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Scenarios of major terrestrial ecosystems in China

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ABSTRACT

The spatial pattern and mean-center shift of major terrestrial ecosystems, termed Holdridge Life Zones (HLZ), during the periods from 1961 to 1990 (T1), from 2010 to 2039 (T2), from 2040 to 2069 (T3) and from 2070 to 2099 (T4) were analyzed by combining the zonal patterns of climatic change in China and the climatic change scenarios of HadCM2 and HadCM3. The results showed that nival area would decrease rapidly with temperature increase in the future. HadCM2 and HadCM3 predicted that the nival areas might disappear in 552 years and 204 years, respectively. Using both HadCM2 and HadCM3, the five HLZ types with the largest areal extent are nival zone, cool temperate moist forest, warm temperate moist forest, subtropical moist forest and boreal wet forest, which collectively account for more than 50% of China's land mass. Among these five HLZ types, nival zone, warm temperate moist forest and boreal wet forest would decrease continuously, whereas subtropical moist forest and cool temperate forest would increase continuously during the four periods. HLZ diversity and patch connectivity would increase continuously in the 21st century. The shift distances of mean centers of HLZ types simulated using HadCM3 were markedly greater than those simulated using HadCM2, in general. The results from both HadCM2 and HadCM3 showed that boreal wet forest, subtropical moist forest, tropical dry forest, warm temperate moist forest and subtropical wet forest had bigger shift ranges, indicating that these HLZ types are more sensitive to the climatic change scenarios of HadCM2 and HadCM3.

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1. Introduction

The spatial pattern of major terrestrial ecosystems in China and the associated pattern of change in the four decades from the 1960s to the 1990s were analyzed by using the Holdridge Life Zone (HLZ) model with daily temperature and precipitation data since 1960, selected from 735 weather stations scattered across China (Yue et al., 2005). The results showed that the HLZ spatial pattern in China changed substantially during the four decades. For instance, the nival zone showed a rapid decrease, indicating that it might disappear in 159 years, if it were to keep shrinking at the average rate observed dur-

ing the four decades. Alpine dry tundra and cool temperate scrub increased continuously over the four decades, giving decadal increase rates of 13.1% and 3.4%, respectively. HLZ patch connectivity exhibited a continuous pattern of increase, and HLZ diversity a continuous pattern of decrease (Yue et al., 2001, 2005). The warm temperate thorn steppe, subtropical wet forest and cool temperate wet forest shifted by 1781.45 km, 1208.14 km and 977.43 km, respectively, over the four decades. These HLZ types were more sensitive to climate change than the others.

In this paper, scenarios of major terrestrial ecosystems in China during the periods 2010–2039 (T2), 2040–2069 (T3) and

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2070–2099 (T4) were simulated by combining zonal patterns of climatic change in China (Yue et al., 2005) with the climatic change scenarios of HadCM2 and HadCM3.

HadCM2 and HadCM3 were developed at the Hadley Centre for Climate Prediction and Research in the United Kingdom on the basis of greenhouse gas and sulfate aerosol forcing experiments. HadCM2 was differentiated into HadCM2GG and HadCM2GS. HadCM2GG uses the combined forcing of all the greenhouse gases as an equivalent CO₂ concentration. HadCM2GS uses the combined equivalent CO₂ concentration plus the negative forcing from sulfate aerosols. HadCM2GS results suggested that global warming could accelerate as greenhouse gas forcing begins to dominate over sulfate aerosol forcing (Mitchell et al., 1995). Both the ocean and atmospheric components of the HadCM2 model employ a spatial horizontal grid point spacing of 3.75° longitude (about 400 km) and 2.5° latitude (about 280 km). The atmosphere model and the ocean model use 19 and 20 vertical levels, respectively (Giorgi, 2002). Compared to HadCM2, HadCM3 includes an enhanced land surface scheme that tends to improve the mid-latitude summer surface climatology (Cox et al., 1999). HadCM3 uses the same horizontal atmospheric and land surface grid as HadCM2. The ocean component of HadCM3 does not require flux adjustments (Collins et al., 2001; Johns et al., 2003), and it is run at a higher horizontal resolution (1.25° × 1.25°).

2. Methods

2.1. HLZ classification

The Holdridge Life Zone (HLZ) classification is a scheme that uses three bioclimatic variables derived from standard meteorological data to formulate the relationship between climate patterns and broad-scale vegetation distribution. It relates the distribution of major ecosystems (termed “life zones”) to the bioclimatic variables. The HLZ classification divides the world into over 100 life zones on the basis of mean annual biotemperature (MAB) in degrees centigrade, average total annual precipitation (TAP) in millimeters and potential evapotranspiration ratio (PER) logarithmically. Biotemperature is defined as the mean of unit-period temperatures with substitution of zero for all unit-period values below 0 °C and above 30 °C (Holdridge et al., 1971). Evapotranspiration is the total amount of water that is returned directly to the atmosphere in the form of vapor through the combined processes of evaporation and transpiration. Potential evapotranspiration is the amount of water that would be transpired under constantly optimal conditions of soil moisture and plant cover. The potential evapotranspiration ratio is the ratio of mean annual potential evapotranspiration to average total annual precipitation, which provides an index of biological humidity conditions. In other words, MAB, TAP and PER at site (x, y) and in the tth year have the following formulation:

$$\text{MAB}(x, y, t) = \frac{1}{365} \sum_{j=1}^{365} \text{TEM}(j, x, y, t) \quad (1)$$

$$\text{TAP}(x, y, t) = \sum_{j=1}^{365} P(j, x, y, t) \quad (2)$$

$$\text{PER}(x, y, t) = \frac{58.93 \text{MAB}(x, y, t)}{\text{TAP}(x, y, t)} \quad (3)$$

where TEM(j, x, y, t) is the value obtained by summing the hourly temperatures above 0 °C and below 30 °C on the jth day and dividing by 24; P(j, x, y, t) is precipitation on the jth day.

Suppose

$$M(x, y, t) = \ln \text{MAB}(x, y, t) \quad (4)$$

$$T(x, y, t) = \ln \text{TAP}(x, y, t) \quad (5)$$

$$P(x, y, t) = \ln \text{PER}(x, y, t) \quad (6)$$

$$d_i(x, y, t) = \sqrt{\frac{(M(x, y, t) - M_{i0})^2 + (T(x, y, t) - T_{i0})^2}{(P(x, y, t) - P_{i0})^2}} \quad (7)$$

where M_{i0} , T_{i0} and P_{i0} are standards of MAB logarithm, TAP logarithm and PER logarithm at the central point of the ith life zone in the hexagonal system of HLZs. When $d_k(x, y, t) = \min_i \{d_i(x, y, t)\}$, the site (x, y) is classified as the kth life zone.

