terms of amplitude and seasonality of climate variables (Table 1). The cold tolerance of plants is expressed in terms of minimum mean temperature of the coldest month. Some PFTs also have chilling requirements expressed in terms of a maximum mean temperature of the coldest month. The heat requirement is a function of temperature sums, growing degree-days (GDD), and the drought resistance is related to the annual soil moisture availability which is the ratio of actual to potential evaportranspiration.

The BIOME1 model predicts which plant functional type will occur in a given environment, i.e. in a given set of climate variables. Competition between different plant functional types is treated indirectly by the application of a dominance hierarchy [32] which effectively masks certain types of plants from a site, based on the presence of others, rather than being excluded by climate. For example, grassland PFTs are masked in the presence of PFTs and can only reappear if the tree PFTs disappear. Finally, biomes are defined as combinations of dominant types (Table 2).

Table 2
Combinations of dominant plant functional types and the names they were given.

Biome name	Plant functional types
1 Tropical rain forest	Tropical evergreen
	Tropical evergreen
2 Tropical seasonal forest	Tropical raingreen
3 Tropical dry forest/savanna	Tropical raingreen
4 Broad-leaved evergreen/ warm mixed forest	Warm-temperate evergreen
	Temperate summergreen
	Cool-temperate conifer
5 Temperate deciduous forest	Boreal summergreen
	Temperate summergreen
	Cool-temperate conifer
	Boreal evergreen conifer
6 Cool mixed forest	Boreal summergreen
	Cool-temperate conifer
	Boreal evergreen conifer
7 Cool conifer forest	Boreal summergreen
	Boreal evergreen conifer
8 Taiga	Boreal summergreen
	Cool-temperate conifer
9 Cold mixed forest	Boreal summergreen
10 Cold deciduous forest	Boreal summergreen
11 Xerophytic woods/scrub	Sclerophyll/succulent
12 Warm grass/shrub	Warm grass/shrub
	Cool grass/shrub
13 Cool grass/grub	Cold grass/shrub
14 Tundra	Cold grass/shrub
15 Hot desert	Hot desert shrub
16 Semidesert	Cool desert shrub
17 Ice/polar desert	Dummy type

2.2. Data

Vegetation data were obtained from the Vegetation Map of China (1:4,000,000) [37] and the Vegetation Division Map of China (1:14,000,000) [38]. The vegetation map was digitized by the Laboratory of Resource and Environment Information System, Institute of Geography, the Chinese Academy of Sciences. In the vegetation map, vegetation was divided into 48 formation classes and 103 formation groups. They were aggregated into the 17 biomes in the BIOME1 and the boundaries between these biomes were adjusted according to the Vegetation Division Map of China [38] (Table 3 and Figure 1).

Some problems existed in the assignment of some vegetation types such as the forests in Northeast of China, the steppes in the Inner-Mongolia, and the alpine vegetation on the Tibetan Plateau because that the classification criteria were different in the two schemes. We employed the following two approaches to deal with these problems. For natural or semi-natural vegetation types, we compared their similarities with the biomes in the BIOME1 to identify which biomes they should belong to. For cultivated areas, the potential vegetation types were estimated by bioclimatic criteria and the references about the potential vegetation of China [38,39].

Climate data. The climate database contains monthly mean temperature, annual precipitation and percent of sunshine of about 900 standard weather stations during 1951∼1980 [40].

Temperature data (mean temperature of warmest month and coldest month, GDD_5 and GDD_0) for $0.1° \times 0.1°$ grid were obtained by reducing to sea level for every station and interpolating followed by extrapolation to the mean elevation of the grid, assuming an temperature lapse rate of 0.6°C/100 m. Precipitation and sunshine data were interpolated to the same resolution without correction for elevation.

Soil data were from the Soil Texture Map of China (1:4,000,000) edited by Institute of soil science, the Chinese Academy of Sciences. The map classified the soils into 12 classes. These types were aggregated into eight categories used by BIOME1 for getting the values of available water capacity.

2.3. Climate scenarios

The climate scenarios [33,34] during the period of 2070∼2100 A.D were derived from a regional climate model, RegCM2/CN [35,36], based on two of the greenhouse gas (GHG) emissions scenarios proposed by IPCC,

Table 3
Biomes distinguished from the Vegetation Map of China [37].

Biomes	Dominant vegetation types
1 Tropical rain forest	Tropical broadleaved evergreen forests
2 Tropical seasonal forest	Tropical broadleaved semi-evergreen forests
3 Tropical dry forest/ savanna	Broadleaved evergreen succulent scrub on coral islands of the tropical zone
4 Broad-leaved evergreen forest	Subtropical evergreen broadleaved forests Subtropical mixed deciduous–evergreen broadleaved forests
5 Temperate deciduous forest	Temperate deciduous broadleaved woodlands/shrubs Temperate deciduous broadleaved forests Temperate cultivated vegetation
6 Cool mixed forest	Temperate mixed deciduous broadleaved-evergreen coniferous forests
7 Cool conifer forest	Temperate evergreen coniferous forest
8 Taiga	Cold-temperate coniferous forests
9 Cold mixed forest	Temperate mixed deciduous broadleaved-evergreen coniferous forests
10 Cold deciduous forest	Cold-temperate deciduous broadleaved shrubs
11 Xerophytic woods/scrub	Tropical and subtropical succulent thorny shrubs
12 Warm grass/shrub	Tropical/Sub-tropical grass/shrub Temperate forestry steppes/meadows
13 Cool grass/shrub	Temperate typical steppes Temperate desert steppes
14 Tundra	Alpine or subalpine meadows/swamps Alpine steppes
15 Hot desert	Temperate deserts
16 Semidesert	Alpine deserts
17 Ice/polar desert	Sparse vegetation regions with rocky fragments over the northwestern part of Tibetan Plateau

