Scenarios of land cover in China

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Abstract

A method for surface modeling of land cover change (SMLC) is developed on the basis of establishing transition probability matrixes between land cover types and HLZ types. SMLC is used to simulate land cover scenarios of China for the years 2039, 2069 and 2099, for which HLZ scenarios are first simulated in terms of HadCM3 climatic scenarios that are downscaled in zonal model of spatial climate change in China. This paper also analyzes spatial distribution of land cover types, area change and mean center shift of each land cover type, ecotope diversity, and patch connectivity under the land cover scenarios. The results show that cultivated land would decrease and woodland would expand greatly with climatic change, which coincides with consequences expected by implementation of Grain-for-Green policy. Nival area would shrink, and desertification area would expand at a comparatively slow rate in future 100 years. Climate change would generally cause less ecotope diversity and more patch connectivity. Ecosystems in China would have a pattern of beneficial cycle after efficient ecological conservation and restoration. However, if human activities would exceed regulation capacity of ecosystems themselves, the ecosystems in China might deteriorate more seriously.

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1. Introduction

Land cover refers to biophysical earth surface, which is a fundamental variable that impacts on and links many parts of the human and physical environments (Geist and Lambin, 2002; Foody, 2002). Land cover change has significant effects on biogeochemical cycling, soil erosion, ecological diversity, sustainable land use and climate change (Chapin et al., 2000). Land cover change affects the ability of biological systems to support human needs by altering ecosystem services (Vitousek et al., 1997).

In recent years, land cover change in China has been studied by combining remotely sensed data and geophysical data such as annual mean temperature, annual precipitation and elevation (Liu et al., 2002, 2003a,b, 2005). The research results showed that both grassland and woodland decreased respectively by more than 13,000 km², cultivated land increased by 15,860 km², and built-up land increased by 5330 km² during the period from 1995 to 2000. The land cover change resulted in rapid desertification expansion. The expansion rate of desertification land was yearly 10,400 km² during the period from 1995 to 2000. There were 2.6844 million km² of desertification land in 2000 in China.

In terms of natural process, climatic change, such as precipitation, temperature and evapotranspiration, forces land cover changes (Fu, 2003). Simulation results (Fig. 1), which are based on observation data of 735

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Fig. 1. Climatic change during the period from 1971 to 2000 (Left map: annual mean temperature; Middle map: annual precipitation; Right map: annual evapo-transpiration).

meteorological stations scattered over China during the period from 1971 to 2000 and lapse rate of temperature in different regions of China (Yue et al., 2005a), show that both temperature and precipitation had a continuously increasing trend in the period from 1971 to 2000 on an average. The increase rates of temperature and precipitation were respectively 0.18 °C and 12 mm per decade. The potential evapotranspiration ratio had an up and down increasing trend and the increase rate was 0.01 per decade on an average.

A method of surface modeling of land cover change (SMLC) is developed in this paper. The SMLC is used to simulate land cover scenarios for the years 2039, 2069 and 2099 in China under the assumption of human activities following the natural process.

2. Methods

2.1. HadCM3 climatic scenarios

In early 1990s, the Intergovernmental Panel on Climate Change (IPCC) developed emission scenarios, which were subsequently used to drive climate models and determine the impacts of climate change. The IS92 family of scenarios (Leggett et al., 1992) was particularly widely used, among which IS92a is usually taken as a reference scenario (Nakićenović et al., 2000). In 2000, the IPCC's Special Report on Emissions Scenarios (SRES) was published (IPCC, 2000). Six SRES marker scenarios were defined, which are from A1FI, A1T, A1B, A2, B1 and B2 experiments. They contain more recent driving force data for emissions than the IS92 family and were constructed in a fundamentally different way (Arnell et al., 2004).