2.2. Models related to spatial pattern

On the basis of HLZ classification, the mean-center model, the ecological diversity index and the patch connectivity index are employed to analyze spatial pattern scenarios of major ecosystems in China. The mean-center model is formulated as (Yue et al., 2005),

$$x_j(t) = \sum_{i=1}^{I_j} \frac{s_{ij}(t) \cdot X_{ij}(t)}{S_j(t)} \quad (8)$$

$$y_j(t) = \sum_{i=1}^{I_j} \frac{s_{ij}(t) \cdot Y_{ij}(t)}{S_j(t)} \quad (9)$$

where t is the variable of time; $I_j(t)$ the patch number of HLZ type j; $s_{ij}(t)$ the area of the ith patch of HLZ type j; $S_j(t)$ the total area of HLZ type j; $(X_{ij}(t), Y_{ij}(t))$ the longitude and latitude coordinates of the geometric center of the ith patch of HLZ type j; and $(x_j(t), y_j(t))$ is the mean center of HLZ type j.

Shift distance and direction of HLZ j in the period from t to t + 1 are, respectively, formulated as,

$$D_j = \sqrt{(x_j(t+1) - x_j(t))^2 + (y_j(t+1) - y_j(t))^2} \quad (10)$$

$$\theta_j = \arctg \left(\frac{y_j(t+1) - y_j(t)}{x_j(t+1) - x_j(t)} \right) \quad (11)$$

where D_j is the shift distance of HLZ type j in the period from t to t + 1; t = 1, 2 and 3, respectively, represent T1 (the period from 1961 to 1990), T2 (the period from 2010 to 2039) and T3

(the period from 2040 to 2069); θ_j the shift direction of HLZ type j , with due east being 0° , due north 90° , due west 180° and due south 270° ; $(x_j(t), y_j(t))$ and $(x_j(t+1), y_j(t+1))$ are, respectively, the coordinates of the mean center of HLZ type j in the years t and $t+1$. When $0^\circ < \theta_j < 90^\circ$, HLZ type j shifts towards the north-east during the period from t to $t+1$; when $90^\circ < \theta_j < 180^\circ$, HLZ type j shifts towards the northwest; when $180^\circ < \theta_j < 270^\circ$, HLZ type j shifts towards the southwest; when $270^\circ < \theta_j < 360^\circ$ HLZ type j shifts towards the southeast.

The ecological diversity index is expressed as (Yue et al., 2003, 2001, 1998),

$$d(t) = - \frac{\ln \left(\sum_{i=1}^{m(\varepsilon)} (p_i(t))^{1/2} \right)^2}{\ln(\varepsilon)} \quad (12)$$

where t is the variable of time; $p_i(t)$ the probability of the i th ecotope; $m(\varepsilon)$ the total number of investigation objects; $\varepsilon = 1/e + a$, where a is the area of the region studied in hectares and e equals 2.71828.

The patch connectivity index is formulated as (Yue et al., 2003, 2004),

$$CO(t) = \sum_{i=1}^{m(t)} \sum_{j=1}^{n_i(t)} p_{ij}(t) \cdot S_{ij}(t) \quad (13)$$

where p_{ij} is proportion of the area of the j th patch in the i th type to the total area under investigation; t the variable of time; $S_{ij}(t)$ the index of movement efficiency of migrants or propagules in the patch (i,j) ; $0 \leq C(t) \leq 1.1$; and when all patches have the shape of a hexagon, $C(t) = 1.0$.

2.3. Simulation process

The data used in the HadCM2 and HadCM3 global change models were downloaded from the IPCC Data Distribution Centre (<http://ipcc-ddc.cru.uea.ac.uk>) and consist of mean monthly data for the four periods, T1, T2, T3 and T4. Data processing included the following steps: (1) matching coordinates to each datum of the downloaded data; (2) converting mean monthly data into mean annual data, transforming the data format into a text file using Visual C++ (VC++); (3) transforming the mean annual data into point coverage with the AML/ArcInfo program; (4) operating the improved gradient-plus-inverse distance squared (GIDS) model in ArcObjects with VBA control and creating mean annual biotemperature surfaces for the four periods on the basis of digital elevation model and point coverage of mean annual biotemperature; (5) operating the improved GIDS model in ArcObjects with VBA control and creating mean annual biotemperature surfaces on the basis of digital elevation model and point coverage of mean annual biotemperature; (6) creating mean annual precipitation surfaces by kriging interpolation and transform-

Fig. 1 – Digital elevation model of China.

Table 1 – Linear relationships between the decrease in temperature (T) with increase in elevation (E) in different regions of China (Yue et al., 2005)

Regions	Correlation coefficients	Decreasing rate (°C/m)	Linear regression equation
Changbai Mountains	−0.96	0.0028	$T = -0.0028E + 9.3481$
Da Hinggan and Xiao Hinggan mountains	−0.84	0.0040	$T = -0.0040E + 8.3638$
Qinghai-Xizang Plateau	−0.95	0.0029	$T = -0.0029E + 14.442$
Hengduan Mountains	−0.95	0.0054	$T = -0.0054E + 24.542$
Loess Plateau	−0.87	0.0036	$T = -0.0036E + 14.111$
Nanling Mountains	−0.90	0.0060	$T = -0.0060E + 18.996$
Qilian Mountains	−0.99	0.0037	$T = -0.0037E + 14.787$
Qinling Mountains	−0.76	0.0040	$T = -0.0040E + 15.681$
Taihang and Lvliang mountains	−0.97	0.0050	$T = -0.0050E + 14.53$
Tianshan Mountains	−0.85	0.0038	$T = -0.0038E + 13.858$
Wuling Mountains	−0.94	0.0055	$T = -0.0055E + 18.112$
Wuyi Mountains	−0.90	0.0044	$T = -0.0044E + 18.848$
Himalaya Mountains	−0.85	0.0064	$T = -0.0064E + 30.978$
Yanshan Mountains	−0.98	0.0046	$T = -0.0046E + 12.258$
Yunnan-Guizhou Plateau	−0.85	0.0045	$T = -0.0046E + 19.979$

Fig. 2 – Holdridge Life Zone spatial distribution predicted by HadCM2 for the periods 1961–1990 (T1), 2010–2039 (T2), 2040–2069 (T3) and 2070–2099 (T4).

ing the point coverage into 1-km grid data using the Spatial Analyst module of ArcInfo; (7) converting the 1-km grid data into ASCII data with the ArcToolbox module and ArcInfo/AML; (8) calculating potential evapotranspiration in ASCII data by using modular programming of VC++ and then transforming the results into grid data; (9) conducting grid computation of biotemperature, precipitation and evapotranspiration; (10) operating the HLZ model with the ASCII data using VC++; (11) transforming the ASCII data from the HLZ model into 1-km grid data and then converting the 1-km grid data into polygon coverage.