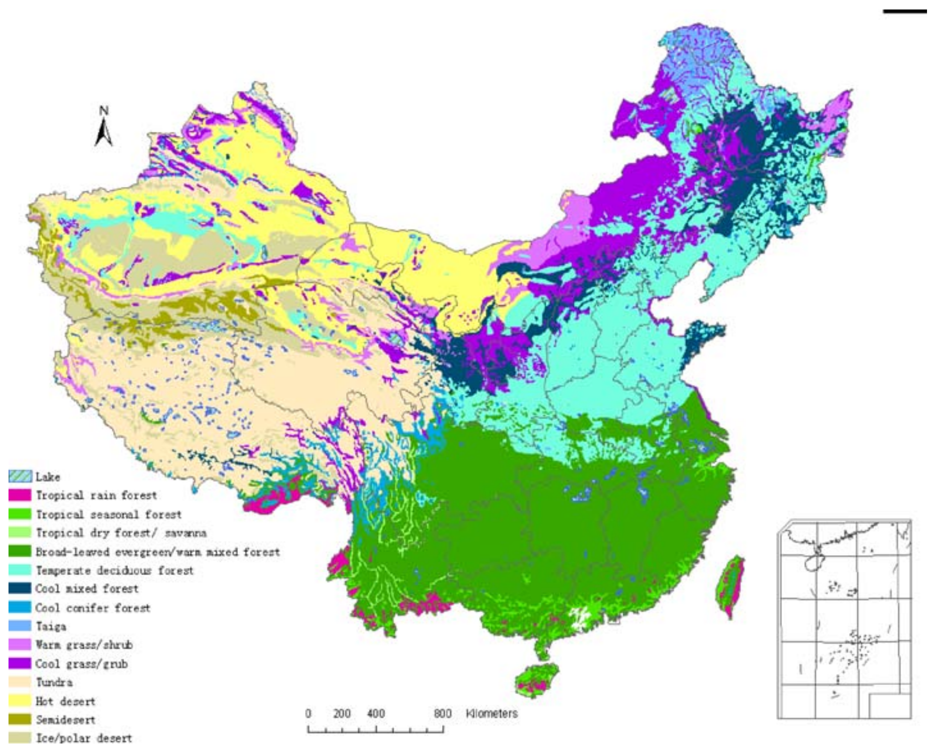


Figure 1. Potential vegetation of China (from the Vegetation Map of China [37]).

SRES-*A*2 and SRES-*B*2 [4]. SRES-*A*2 is the high emission of GHG, and SRES-*B*2 the low emission of GHG [4].

The climate scenarios (Figure 2) showed that air temperature would increase by 2∼9°C, and precipitation would increase by 11∼17% in China. The climate scenarios were provided at province scale and were interpolated to 0.1° × 0.1° grid by ordinary kriging method. They were used to produce future climate cover-

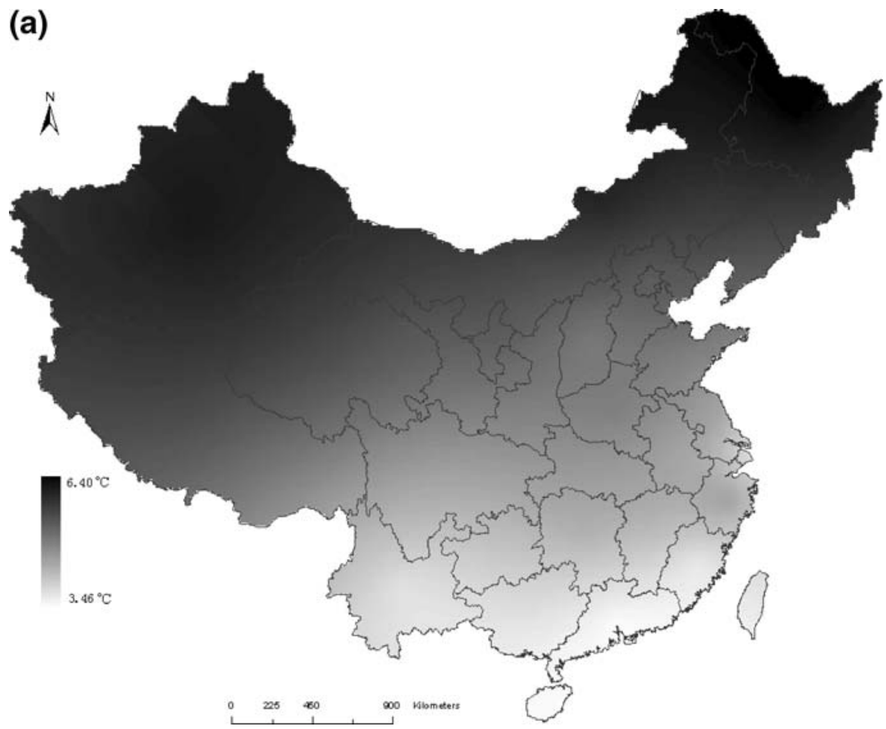
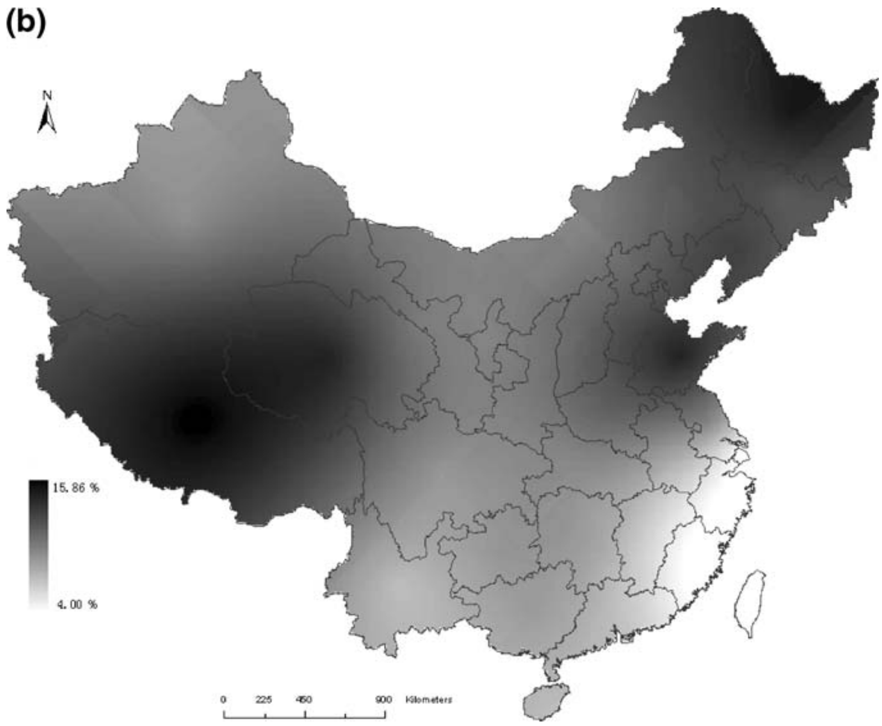


Figure 2. Climate scenarios during 2070–2100: (a) Temperature increased based on SRES-A2; (b) Precipitation increased based on SRES-A2 (%); (c) Temperature increased based on SRES-B2; (d) Precipitation increased based on SRES-B2 (%).