HadCM3, the third version of the Hadley Center coupled model, requires no flux adjustment and has a stable climate in the global mean (Collins et al., 2001). The HadCM3 climatic scenarios, to be used in this paper, were developed by A1FI, A2 and B2 experiments (Johns et al., 2003). The A1 scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies; the A1 scenario family develops into three groups and its A1FI group describes that technological change in the energy system is fossil intensive (Watson et al., 2001). The A2 storyline and scenario family describes a very heterogeneous world with more rapid population growth but less rapid economic growth than A1, which is self-reliance and preservation of local identities. The B2 describes a world, in which population increases at a lower rate than

A2 and the emphasis is on local solutions to economic, social, and environmental sustainability. In the HadCM3A1FI and HadCM3A2 scenario, greenhouse gas emissions eventually increase faster than in IS92a, whereas in B2, CO₂ emissions are lower than under IS92a. In HadCM3A1FI, and especially HadCM3A2, sulfur emissions increase but then decrease, whereas in HadCM3B2 sulfur emissions decrease throughout the twenty first century. According to these three scenarios, in the next two decades global-mean warming rate would be similar to that seen in recent decades. However, the global-mean warming in HadCM3A1FI and HadCM3A2 would be noticeably greater than in HadCM3B2 by the middle of the twenty first century, and would be greater than in IS92a by the end of the century (Johns et al., 2003).

The three HadCM3 climatic scenarios have been downscaled in zonal model of spatial climate change in China (Yue et al., 2005a). The downscaled results show that temperature, precipitation, and potential evapotranspiration ratio would all increase in future 100 years. According to HadCM3A1FI, the increase rates of temperature, precipitation, and potential evapotranspiration ratio would be 0.31 °C, 14 mm and 0.009 per decade respectively (Fig. 2); according to HadCM3A2, the increase rates would be 0.25 °C, 19 mm and 0.007 per decade (Fig. 3); according to HadCM3B2, the increase rate would be 0.19 °C, 9 mm and 0.003 per decade (Fig. 4).

2.2. Surface modeling of land cover scenarios

2.2.1. HLZ classification

Holdridge Life Zone (HLZ) classification is a scheme that uses the three bioclimatic variables derived from standard meteorological data to formulate the relation of climate patterns and broad-scale vegetation distribution (Holdridge, 1947). 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 in terms of mean annual biotemperature in degrees centigrade (MAB), average total annual precipitation in millimeters (TAP), and potential evapotranspiration ratio (PER) logarithmically (Holdridge, 1964). 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

Fig. 2. Climate change in terms of HadCM3A1FI scenarios in future 100 years (Left map: annual mean temperature; Middle map: annual precipitation; Right map: annual evapo-transpiration).

Fig. 3. Climate change in terms of HadCM3A2 scenarios in future 100 years (Left map: annual mean temperature; Middle map: annual precipitation; Right map: annual evapo-transpiration).

Fig. 4. Climate change in terms of HadCM3B2 scenarios in future 100 years (Left map: annual mean temperature; Middle map: annual precipitation; Right map: annual evapo-transpiration).

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.

Daily temperature and precipitation data from 1971 to 2000 were selected from 735 weather stations that are scattered over China. After comparatively analyzing relative interpolation methods, high accuracy surface modeling (HASM) was applied to create annual mean bio-temperature, precipitation and potential evapotranspiration ratio surfaces during the period from 1971 to 2000 on an average (Yue et al., 2004a; Yue and Du, 2005). Digital elevation model of China was combined with the Holdridge Life Zone (HLZ) model on the basis of simulating relationships between temperature and elevation in different regions of China (Yue et al., 2005a). HLZ ecosystem classification was created by operating the HLZ model on the created surfaces. The HLZ ecosystems were distinguished into 28 types that are nival area, alpine dry tundra, alpine moist tundra, alpine wet tundra, alpine rain tundra, boreal desert, boreal dry scrub, boreal moist forest, boreal wet forest, boreal rain forest, cool temperate desert, cool temperate scrub, cool temperate steppe, cool temperate moist forest, cool temperate wet forest, warm temperate desert, warm temperate desert scrub, warm temperate thorn steppe, warm temperate dry forest, warm temperate moist forest, warm temperate wet forest, subtropical desert, subtropical thorn woodland, subtropical dry forest, subtropical moist forest, subtropical wet forest, tropical desert, tropical dry forest and tropical moist forest.

temperate moist forest, cool temperate wet forest, warm temperate desert, warm temperate desert scrub, warm temperate thorn steppe, warm temperate dry forest, warm temperate moist forest, warm temperate wet forest, subtropical thorn woodland, subtropical dry forest, subtropical moist forest, subtropical wet forest, tropical desert, tropical dry forest and tropical moist forest (Fig. 5).