We should note that there is a significant negative correlation between temperature and elevation in China. The multivariate regression model of the relationship between temperature T , longitude X , latitude Y and elevation E gave $T = 43.312 - 0.106X - 0.469Y - 0.00361E$, with a correlation coefficient of -0.98 (Yue et al., 2005). Primary temperature sur-

faces were created using the improved GIDS model, which was specifically formulated as,

$$T_{jk} = \sum_{i=1}^{N_{jk}} \frac{2T_i - [0.0046 \cdot (E_{jk} - E_i) + 0.106 \cdot (X_{jk} - X_i) + 0.469 \cdot (Y_{jk} - Y_i) + 0.0036 \cdot (E_{jk} - E_i)]}{2d_{ijk}^2 \left(\sum_{i=1}^{N_{jk}} d_{ijk}^{-2} \right)} \quad (14)$$

Then, the primary temperature surfaces were corrected using a $1 \text{ km} \times 1 \text{ km}$ digital elevation model of China (Fig. 1) and relationships between temperature and elevation (Table 1). Because there was no statistically significant correlation between precipitation and elevation, the kriging interpolation method was selected to create $1 \text{ km} \times 1 \text{ km}$ precipitation surfaces, providing a higher accuracy than the Inverse Distance Weighted method (Yue and Du, 2005).

Fig. 3 – Holdridge Life Zone spatial distribution predicted by HadCM3 for the periods 1961–1990 (T1), 2010–2039 (T2), 2040–2069 (T3) and 2070–2099 (T4).

3. Results

3.1. HLZ spatial distribution

According to HadCM2, there would be 30 HLZ types in T1. Subtropical desert scrub would appear in the northern part of lower Altun Mountains in T2, subtropical desert in the eastern Tarim Basin in T3 and tropical wet forest in the archipelagoes of the South China Sea in T4 (Fig. 2). HadCM3 generated 28 HLZ types in T1 (Fig. 3). Tropical dry forest would appear in the southwestern Yunnan and the southwestern Hainan in T2. In T3, subtropical desert would appear in the eastern Tarim Basin and would have a rapid expansion trend; subtropical thorn woodland would appear in the northern part of the lower Altun Mountains. Subtropical desert scrub would appear in the area between the subtropical desert and the subtropical thorn woodland arising in T3. Subtropical dry forest would be distributed in southwestern Yunnan in T1, which would disappear in T2 and T3, and would reappear in the Taishan Mountain area of the North China Plain in T4.

In general, HadCM2 and HadCM3 created a similar HLZ spatial distribution pattern in the 21st century (Figs. 2 and 3).

Nival area, alpine dry tundra and alpine moist tundra would be distributed mainly in the Qinghai-Xizang Plateau and in the Tianshan and Qilian high mountains. Alpine wet tundra and alpine rain tundra would appear around the nival area, the alpine dry and alpine moist tundra as well as the northern mountaintops of the Da Hingan Mountains. The boreal desert would occur in the Beishan Mountain area of the northern Qinghai-Xizang Plateau, Tarim Basin and north of Turpan Basin. The tropical desert would appear in the central areas of the Tarim, Turpan and Junggar basins. The warm temperate desert would be located around the tropical desert, while the inner cool temperate desert would be distributed mainly in the middle of the Alashan Plateau and Junggar Basin. Cool temperate scrub, warm temperate desert scrub and subtropical desert scrub would be found on the margins of the northern Qinghai-Xizang Plateau, the western Tarim Basin, the western and northeastern Junggar Basin as well as the southeastern Alashan Plateau and the southwestern Inner Mongolian Plateau. Boreal dry scrub would be present mainly in low mountain areas of the Qinghai-Xizang Plateau, and the Tianshan and Qilian mountains. Cool temperate steppe would be found mainly in the Mongolian and Loess Plateau regions and southwest of Northeast Plain. The warm temperate thorn steppe would appear in the southeast of Himalaya

Table 2 – Holdridge Life Zone mean-center shift predicted by HadCM2

Code	HLZ type (name)	From T1 to T2		From T2 to T3		From T3 to T4	
		Distance (km)	Direction	Distance (km)	Direction	Distance (km)	Direction
1	Nival	21.3724	Southwest	9.2447	Northwest	6.0281	Southeast
2	Alpine dry tundra	42.0014	Southwest	157.6814	Northwest	27.5054	Southwest
3	Alpine moist tundra	53.9373	Northwest	173.6284	Northeast	151.3185	Northeast
4	Alpine wet tundra	20.4538	Southwest	59.7608	South	11.2154	Southwest
5	Alpine rain tundra	138.1902	Southwest	32.9498	Northwest	35.0088	West
6	Boreal desert	44.0795	Northwest	61.4476	Northeast	29.7994	Northwest
7	Boreal dry scrub	21.6816	Northwest	85.6761	Northwest	40.4330	Northwest
8	Boreal moist forest	639.6778	Southwest	310.7023	Southwest	208.5016	Southwest
9	Boreal wet forest	226.2427	Southwest	90.8159	Northwest	174.1970	Southwest
10	Boreal rain forest	58.2990	Northwest	95.4113	Southwest	50.1217	Southwest
11	Cool temperate desert	97.9508	Southwest	46.6987	Northeast	125.2279	Northeast
12	Cool temperate scrub	55.1869	Northwest	72.9184	Northwest	32.5187	Northwest
13	Cool temperate steppe	123.6467	Northwest	220.6709	Southwest	66.4193	Northwest
14	Cool temperate moist forest	227.0825	Northwest	168.4700	Southwest	11.1340	Northwest
15	Cool temperate wet forest	123.9504	Northeast	95.6483	Northeast	130.3338	Northeast
16	Cool temperate rain forest	95.4109	Southwest	28.6009	Southeast	15.2249	Southeast
17	Warm temperate desert	38.6474	East	79.3850	West	32.5365	Northeast
18	Warm temperate desert scrub	217.7506	Northeast	72.2842	North	125.3002	Northeast
19	Warm temperate thorn steppe	253.4637	Northeast	232.9484	Southeast	13.5248	Northeast
20	Warm temperate dry forest	81.5412	Northeast	13.1024	Southwest	139.4464	North
21	Warm temperate moist forest	130.0008	Southeast	322.9908	Northwest	45.9446	Northwest
22	Warm temperate wet forest	205.8891	West	129.8224	Southeast	55.3369	Southwest
24	Subtropical desert					36.4379	Northwest
25	Subtropical desert scrub			45.6468	Northwest	18.2872	Northwest
26	Subtropical thorn woodland	5.0000	West	869.6082	Northwest	448.5919	Northwest
27	Subtropical dry forest	58.7632	Southeast	371.4169	Northwest	108.5210	Northwest
28	Subtropical moist forest	245.9084	Northwest	31.2406	Southeast	303.1905	Southwest
29	Subtropical wet forest	629.2746	Southwest	1809.9737	Northeast	115.1788	Northwest
31	Tropical desert	59.8149	Northeast	59.1494	Southwest	11.8325	Northeast
34	Tropical very dry forest	110.0239	Northwest	151.6962	Southwest	190.1670	Northwest
35	Tropical dry forest	43.0813	East	341.9647	Southwest	83.2305	Northeast
36	Tropical moist forest	174.5450	Northwest	357.3161	Southeast	35.2427	Northwest
37	Tropical wet forest						