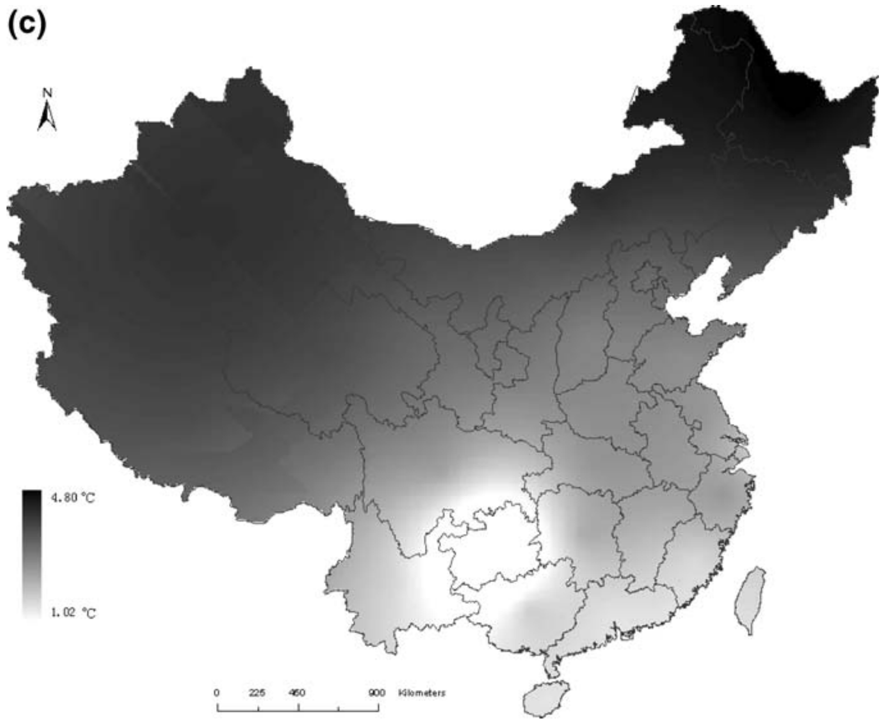


Figure 2. (Continued.)

ages by adding the relevant coverages of current climate. The future climate coverages were used to drive the BIOME1.

2.4. The Kappa statistic

The *Kappa* statistic [41] is employed to assess the agreement between the biome maps derived from the BIOME1 and from the vegetation map of China. The *Kappa* statistic is a useful and straightforward measure of agreement between the different maps [42]. It could clearly indicate differences and similarities between maps and rank ordering of agreement across maps and across the various vegetation zones within a map [28]. The algorithm of *Kappa* statistic was described by Monserud and Leemans [42] and Prentice et al. [18] in detail.

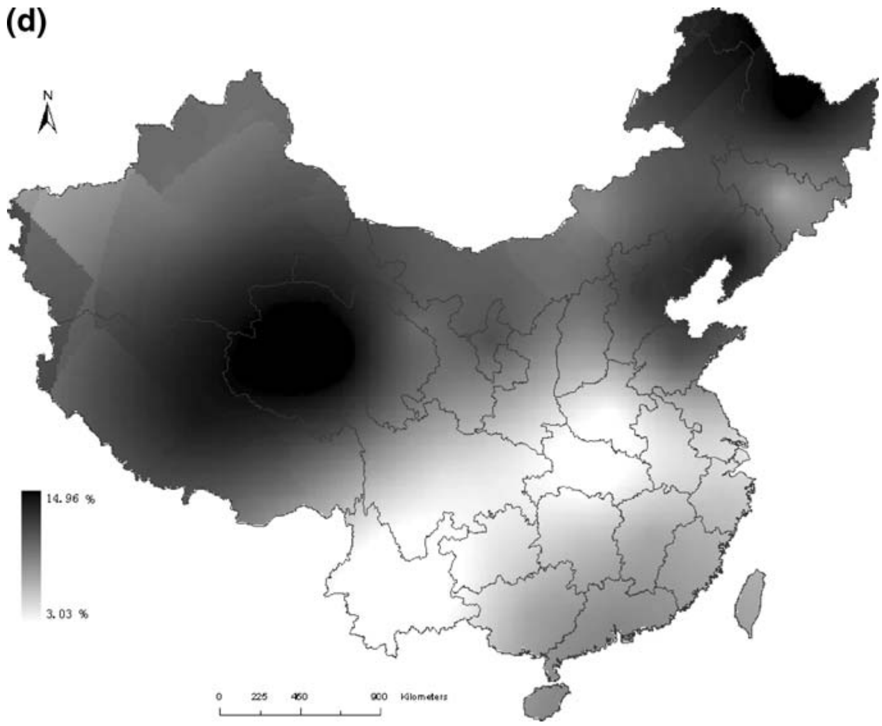


Figure 2. (Continued.)

Monserud and Leemans [42] provided different ranges of *Kappa* based on the degree of agreement. Values < 0.4 is considered poor or very poor, 0.4∼0.55 fair, 0.55∼0.7 good, 0.7∼0.85 very good and >0.85 excellent. Usually the agreement should be more than 0.4. Generally, when the value is more than 0.4 the significance of Kappa statistics is greater than model errors [28].