2.2.2. Land cover classification

Land cover classification in China was conducted by a combination of remotely sensed data from Advanced Very High Resolution Radiometer (AVHRR) and geophysical data sets (Liu et al., 2003a). The geophysical data sets include annual mean temperature, annual precipitation and elevation. China was first divided into 9 bioclimatic regions by using the long-term mean climatic data. For each of the 9 regions, AVHRR data, AVHRR-derived normalized difference vegetation index and the geophysical data were analyzed to generate a land cover map. The 9 land cover maps for individual regions were assembled together for the whole China. An existing land cover data set derived from Landsat Thematic Mapper (TM) images was used to assess the accuracy of the classification based on

Fig. 5. HLZ types in China during the period from 1971 to 2000 on an average.

AVHRR and geophysical data. The accuracy of individual regions varied from 73% to 89%, with an overall accuracy of 81% for the whole China. The land cover types include cultivated land, woodland, grassland, built-up land, water area, wetland, nival area, desert, bare rock and desertification land (Fig. 6).

2.2.3. Transition probability matrixes

For establishing the transition probability matrix between HLZ types in T_1 on an average and land cover types in 2000 (Table 1), in which T_1 represents the period from the year 1971 to 2000, it is essential to develop a grid-oriented code matrix. The code of grid (i, j) is formulated as,

$$C_{i,j}^{2000} = 1000A_{i,j}^{2000} + A_{i,j}^{T_1} \quad (1)$$

where $C_{i,j}^{2000}$ is the code of element (i, j) of the grid-oriented code matrix for the transition probability matrix; $A_{i,j}^{2000}$ is type code of land cover at grid (i, j) in 2000; $A_{i,j}^{T_1}$ is type code of HLZ ecosystem at grid (i, j) in T_1 .

To build land cover scenarios in the year of 2039, another new grid-oriented code matrix for transition

probability matrix from HLZ ecosystem types in T_1 and T_2 to land cover types in 2039 is established, in which T_2 represents the period from the year 2010 to 2039. The code of grid (i, j) is formulated as,

$$C_{i,j}^{2039} = 1000A_{i,j}^{T_1} + A_{i,j}^{T_2} \quad (2)$$

where $C_{i,j}^{2039}$ is the code of element (i, j) of the grid-oriented code matrix for land cover scenarios in 2039; $A_{i,j}^{T_1}$ is type code of HLZ ecosystem at grid (i, j) in T_1 ; $A_{i,j}^{T_2}$ is type code of HLZ ecosystems at grid (i, j) in T_2 .

In the process of building land cover scenarios in 2039, if HLZ type at grid (i, j) would have no change during the period from T_1 to T_2 , land cover type at grid (i, j) in 2039 would be assigned as the same one as in 2000. If the HLZ type at grid (i, j) would convert from type K to type L , land cover type at grid (i, j) in 2039 would be assigned as the one that has a maximum transition probability to HLZ type L in 2000.

Similarly, land cover scenarios in the years of 2069 and 2099 are built by establishing grid-oriented code matrixes for transition probability matrixes from HLZ

Fig. 6. Land cover map of China in 2000.

Table 1

Transition probability matrix from HLZ types in T_1 on an average to land cover types in 2000