Mountains, the northwest of Tianshan Mountains, Qarqan River area of the northern Altun Mountains and Yarkant River area of the western Tarim basin. The boreal moist, wet and rain forests, and cool temperate moist and wet forests would be distributed in the east and the south of Qinghai-Xizang Plateau and Da Hinggan, Xiao Hinggan and Taihang mountains. The warm temperate dry forest would appear in most of the North China Plain, while the warm temperate moist and wet forests would be found in the north of the Yunnan-Guizhou Plateau and most of the lower reaches of the Yangtze River. Subtropical dry, moist and wet forests would be distributed mainly in the south of the Yunnan-Guizhou Plateau, the Nanling Mountains, the Jiangnan Hills and its southern area, and the high mountains of Taiwan. Tropical dry forest would occur in the western Hainan; tropical moist forest in the eastern Hainan, Hong Kong and the low mountains of Taiwan; and tropical wet forests in the archipelagoes of the South China Sea.

3.2. HLZ mean-center shift

According to HadCM2 (Table 2; Fig. 4), HLZ types that would have their cumulative shift distances of mean centers shortened by less than 200 km from T1 to T4 include nival areas (37 km), subtropical desert scrub (64 km), alpine wet tundra (91 km), tropical desert (131 km), boreal desert (135 km), cool temperate rain forest (139 km), boreal dry scrub (148 km), warm temperate desert (151 km) and cool temperate scrub (161 km). The HLZ types that would see the range of their cumulative shift distances move between 200 km and 1000 km over the four periods include boreal rain forest (204 km), alpine rain tundra (206 km), alpine dry tundra (227 km), warm temperate dry forest (239 km), cool temperate desert (270 km), cool temperate wet forest (350 km), alpine moist tundra (379 km), warm temperate wet forest (391 km), cool temperate moist forest (406 km), cool temperate steppe (411 km), warm temperate desert scrub (415 km), tropical very dry forest (452 km), tropical

Fig. 4 – Holdridge Life Zone mean-center shift predicted by HadCM2 for the periods 1961–1990 (T1), 2010–2039 (T2), 2040–2069 (T3) and 2070–2099 (T4).

dry forest (468 km), boreal wet forest (491 km), warm temperate moist forest (499 km), warm temperate thorn steppe (500 km), subtropical dry forest (539 km), tropical moist forest (567 km) and subtropical moist forest (580 km). Boreal moist forest, subtropical thorn woodland and subtropical wet forest would see their cumulative shift distances move by more than 1000 km. The mean center of boreal moist forest would continuously shift, moving 1159 km towards the southwest during the four periods; subtropical thorn woodland would shift 5 km towards the west from T1 to T2 and then continuously, moving 1318 km towards the northwest from T2 to T3 and from T3 to T4. Subtropical wet forest would shift 629 km towards the southwest from T1 to T2, 1810 km towards the northeast from T2 to T3 and 115 km towards the northwest from T3 to T4.

According to HadCM3 (Table 3; Fig. 5), the HLZ types that would see their cumulative shift distances shortened by less than 200 km from T1 to T4 include tropical desert (19 km), tropical wet forest (43 km), boreal desert (158 km) and alpine dry tundra (189 km). The HLZ types with cumulative shift distances between 200 km and 1000 km include warm temperate desert (223 km), cool temperate desert (244 km), warm temperate desert scrub (263 km), alpine wet tundra (297 km), alpine moist tundra (309 km), nival areas (321 km), tropical moist forest (337 km), cool temperate scrub (404 km),

alpine rain tundra (425 km), boreal dry scrub (428 km), boreal moist forest (433 km), cool temperate steppe (521 km), boreal rain forest (547 km), warm temperate thorn steppe (635 km), subtropical wet forest (651 km), warm temperate dry forest (669 km), warm temperate moist forest (675 km), cool temperate wet forest (728 km), cool temperate rain forest (794 km) and tropical dry forest (863 km). Cumulative shift distances greater than 1000 km include subtropical moist forest (1104 km), cool temperate moist forest (1336 km), warm temperate wet forest (1435 km), boreal wet forest (2196 km) and subtropical dry forest (2272 km). The mean center of subtropical moist forest would shift 156 km towards the southwest from T1 to T2, 436 km towards the north from T2 to T3 and 513 km towards the southwest from T3 to T4. The cool temperate moist forest would shift 401 km towards the northwest from T1 to T2, 329 km towards the southwest from T2 to T3 and 606 km towards the northeast from T3 to T4. The warm temperate wet forest would shift 179 km towards the northwest from T1 to T2, 846 km towards the west from T2 to T3 and 411 km towards the northwest from T3 to T4. The boreal wet forest would shift continuously, moving 2196 km towards the southwest during the four periods. The subtropical dry forest would disappear during T2 and T3 and reappear in T4, and its mean center would shift 2272 km towards the northeast from T1 to T4.