3. Results

3.1. Validation of the BIOME1

All of the 17 biome types in the BIOME1 were obtained in China under current climate (Figure 3a). The general distribution pattern of Chinese vegetation was roughly captured, such as, the forests in Eastern China, steppes and deserts in the Northwest and tundra on the Tibetan Plateau. However, there are many obvious disagreements. The boundaries of many forest types are expanded southwards. The temperate deciduous forest has an extraordinary southward displacement, taking the northern part of the broadleaved evergreen forest. The broadleaved evergreen forest moves southwards too. The tropical rain forest takes so little area that it couldn't be distinguished from the simulated map. The boundaries between forest, grassland, and desert are predicted poorly too. For example, the Huabei Plain (Northern China Plain), where the actual vegetation type should be deciduous broadleaved forest [39], is predicted to be warm grass/shrub. On the Tibetan Plateau, the vegetation is predicted to be tundra and semi-desert while the actual vegetation types over the plateau are alpine meadows/shrubs, alpine steppes, as well as alpine deserts. The overall value of the *Kappa* statistic is only 0.22, at the 'poor' level. Therefore, it is essential to calibrate the BIOME1 with the relationships between climate and vegetation of China.

In the BIOME1, Priestley–Taylor coefficient is the index to differentiate forests, steppes and deserts. By comparing global maps of Priestley–Taylor coefficient and vegetation, the minimum values that the PFTs could resist except desert shrubs were obtained. In the same way, we obtained the minimum values of Priestley–Taylor coefficient for every PFTs except desert shrubs by comparing the maps of Priestley–Taylor coefficient and vegetation of China. The driest conditions that the PFTs in China can resist are 0.5 and 0.2, respectively rather than 0.65 and 0.33 shown in the BIOME1.

The mean temperature of the coldest month that PFTs could tolerate was re-evaluated according to the relationships between the distribution of vegetation and the mean temperature of the coldest month. The southern boundary of boreal forest, which is determined by the cold limit of cool–temperate conifer, coincides with −28°C isotherm of January. The lowest temperature that the temperate cool conifer could tolerate was revised from −19°C to −28°C, which is equivalent to the absolute minimum temperature of −50°C according to the Equation (1) [18].

$$T_{\min} = 0.006T_c^2 + 1.316T_c - 21.9 \tag{1}$$

Where T_c is the mean temperature of coldest month, $T_{\min}$ is the absolute minimum temperature.

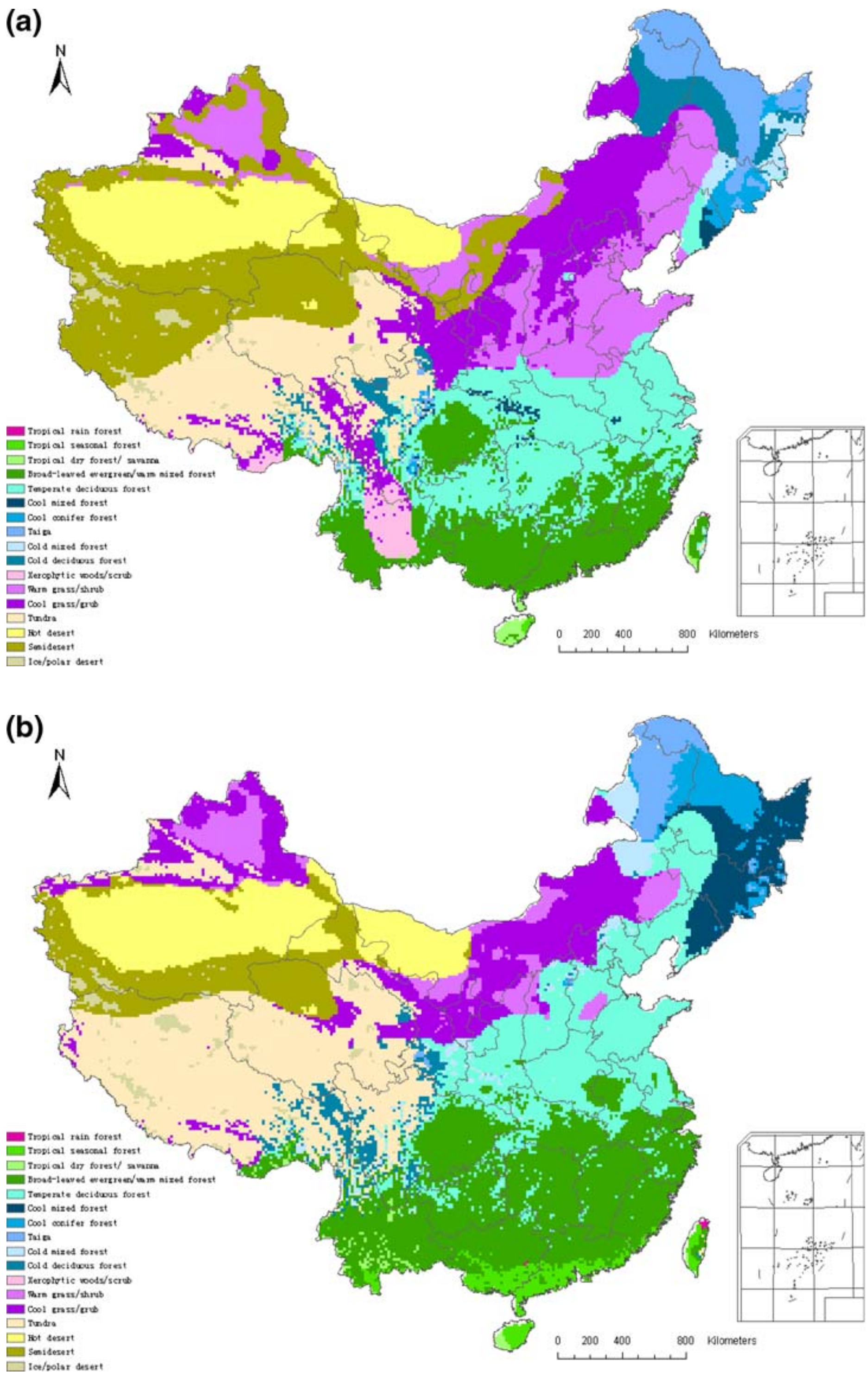


Figure 3. Simulation biome maps: (a) from the original BIOME1; (b) from the validated BIOME1.