Table 3 – Holdridge Life Zone mean-center shift predicted by HadCM3

Code	HLZ type (name)	From T1 to T2		From T2 to T3		From T3 to T4	
		Distance (km)	Direction	Distance (km)	Direction	Distance (km)	Direction
1	Nival	124.4070	Northwest	74.8280	Southwest	122.0751	Northwest
2	Alpine dry tundra	94.2771	Northeast	11.1873	Northeast	83.6462	West
3	Alpine moist tundra	126.6003	Northwest	115.8568	Northwest	66.5508	Northwest
4	Alpine wet tundra	68.3549	Northeast	120.5977	Northeast	108.2577	Southwest
5	Alpine rain tundra	118.8643	Northwest	191.8150	Northwest	114.0076	West
6	Boreal desert	70.4827	Northwest	56.1247	Northwest	31.0157	Northeast
7	Boreal dry scrub	77.5663	Northwest	195.7217	Northwest	154.2397	Northwest
8	Boreal moist forest	286.8680	Southwest	123.1138	Northwest	23.0960	Northwest
9	Boreal wet forest	558.5189	Southwest	1006.3419	Southwest	631.1571	Southwest
10	Boreal rain forest	46.9533	Northwest	196.5050	Southwest	303.8355	Northwest
11	Cool temperate desert	90.5719	Northeast	97.0943	East	56.0373	Northwest
12	Cool temperate scrub	95.7755	Northwest	139.9974	Northwest	168.4242	West
13	Cool temperate steppe	62.6888	Southwest	123.1965	Northwest	335.4326	Northwest
14	Cool temperate moist forest	401.2267	Northwest	328.5963	Southwest	605.9601	Northeast
15	Cool temperate wet forest	116.6780	Northeast	357.6011	Northeast	254.0943	Northwest
16	Cool temperate rain forest	661.1538	Southwest	76.6340	Southeast	56.2465	Northwest
17	Warm temperate desert	116.7835	Northeast	58.0957	Southwest	47.9030	Northeast
18	Warm temperate desert scrub	60.8555	Northeast	146.5193	East	55.7731	Northeast
19	Warm temperate thorn steppe	325.5924	Northeast	223.2580	East	85.9428	Northwest
20	Warm temperate dry forest	171.3690	Northwest	237.9701	Northwest	259.4049	Northwest
21	Warm temperate moist forest	248.2847	Northeast	159.7227	Northwest	266.5399	Northwest
22	Warm temperate wet forest	178.4653	Northwest	845.5714	West	410.5398	West
24	Subtropical desert					149.9273	Northwest
25	Subtropical desert scrub					52.1445	Northwest
26	Subtropical thorn woodland					43.0437	Southwest
27	Subtropical dry forest						
28	Subtropical moist forest	155.8283	Southwest	435.8816	North	512.4857	Southwest
29	Subtropical wet forest	110.3578	Northwest	153.5290	Southwest	387.1327	Northwest
31	Tropical desert	5.0000	East	8.5715	West	5.2001	Northwest
35	Tropical dry forest			847.8571	Southeast	14.7862	Northwest
36	Tropical moist forest	77.6888	West	105.0244	Northwest	153.9917	Northwest
37	Tropical wet forest	34.6386	Northwest	59.2569	North	36.8389	Southeast

Fig. 5 – Holdridge Life Zone mean-center shift predicted by HadCM3 for the periods 1961–1990 (T1), 2010–2039 (T2), 2040–2069 (T3) and 2070–2099 (T4).

3.3. Average HLZ area changes

Based on the HadCM2 simulation, HLZ types that would have an areal extent larger than 10 million ha on average included nival areas, cool temperate moist forest, warm temperate moist forest, subtropical moist forest, boreal wet forest, cool temperate steppe, warm temperate desert, alpine rain tundra, cool temperate wet forest, boreal rain forest, cool temperate scrub, subtropical dry forest, warm temperate dry forest, cool temperate desert, boreal moist forest, warm temperate desert scrub, tropical dry forest and alpine wet tundra (Table 4). Tropical wet forest, tropical moist forest, subtropical desert, subtropical wet forest, subtropical thorn woodland, alpine dry tundra, tropical very dry forest, subtropical desert scrub, alpine moist tundra, boreal desert, boreal dry scrub, cool temperate rain forest, tropical desert, warm temperate wet forest and warm temperate thorn steppe underwent an area change

of less than 10 million ha. The HLZ types whose area decreased continuously during the four periods (Table 5) include nival zone, alpine moist tundra, boreal desert, boreal dry scrub, boreal moist forest, cool temperate desert, cool temperate scrub, cool temperate wet forest and warm temperate moist forest. Alpine wet tundra, alpine rain tundra, boreal rain forest, cool temperate rain forest, warm temperate desert scrub, warm temperate thorn steppe, subtropical desert, subtropical moist forest and tropical dry forest showed a continuous increase in areal extent during the four periods.

Based on the HadCM3 simulation, HLZ types that would have an area larger than 10 million ha on average include cool temperate moist forest, subtropical moist forest, warm temperate moist forest, nival areas, boreal wet forest, alpine rain tundra, warm temperate dry forest, cool temperate steppe, cool temperate wet forest, boreal rain forest, warm temperate desert scrub, cool temperate scrub, cool temperate desert,