After validating, a new set of environmental constraints was obtained (Table 4). According to the validated BIOME1, we generated a new simulated biome map (Figure 3b).

The biome types, derived from the validated BIOME1, were aggregated into eight categories for comparing with the actual vegetation map by *Kappa* statistic. They are 1. tropical forests (including tropical rain forest, tropical seasonal forest, and tropical dry forest/Savanna), 2. broad-leaved evergreen forest, 3. broad-leaved deciduous forest, 4. mixed broad- and needle-leaved forest (including cool mixed forest, cool conifer forest, and cold mixed forest), 5. taiga (including cold deciduous forest), 6. steppes (including xerophytic woods/scrub, warm grass/

Table 4
Modified environmental constraints for each plant functional type.

	T_{min}		GDD_0	GDD_5	T_{max}	α		
Plant functional types	Min	Max	Min	Min	Min	Min	Max	D
Trees								
1 Tropical evergreen	12	–	–	–	–	0.70	–	1
2 Tropical raingreen	12	–	–	–	–	0.45	0.90	1
3 Warm-temperate evergreen	2.0	–	–	–	–	0.5	–	2
4 Temperate summergreen	−23.0	12	–	1200	–	0.5	–	3
5 Cool-temperate conifer	−28.0	2.0	–	900	–	0.5	–	3
6 Boreal evergreen conifer	−35.0	−2.0	–	350	–	0.5	–	3
7 Boreal summergreen	–	2.0	–	350	–	0.5	–	3
Non-trees								
8 Sclerophyll/succulent	5.0	–	–	–	–	0.28	–	4
9 Warm grass/shrub	–	–	–	–	22.0	0.18	–	5
10 Cool grass/shrub	–	–	–	500	–	0.2	–	6
11 Cold grass/shrub	–	–	100	–	–	0.2	–	6
12 Hot desert shrub	–	–	–	–	22.0	–	–	7
13 Cold desert shrub	–	–	100	–	–	–	–	8

shrub and cool grass/grub), 7. deserts (including hot desert, and semidesert), eight tundra (alpine vegetations and ice/polar desert).

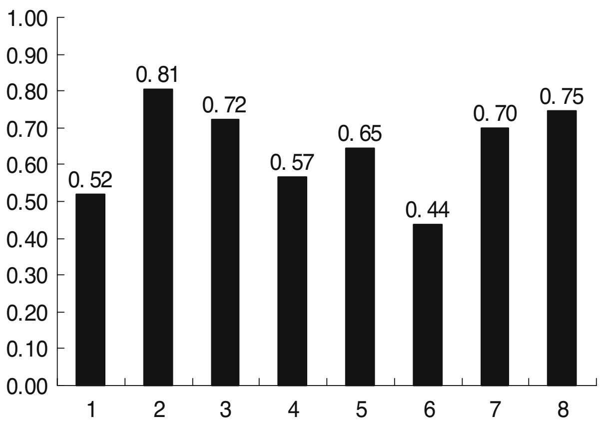
The overall value of the *Kappa* statistic is 0.67, at the 'very good' level. The values of the individual biomes ranged from 0.44 to 0.81 (Figure 4), which showed that most of the biomes were predicted well. The *Kappa* statistics suggest that the modified values of environmental constraints can capture the physiological properties of the PFTs in China.

3.2. The changes of biome distribution

Based on the validated BIOME1, two biome maps under the two climate scenarios were produced (Figure 5). They showed obvious differences with the map predicted under the current climate (Figure 3b). The forest belts in eastern China will shift northwards significantly. Taiga will retreat to the northeastern Daxing'anling Mountains, even out of China. Mixed broad- and needle- leaved forest will occupy most areas of the Northeastern China. The regions occupied by the temperate deciduous forest under current climate will be reduced largely because of the occupation of the steppes from the northwest and the broadleaved evergreen forests from the south. The broad-leaved evergreen forest will greatedly extend its distribution northwards greatly, even to the north of Shandong Province, where the potential vegetation is temperate deciduous forest under current climate. Most of tropical rain forest appears next to the south edge of broadleaved evergreen forest. Tropical seasonal forest will still dominate the largest part of the tropical regions, and expand its boundary northwards. Tropical dry forest/Savanna will outspread from the valleys of southeastern mountains and take the most regions of Yunnan Province. The warm grass/shrub will replace the cool grass/shrub in most places of the Inner-Mongolia and expand its southeastern boundary to Huabei Plain.

The area taken by hot desert will expand 20% (Scenario A2) or 16% (Scenario B2) of its area (Table 5), most of which is from the regions taken by the semidesert. But the areas taken by hot desert and semi-desert in total is nearly the same as those under current climate. In general, the regions taken by forests and grasslands will increase while tundra will decrease largely under the two scenarios and deserts will be approximately the same with those of the current (Table 5).

For describing the shifts between biomes in detail, two matrixes describing distributional changes between the biomes derived from current climate and the climate scenarios were designed (Tables 6 and 7). The matrixes are interpreted in the following way. A value y_{ij} in row i and column j indicates that y 10^3 km^2 of the land



1.Tropical forests 2.Broad-leaved evergreen forest 3.Broad-leaved deciduous forest 4. Mixed broad- and needle-leaved forests 5.Taiga 6.Steppes 7.Deserts 8. Tundra

Figure 4. Kappa values of different biomes simulated by modified BIOME1.

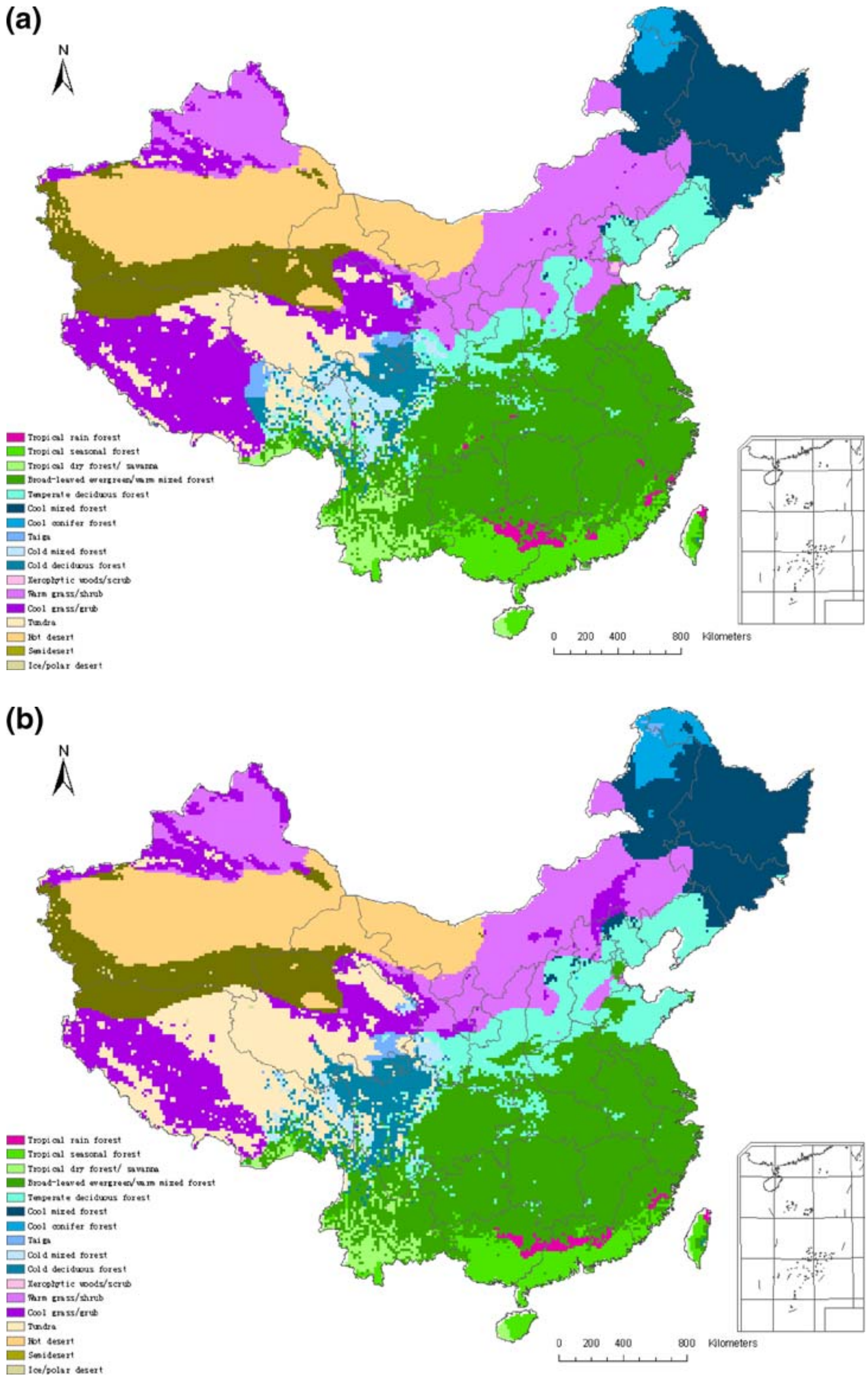


Figure 5. Biome maps based on climate scenarios: (a) from climate scenario SRES-A2; (b) from climate scenario SRES-B2.

surface which is covered by biome *i* in current climate will be covered by biome *j* in scenario A2 (Table 6) or B2 (Table 7). The sum of row *i* is area taken by biome *i* under current climate, which is the same with *current* column of Table 5. The sum of column *j* is area taken by biome *j* under scenario A2 (Table 6) or B2 (Table 7), which is the same with the column *Scenario A*2 or *Scenario B*2 of Table 5, respectively.

The area taken by the tropical dry forest/savanna under the climate scenarios will increase about three ~ four times, from 44.43×10^3 km^2 (sum of row 3) to 180.07×10^3 km^2 (scenario A) or 133.84×10^3 km^2 (scenario B) (sum of

Table 5
Area of biomes derived from BIOME1 under current climate and the scenarios.

	Areas (10^3 km^2)		
Biomes	Current	Scenario A2	Scenario B2
1 Tropical rain forest	4.50	60.26	53.07
2 Tropical seasonal forest	223.78	442.17	356.18
3 Tropical dry forest/savanna	44.43	180.07	133.84
4 Broad-leaved evergreen forest	1814.91	2140.15	2126.12
5 Temperate deciduous forest	1129.17	627.82	770.11
6 Cool mixed forest	661.99	815.26	839.37
7 Cool conifer forest	344.49	94.44	139.59
8 Taiga	239.43	56.31	42.09
9 Cold mixed forest	71.78	182.05	110.45
10 Cold deciduous forest	155.96	232.24	292.86
11 Xerophytic woods/scrub	0.90	8.27	4.50
12 Warm grass/shrub	404.57	1345.94	1140.86
13 Cool grass/grub	1014.40	991.55	865.63
14 Tundra	1733.42	565.93	930.03
15 Hot desert	969.07	1238.90	1171.62
16 Semidesert	649.04	613.06	611.81
17 Ice/polar desert	138.16	5.58	11.87

column 3). The areas are mainly taken from the west portions of broad-leaved evergreen forest. The area of temperate deciduous forest (sum of column 5 and sum of row 5) will shrink sharply. A larger part of it will be taken by broad-leaved evergreen forest (column 4). The tundra over the Tibetan Plateau will show diverse changes. About 1 of 2~2 of 3 of the regions taken by tundra will be transformed into cool conifer forest, taiga, cold mixed forest, cold deciduous forest or cool grass/shrub. The area taken by the cool grass/shrub is about 539.1~794 × 10^3 km^2, which is 1 of 3~1of 2 of the area taken by tundra under current climate.