Table 4 – Area (million ha) of each Holdridge Life Zone type predicted by HadCM2

Code	HLZ type	T1	T2	T3	T4	Average
1	Nival	150.2506	134.9758	122.4263	112.2238	129.9691
2	Alpine dry tundra	1.9102	1.9919	0.8971	0.7571	1.3891
3	Alpine moist tundra	3.5219	3.3135	2.9595	2.1609	2.989
4	Alpine wet tundra	9.234	9.7529	10.5353	10.9642	10.1216
5	Alpine rain tundra	44.0494	44.927	47.7646	48.9187	46.4149
6	Boreal desert	8.2232	6.4733	3.9724	3.1	5.4422
7	Boreal dry scrub	7.0476	6.4505	6.1645	5.7634	6.3565
8	Boreal moist forest	21.1151	14.0923	13.8538	12.7914	15.4631
9	Boreal wet forest	64.0624	52.8971	53.0569	48.4823	54.6247
10	Boreal rain forest	37.5379	38.6973	39.5161	42.2789	39.5076
11	Cool temperate desert	34.6583	30.1473	27.749	25.2188	29.4434
12	Cool temperate scrub	34.3058	32.376	32.3421	28.4917	31.8789
13	Cool temperate steppe	52.6884	51.2058	50.8419	46.9681	50.426
14	Cool temperate moist forest	104.5457	121.1219	127.0342	129.8499	120.6379
15	Cool temperate wet forest	46.6909	45.8087	39.9543	38.7208	42.7937
16	Cool temperate rain forest	5.0712	5.6851	6.9383	7.7876	6.3706
17	Warm temperate desert	51.723	55.465	46.2715	45.7553	49.8037
18	Warm temperate desert scrub	8.7875	11.8125	14.7555	17.4259	13.1953
19	Warm temperate thorn steppe	2.69	6.2136	12.94	16.8036	9.6618
20	Warm temperate dry forest	20.5765	24.6689	33.5267	40.2289	29.7503
21	Warm temperate moist forest	118.2711	101.6729	89.2205	74.8149	95.9949
22	Warm temperate wet forest	6.4688	6.1378	9.887	11.2504	8.436
24	Subtropical desert			0.12	1.77	0.4725
25	Subtropical desert scrub		0.43	2.65	3.99	1.7675
26	Subtropical thorn woodland	0.68	0.66	1.01	1.44	0.9475
27	Subtropical dry forest	41.0577	44.1673	20.8644	16.5104	30.65
28	Subtropical moist forest	63.5571	83.0373	105.3638	123.5338	93.873
29	Subtropical wet forest	0.0556	0.0451	0.9712	1.6411	0.6783
31	Tropical desert	6.71	7.38	6.1	5.4	6.3975
34	Tropical very dry forest	1.1643	3.1287	1.1882	1.1569	1.6596
35	Tropical dry forest	2.7073	4.6316	18.4487	23.1234	12.2277
36	Tropical moist forest	0.0217	0.0151	0.0583	0.0516	0.0367
37	Tropical wet forest				0.0075	0.0019

warm temperate desert, warm temperate thorn steppe, boreal moist forest and warm temperate wet forest (Table 6). Tropical wet forest, tropical desert, tropical dry forest, alpine dry tundra, boreal desert, subtropical thorn woodland, alpine moist tundra, cool temperate rain forest, subtropical dry forest, subtropical desert, subtropical desert scrub, boreal dry scrub, alpine wet tundra, subtropical wet forest and tropical moist forest would decrease in area by less than 10 million ha. The HLZ types whose area would decrease continuously during the four periods include nival areas, alpine dry tundra, alpine moist tundra, alpine wet tundra, boreal desert, boreal dry scrub, boreal moist forest, boreal wet forest, cool temperate desert, cool temperate scrub and warm temperate moist forest (Table 7). Warm temperate desert scrub, warm temperate thorn steppe, warm temperate dry forest, subtropical moist forest, subtropical wet forest and tropical moist forest would undergo a continuous increase in areal extent during the four periods.

4. Discussion

Based on both HadCM2 and HadCM3, the nival areas in the Qinghai-Xizang Plateau would rapidly shrink towards the northwest and the nival zones in the Tianshan and Qilian mountains would shrink back to the mountaintops in

response to the projected increase in temperature and precipitation (Tables 5 and 7; Figs. 2 and 3). HadCM3 predicted a faster rate of shrinking than did HadCM2. Except for desert and desert scrub, warm temperate HLZ and subtropical HLZ types currently are distributed south of the Yangtze River, while they would cross the Yangtze River and shift towards the north in the 21st century. Tropical dry and tropical moist forests would expand from the southeastern coastal area towards the north, with HadCM3 predicting a faster expansion rate than HadCM2. Arid HLZ types, such as warm temperate desert scrub and warm temperate thorn steppe, would increase continuously, which means that desertification might become a more serious problem in the 21st century in China. The area of arid and cold HLZ types would gradually decrease and be replaced by HLZ types characteristic of arid and warm environments, such as warm temperate desert scrub, warm temperate thorn steppe and warm temperate dry forest.

Nival areas, cool temperate moist forest, warm temperate moist forest, subtropical moist forest and boreal wet forest would be the five HLZ types with the biggest area according to both HadCM2 and HadCM3. The combined area of these five HLZ types would be greater than 50% of China's land mass. Among these five HLZ types, nival areas and warm temperate moist and boreal wet forests would decrease continuously by 38 million ha, 43 million ha and 16 million ha, respectively, during the four periods, while subtropical moist and cool tem-

Table 5 – Area (million ha) change of each Holdridge Life Zone type predicted by HadCM2

Code	HLZ type (name)	From T1 to T2		From T2 to T3		From T3 to T4	
		Increase in area	Rate of increase (%)	Increase in area	Rate of increase (%)	Increase in area	Rate of increase (%)
1	Nival	–15.2748	–10.1662	–12.5495	–9.2976	–10.2024	–8.3335
2	Alpine dry tundra	0.0817	4.2751	–1.0948	–54.9617	–0.1400	–15.6054
3	Alpine moist tundra	–0.2084	–5.9160	–0.3540	–10.6837	–0.7986	–26.9838
4	Alpine wet tundra	0.5189	5.6195	0.7824	8.0223	0.4289	4.0711
5	Alpine rain tundra	0.8776	1.9923	2.8376	6.3161	1.1541	2.4161
6	Boreal desert	–1.7499	–21.2800	–2.5009	–38.6341	–0.8724	–21.9611
7	Boreal dry scrub	–0.5971	–8.4723	–0.2860	–4.4340	–0.4011	–6.5069
8	Boreal moist forest	–7.0228	–33.2594	–0.2385	–1.6923	–1.0624	–7.6690
9	Boreal wet forest	–11.1653	–17.4288	0.1598	0.3021	–4.5746	–8.6221
10	Boreal rain forest	1.1594	3.0887	0.8188	2.1158	2.7629	6.9917
11	Cool temperate desert	–4.5110	–13.0156	–2.3983	–7.9553	–2.5303	–9.1184
12	Cool temperate scrub	–1.9298	–5.6253	–0.0339	–0.1047	–3.8504	–11.9053
13	Cool temperate steppe	–1.4826	–2.8139	–0.3640	–0.7108	–3.8737	–7.6192
14	Cool temperate moist forest	16.5762	15.8555	5.9123	4.8813	2.8157	2.2165
15	Cool temperate wet forest	–0.8822	–1.8894	–5.8545	–12.7802	–1.2334	–3.0871
16	Cool temperate rain forest	0.6139	12.1046	1.2532	22.0443	0.8493	12.2405
17	Warm temperate desert	3.7420	7.2346	–9.1935	–16.5754	–0.5162	–1.1155
18	Warm temperate desert scrub	3.0250	34.4243	2.9430	24.9146	2.6704	18.0978
19	Warm temperate thorn steppe	3.5236	130.9873	6.7264	108.2541	3.8636	29.8579
20	Warm temperate dry forest	4.0924	19.8886	8.8578	35.9067	6.7022	19.9907
21	Warm temperate moist forest	–16.5982	–14.0341	–12.4523	–12.2475	–14.4056	–16.1460
22	Warm temperate wet forest	–0.3310	–5.1168	3.7493	61.0852	1.3634	13.7895
24	Subtropical desert			0.1200		1.6500	1374.9999
25	Subtropical desert scrub	0.4300		2.2200	516.2791	1.3400	50.5660
26	Subtropical thorn woodland	–0.0200	–2.9412	0.3500	53.0303	0.4300	42.5743
27	Subtropical dry forest	3.1096	7.5737	–23.3029	–52.7606	–4.3540	–20.8682
28	Subtropical moist forest	19.4801	30.6498	22.3265	26.8873	18.1700	17.2451
29	Subtropical wet forest	–0.0105	–18.9094	0.9261	2053.3004	0.6699	68.9715
31	Tropical desert	0.6700	9.9851	–1.2800	–17.3442	–0.7000	–11.4754
34	Tropical very dry forest	1.9644	168.7180	–1.9405	–62.0214	–0.0313	–2.6353
35	Tropical dry forest	1.9242	71.0757	13.8171	298.3252	4.6747	25.3387
36	Tropical moist forest	–0.0066	–30.3427	0.0432	285.8839	–0.0067	–11.5440
37	Tropical wet forest					0.0075	

perate forests would increase continuously by 60 million ha and 25 million ha, respectively (Figs. 6 and 7; Tables 4 and 6). These changes would alter terrestrial ecosystem services in China considerably.

In terms of the mean-center model, the shift ranges of HLZ types would be markedly greater based on the simula-

tion using HadCM3 data compared with HadCM2, in general. The results from both HadCM2 and HadCM3 showed that boreal wet forest, subtropical moist forest, tropical dry forest, warm temperate moist forest and subtropical wet forest would have a bigger shift range, indicating that these HLZ types are more sensitive to the climate change scenarios simulated by

Fig. 6 – Area change of each Holdridge Life Zone type predicted by HadCM2 for the periods 1961–1990 (T1), 2010–2039 (T2), 2040–2069 (T3) and 2070–2099 (T4).

Table 6 – Area (million ha) of each Holdridge Life Zone type predicted by HadCM3

Code	HLZ type	T1	T2	T3	T4	Average
1	Nival	133.3525	109.2512	68.5638	30.7545	85.4805
2	Alpine dry tundra	0.41	0.3619	0.3026	0.17	0.3111
3	Alpine moist tundra	2.806	2.0166	1.5161	1.04	1.8447
4	Alpine wet tundra	9.1413	7.0844	5.1115	4.4639	6.4503
5	Alpine rain tundra	60.4742	66.7798	67.9223	54.2776	62.3635
6	Boreal desert	3.0052	1.4068	0.84	0.6271	1.4698
7	Boreal dry scrub	8.9302	5.6615	3.7826	2.8178	5.298
8	Boreal moist forest	15.549	13.761	11.3866	9.1018	12.4496
9	Boreal wet forest	86.3131	65.0367	55.8743	53.759	65.2458
10	Boreal rain forest	25.9707	30.2383	37.0423	48.8282	35.5199
11	Cool temperate desert	44.7555	33.0334	17.9614	5.2283	25.2446
12	Cool temperate scrub	39.2906	36.1426	21.8211	9.7506	26.7512
13	Cool temperate steppe	45.5211	49.6304	41.2574	29.2733	41.4206
14	Cool temperate moist forest	140.4889	165.2606	176.1198	161.4196	160.8222
15	Cool temperate wet forest	42.2757	37.5041	40.6728	42.8885	40.8353
16	Cool temperate rain forest	0.377	0.8416	2.2847	4.4949	1.9996
17	Warm temperate desert	22.3657	16.5007	32.9674	26.3792	24.5532
18	Warm temperate desert scrub	13.8142	24.6593	37.5161	46.405	30.5986
19	Warm temperate thorn steppe	7.32	18.0248	26.5009	41.4475	23.3233
20	Warm temperate dry forest	33.0814	39.9026	39.9059	54.7349	41.9062
21	Warm temperate moist forest	139.2936	122.7745	84.6871	51.4013	99.5391
22	Warm temperate wet forest	7.6439	9.1917	8.9468	14.2244	10.0017
24	Subtropical desert			0.1	10.8677	2.7419
25	Subtropical desert scrub			1.93	9.2279	2.7895
26	Subtropical thorn woodland			2.88	4.02	1.725
27	Subtropical dry forest	0.0005			8.3364	2.0842
28	Subtropical moist forest	61.5946	85.4271	139.3057	186.4402	118.1919
29	Subtropical wet forest	3.0251	4.531	12.4354	13.5458	8.3843
31	Tropical desert	0.02	0.01	0.07	0.15	0.0625
35	Tropical dry forest		0.046	0.0352	0.2696	0.0877
36	Tropical moist forest	2.5151	4.2539	9.5889	22.9878	9.8364
37	Tropical wet forest	0.0482	0.0511	0.0538	0.0503	0.0508

HadCM2 and HadCM3 (Tables 2 and 3; Figs. 4 and 5). The continuous shift of both boreal dry and cool temperate scrubs towards the northwest in the 21st century means that the HLZ types present in arid environments would move towards the northwest in response to the projected temperature and precipitation increase in northwest China. Mean centers of alpine moist tundra and cool temperature wet forest would shift towards the north in general, possibly because of the

areal expansion of the two HLZ types in the high mountains of northern China and the precipitation increase in northern China. HLZ types in cold and frigid environments, such as alpine moist tundra, would be replaced by other HLZ types, such as boreal wet forest, such that the relative ratio of boreal forest in Qinghai-Xizang Plateau to that in the Da Hinggan, Xiao Hinggan and Changbai mountains would increase in the 21st century because of temperature and precipitation

Fig. 7 – Area change of each Holdridge Life Zone type predicted by HadCM3 for the periods 1961–1990 (T1), 2010–2039 (T2), 2040–2069 (T3) and 2070–2099 (T4).