3.3. The changed areas

Two figures (Figure 6) showing the regions where vegetation types will be changed were produced by comparing the digital maps of Figure 5a and b with that of Figure 3b respectively in ArcGIS©8.1. The regions that vegetation types will be changed by climate change take up about 39~49% of the total terrestrial area of China. These regions are mainly situated on a belt from the northeast to the southwest of China, which lies between the eastern forest zone and the northwestern steppe zone.

On the southwest of China, especially in Yunnan Province, west of Sichuan Province and Hengduan Mountains, the broadleaved evergreen forest will be replaced by the tropical dry forest/savanna or xerophytic wood/scrub. From column 3 (tropical dry forest/savanna) of Tables 6 and 7, it was found that the areas (127.2 + 8.1 and 82.4 + 7.2) taken by the tropical dry forest under the climate scenarios were mainly from the row 4 (broad-leaved evergreen forest of current climate). Most of these regions are in the southwest of China. These changes indicated that the western portions of the broadleaved evergreen forest zone would meet drier climate and the broadleaved evergreen forest would reduce from these areas.

Additionally, we analyzed the following regions to evaluate their possible changes under climate scenario by the same way. Most areas of the northern China, where the potential vegetation is temperate deciduous forest under current climate, will be taken by warm grass/shrub and broad-leaved evergreen forest. The Tibetan Plateau, where the biome is predicted to be tundra under current climate, will be covered by conifer forest and cool grass/shrub in its eastern and southwestern portions respectively. In central

Table 6
Difference matrix of biome pattern from simulations of current climate and Scenario A.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.2	215.5	8.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	44.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	55.6	226.7	127.2	1402.1	0	0	0	0	0	0	3.4	0	0	0	0	0	0
5	0	0	0	691.1	356.7	0	0	0	0	0	3.1	77.5	0.7	0	0	0	0
6	0	0	0	0	161.9	419.9	0	0	0	0	0	80.2	0	0	0	0	0
7	0	0	0	0	9.2	282.8	0	0	0	0	0	52	0.5	0	0	0	0
8	0	0	0	0	7.4	112.6	93.9	0	19.2	0	0	0.7	5.6	0	0	0	0
9	0	0	0	34.4	30.9	0	0	0	0	0	0	6.1	0.4	0	0	0	0
10	0	0	0	11.7	61.7	0	0	0	80.2	0	0	0	2.3	0	0	0	0
11	0	0	0.4	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0.2	363	0	0	41.4	0	0
13	0	0	0	0	0	0	0	0	0	0	1.1	766.3	188	0	39.9	19.1	0
14	0	0	0	0.9	0	0	0.5	56.3	82.6	232.2	0	0	794	479.4	0	87.4	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	969.1	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	188.5	460.5	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	86.5	0	46.1	5.6

The first row and the first column indicate the biome number (for allocation of biome names, see Table 2 or Table 4); the unit of numbers in this table is 10^3 km^2.

Table 7
Difference matrix of biome pattern from simulations of current climate and Scenario B.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.7	215.9	7.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0.2	44.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	47.9	140.1	82.4	1541.8	0	0	0	0	0	0	2.7	0	0	0	0	0	0
5	0	0	0	551.2	556.0	0	0	0	0	0	0.2	20.1	1.6	0	0	0	0
6	0	0	0	0	138.0	473.3	0	0	0	0	0	50.7	0	0	0	0	0
7	0	0	0	0	5.6	296.6	6.8	0	0	0	0	26.1	9.4	0	0	0	0
8	0	0	0	0	2.3	69.4	132.8	7.4	21.2	2.9	0	0	3.4	0	0	0	0
9	0	0	0	27.2	42.8	0	0	0	0	0	0	0	1.8	0	0	0	0
10	0	0	0	5.4	24.3	0	0	0	89.0	35.3	0	0	2.0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0
12	0	0	0	0.4	1.1	0	0	0	0	0	0.2	374.4	0	0	28.6	0	0
13	0	0	0	0	0	0	0	0	0	0	0.5	669.5	308.3	0	20.3	15.7	0
14	0	0	0	0.2	0	0	0	34.7	0.2	254.7	0	0	539.1	844.2	0	60.3	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	969.1	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	153.6	495.4	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	85.8	0	40.5	11.9

The first row and the first column indicate the biome number (for allocation of biome names, see Table 2 or Table 4); the unit of numbers in this table is 10^3 km^2.

China, the temperate deciduous forest will be replaced by the broadleaved evergreen forest. But because it is an alternative among forest types, it is not so serious as an alternative between forests and steppes or steppes and deserts to the environmental conditions [10].

4. Discussion

4.1. The vulnerable regions to climate change

Our results are based on the logics of the BIOME1. But the results showed some similar changes of vegetation distribution with the results from other models, e.g., Holdridge [28], MAPSS [30] and BIOME3 [29], in some areas.

In northern China, significant changes from deciduous forest to grassland and from cold grass/shrub to warm grass/shrub will occur. The temperate deciduous forest on Huabei Plain will be largely reduced and only remain in a narrow belt from the northeast to the southwest of the Huabei Plain. Zhao et al. [30] also pointed out that the climate of Huabei Plain will be drier and the vegetation will be replaced by steppes based on the simulation of MAPSS.

The Tibetan Plateau is emphasized by many researchers as a vulnerable region to climate change [28,43]. From our results based on the BIOME1, a large part of the tundra will be replaced by the cool grass/shrub in the southern parts of the Tibetan Plateau. Ni (2000) also found from the simulation of the BIOME3 [29,44] that the tundra would be largely reduced from the Plateau.

In Southeast of China, especially in the western Sichuan Province, Yunnan Province and the Hengduan Mountains, the vegetation will meet greatest changes among the three regions mentioned here. The broadleaved evergreen forests will be replaced by savannas or xerophytic woods/scrub, which only exist in the dry and hot valleys of Southeastern China under current climate.

Though the principles and logics of these models are different, similar predictions for these regions mean that vegetation in these regions has high probability to be changed by climate change. From these results, it may be concluded that the three regions, the northern China, the Tibetan Plateau, and the Southeastern China, are sensitive to climate change.