Table 7 – Area (million ha) change of each Holdridge Life Zone type predicted by HadCM3

Code	HLZ type (name)	From T1 to T2		From T2 to T3		From T3 to T4	
		Increase in area	Rate of increase (%)	Increase in area	Rate of increase (%)	Increase in area	Rate of increase (%)
1	Nival	–24.1013	–18.0734	–40.6874	–37.2421	–37.8093	–55.1447
2	Alpine dry tundra	–0.0481	–11.7292	–0.0593	–16.3959	–0.1326	–43.8149
3	Alpine moist tundra	–0.7893	–28.1312	–0.5005	–24.8210	–0.4761	–31.4013
4	Alpine wet tundra	–2.0570	–22.5020	–1.9728	–27.8476	–0.6476	–12.6693
5	Alpine rain tundra	6.3056	10.4270	1.1426	1.7109	–13.6447	–20.0887
6	Boreal desert	–1.5984	–53.1889	–0.5668	–40.2881	–0.2129	–25.3425
7	Boreal dry scrub	–3.2686	–36.6020	–1.8790	–33.1886	–0.9647	–25.5050
8	Boreal moist forest	–1.7880	–11.4991	–2.3744	–17.2545	–2.2848	–20.0658
9	Boreal wet forest	–21.2764	–24.6502	–9.1624	–14.0881	–2.1153	–3.7858
10	Boreal rain forest	4.2676	16.4323	6.8039	22.5010	11.7859	31.8174
11	Cool temperate desert	–11.7221	–26.1914	–15.0720	–45.6267	–12.7331	–70.8914
12	Cool temperate scrub	–3.1480	–8.0121	–14.3214	–39.6249	–12.0705	–55.3156
13	Cool temperate steppe	4.1092	9.0271	–8.3729	–16.8706	–11.9841	–29.0471
14	Cool temperate moist forest	24.7717	17.6325	10.8592	6.5709	–14.7002	–8.3467
15	Cool temperate wet forest	–4.7716	–11.2870	3.1687	8.4490	2.2157	5.4477
16	Cool temperate rain forest	0.4646	123.2441	1.4430	171.4528	2.2103	96.7429
17	Warm temperate desert	–5.8650	–26.2231	16.4667	99.7936	–6.5882	–19.9840
18	Warm temperate desert scrub	10.8451	78.5071	12.8568	52.1379	8.8889	23.6935
19	Warm temperate thorn steppe	10.7048	146.2401	8.4760	47.0243	14.9467	56.4008
20	Warm temperate dry forest	6.8213	20.6196	0.0033	0.0083	14.8289	37.1598
21	Warm temperate moist forest	–16.5191	–11.8592	–38.0873	–31.0222	–33.2858	–39.3044
22	Warm temperate wet forest	1.5478	20.2485	–0.2449	–2.6641	5.2775	58.9878
24	Subtropical desert			0.1000		10.7677	10767.7306
25	Subtropical desert scrub			1.9300		7.2979	378.1307
26	Subtropical thorn woodland			2.8800		1.1400	39.5835
27	Subtropical dry forest	–0.0005	–100.0000			8.3364	
28	Subtropical moist forest	23.8325	38.6926	53.8785	63.0695	47.1345	33.8353
29	Subtropical wet forest	1.5058	49.7769	7.9045	174.4548	1.1104	8.9295
31	Tropical desert	–0.0100	–50.0000	0.0600	600.0000	0.0800	114.2857
35	Tropical dry forest	0.0460		–0.0107	–23.3423	0.2343	665.0298
36	Tropical moist forest	1.7388	69.1370	5.3350	125.4138	13.3989	139.7329
37	Tropical wet forest	0.0029	6.1032	0.0027	5.3724	–0.0036	–6.6411

increases in Qinghai-Xizang Plateau. This would lead to a considerable shift of the mean center of boreal forest towards the southwest.

Results from the operating diversity index and the patch connectivity index for data corresponding to Figs. 2 and 3 show that HLZ diversity and patch connectivity would increase continuously during the four periods. The increase rates of HLZ diversity and patch connectivity according to HadCM2 would be 0.22% and 0.14%, respectively, per decade on average; the corresponding rates according to HadCM3 would be 0.38% and 0.42%, respectively, per decade. In short, climate change would have a considerable impact on the spatial pattern of terrestrial ecosystems in China in the 21st century.

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REFERENCES

- Collins, M., Tett, S.F.B., Cooper, C., 2001. The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments. *Climate Dyn.* 17, 61–81.
- Cox, P.M., Betts, R.A., Bunton, C.B., Essery, R.L.H., Rowntree, P.R., Smith, J., 1999. The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Climate Dyn.* 15, 183–203.
- Giorgi, F., 2002. Variability and trends of sub-continental scale surface climate in the twentieth century. Part II: AOGCM simulations. *Climate Dyn.* 18, 693–708.
- Holdridge, L.R., Grenke, W.C., Hatheway, W.H., Liang, T., Tosi Jr., J.A., 1971. *Forest Environments in Tropical Life Zones: A Pilot Study*. Pergamon Press, Oxford.
- Johns, T.C., Gregory, J.M., Ingram, W.J., Johnson, C.E., Jones, A., Lowe, J.A., Mitchell, J.F.B., Roberts, D.L., Sexton, D.M.H., Stevenson, D.S., Tett, S.F.B., Woodage, M.J., 2003. Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. *Climate Dyn.* 20, 583–612.
- Mitchell, J.F.B., Johns, T.C., Gregory, J.M., Tett, S.F.B., 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosol. *Nature* 376, 501–504.

- Yue, T.X., Du, Z.P., 2005. High precision surface modeling: a core module of new generation GIS and CAD. *Prog. Nat. Sci.* 15, 73–82 (in Chinese).
- Yue, T.X., Fan, Z.M., Liu, J.Y., 2005. Changes of major terrestrial ecosystems in China since 1960. *Global Planet. Change* 48, 287–302.
- Yue, T.X., Haber, W., Grossmann, W.D., Kasperidus, H.D., 1998. Towards the satisfying model for biological diversity. *Ekologia* 17 (Suppl. 1), 129–141.
- Yue, T., Liu, J., Jørgensen, S.E., Gao, Z., Zhang, S., Deng, X., 2001. Changes of Holdridge life zone diversity in all of China over a half century. *Ecol. Model.* 144, 153–162.
- Yue, T.X., Liu, J.Y., Jørgensen, S.E., Ye, Q.H., 2003. Landscape change detection of the newly created wetland in Yellow River Delta. *Ecol. Model.* 164, 21–31.
- Yue, T.X., Xu, B., Liu, J.Y., 2004. A patch connectivity index and its change on a newly born wetland at the Yellow River Delta. *Int. J. Remote Sensing* 25, 4617–4628.