China has a large population, its per-capita average of natural resources is low, and its economic development as well as scientific and technological level remain backward. Along with the growth of China's population, the development of the economy and the continuous improvement of the people's consumption level since the 1980s, the pressure on resources, which are already in rather short supply, and on the fragile environment has become greater and greater [45]. Climate change may stimulate these problems with deforestation, desertification, land erosion and so on. To evaluate the effects of climate change on China's environment and health is an urgent task of the following studies.

4.2. The plant functional types and biomes

The prediction for Chinese biome distributions is greatly improved after the model has been validated according to the climate–vegetation relationships of China. However, some predictions are still in 'fair' agreement with natural vegetation distributions, e.g., the steppes (0.44). Additionally, there remain problems in the definition of some biome types. For example, on the Tibetan Plateau, only one biome type, tundra, occurred under current climate. But, in fact, the vegetation on the Tibetan Plateau includes alpine meadows, alpine steppes, as well as alpine deserts [38]. On the Northeast of China, the taiga is

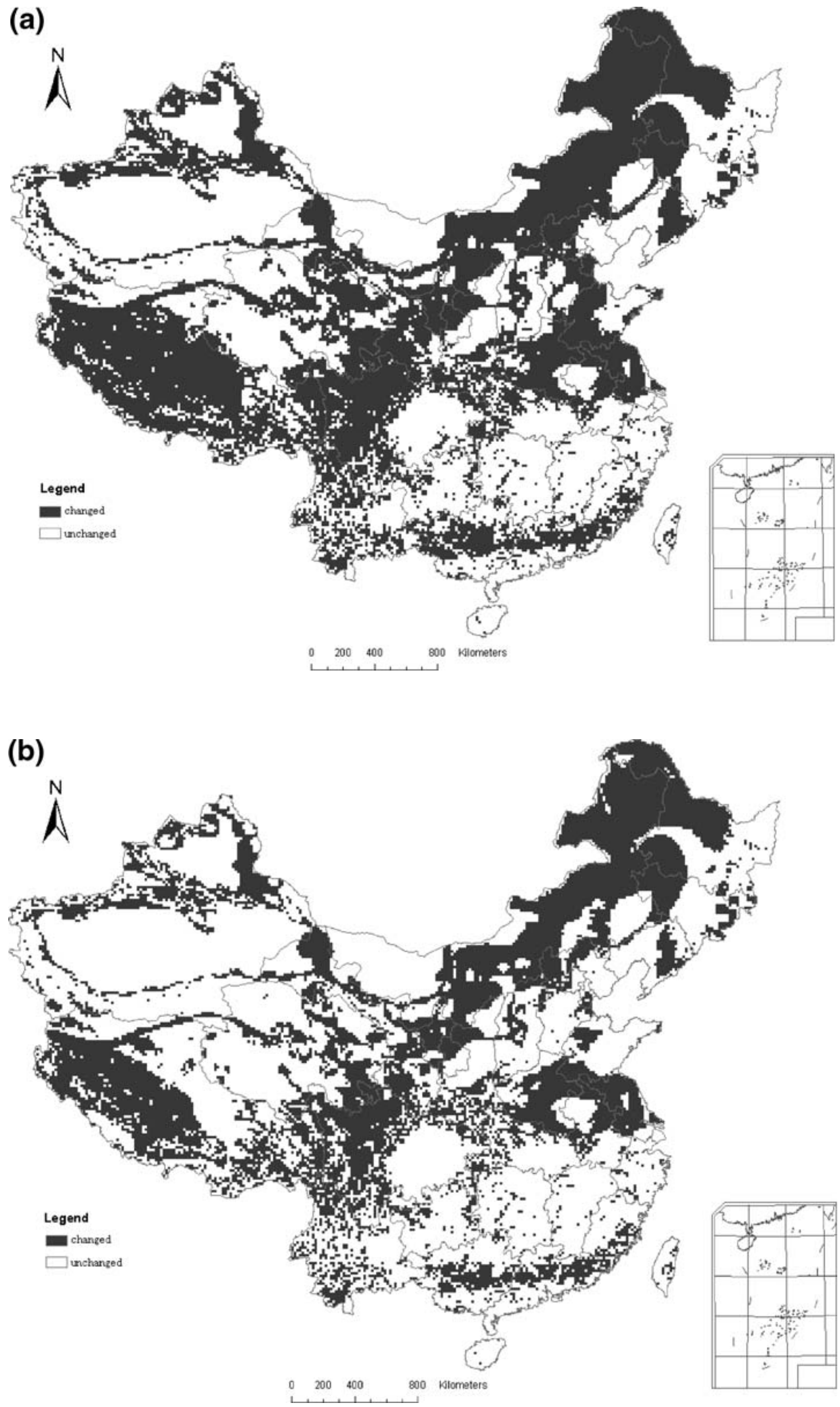


Figure 6. Regions that biome would be changed under climate scenarios (shown in *black grids*); (a) under climate scenario SRES-A2; (b) under climate scenario SRES-A2.

not the evergreen but the deciduous. And in the Inner-Mongolia, the steppes were divided into meadow and typical steppes traditionally [46], rather than warm and cold grass as in the BIOME1.

These deficiencies cannot be made up by regulating the climatic constraints only. A set of PFTs-Biomes for Chinese vegetation modeling is needed. Ni [47] proposed a set of PFTs and biomes according to Chinese vegetation classification schemes [38,48], but the environmental constraints of these PFTs were not given. This makes it difficult to be used in vegetation models directly.

This study gives us strong information on proposing a set of PFTs and biomes for model development. As the tundra, which was predicted on the Tibetan Plateau, should be classified into several types according to the actual vegetation types on the plateau. Additionally, because tundra is identified by a PFT, cold grass/shrub, in the BIOME1, the cold grass/shrub should be replaced by several PFTs representing the dominant plants on the Tibetan Plateau.

With the adjustment of PFTs, some new climatic variables limiting the presence of the PFTs should be introduced too. And some special traits of the plants in China should be considered. For example, it was shown that the PFTs in China have wider climatic envelopes extending to the drier and colder climate end from the revised environmental constraints (Table 4). It seems that the monsoon climate that aggregated rainfall in summer is beneficial to the plants for surviving in the cold and rainless winter.

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