HLZ type	Land cover type									
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land
Nival	0.0004	0.0009	0.4717	0	0.0155	0.0018	0.0488	0.0006	0.2638	0.1089
Alpine dry tundra	0.0003	0.0231	0.6034	0	0.0049	0	0.0053	0.0163	0.0461	0.3007
Alpine moist tundra	0.0008	0.0767	0.7295	0	0.0304	0	0.0110	0.0047	0.0244	0.1226
Alpine wet tundra	0.0041	0.1694	0.6816	0	0.0339	0.0001	0.0077	0	0.0790	0.0243
Alpine rain tundra	0.0099	0.4694	0.4258	0	0.0084	0.0061	0.0057	0	0.0510	0.0238
Boreal desert	0.0043	0.0206	0.2970	0.0001	0.0084	0	0.0027	0.0296	0.0588	0.5785
Boreal dry scrub	0.0457	0.0671	0.6012	0.0001	0.0127	0	0.0026	0.0136	0.0096	0.2474
Boreal moist forest	0.0431	0.4317	0.4526	0.0006	0.0333	0.0095	0.0020	0.0003	0.0161	0.0109
Boreal wet forest	0.0402	0.6631	0.2490	0.0001	0.0051	0.0030	0.0026	0	0.0188	0.0182
Boreal rain forest	0.1388	0.5341	0.3222	0	0	0.0022	0	0	0.0010	0.0017
Cool temperate desert	0.0326	0.0020	0.0644	0.0006	0.0044	0	0.0001	0.2007	0.0370	0.6582
Cool temperate scrub	0.1097	0.0047	0.3718	0.0015	0.0041	0.0001	0	0.0786	0.0051	0.4245
Cool temperate steppe	0.3285	0.1013	0.4954	0.0030	0.0090	0.0178	0.0001	0	0.0007	0.0443
Cool temperate moist forest	0.3240	0.5083	0.1301	0.0047	0.0060	0.0239	0.0001	0	0.0008	0.0021
Cool temperate wet forest	0.1740	0.6697	0.1546	0.0001	0	0	0	0	0	0.0015
Warm temperate desert	0.0249	0.0001	0.0292	0.0002	0.0040	0	0	0.5098	0.0276	0.4042
Warm temperate desert scrub	0.0878	0.0004	0.1710	0.0012	0.0082	0	0	0.1442	0	0.5873
Warm temperate thorn steppe	0.2264	0.4831	0.1876	0.0018	0.0022	0	0	0	0	0.0988
Warm temperate dry forest	0.7009	0.1864	0.0751	0.0139	0.0114	0.0114	0	0	0	0.0009
Warm temperate moist forest	0.4152	0.4971	0.0569	0.0055	0.0252	0.0001	0	0	0	0.0001
Warm temperate wet forest	0.1169	0.8516	0.0290	0.0005	0.0020	0	0	0	0	0
Subtropical thorn woodland	0.0045	0.9676	0	0	0.0020	0	0	0	0	0.0259
Subtropical dry forest	0.3905	0.5177	0.0630	0.0136	0.0086	0	0	0	0	0.0065
Subtropical moist forest	0.3446	0.6009	0.0287	0.0137	0.0121	0	0	0	0	0
Subtropical wet forest	0.2012	0.7888	0	0.0101	0	0	0	0	0	0
Tropical desert	0.0008	0	0.0044	0	0.0007	0	0	0.1351	0.0191	0.8399
Tropical dry forest	0.4083	0.1429	0.4365	0.0079	0.0044	0	0	0	0	0
Tropical moist forest	0.4894	0.3384	0	0.0725	0.0997	0	0	0	0	0

types in T_2 and T_3 to land cover types in 2069 and from T_3 and T_4 to 2099, in which T_3 represents the period from the year 2040 to 2069 and T_4 from 2070 to 2099. The codes of grid (i, j) in the years 2069 and 2099 are respectively formulated as,

$$C_{i,j}^{2069} = 1000A_{i,j}^{T_2} + A_{i,j}^{T_3} \quad (3)$$

and

$$C_{i,j}^{2099} = 1000A_{i,j}^{T_3} + A_{i,j}^{T_4} \quad (4)$$

where $C_{i,j}^{2069}$ and $C_{i,j}^{2099}$ are respectively the codes of element (i, j) of the grid-oriented code matrix for land cover scenarios in 2069 and in 2099; $A_{i,j}^{T_k}$ is type code of HLZ ecosystem at grid (i, j) in T_k , $k=2, 3$ and 4.

2.3. Models related to spatial pattern of land cover

The models relative to spatial pattern include ecological diversity index, patch connectivity index, mean center model, and shift distance and direction of

land cover types. The ecological diversity index is formulated as (Yue et al., 2001, 2003),

$$d(t) = -\frac{\ln\left(\sum_{i=1}^{m(\varepsilon)} (p_i(t))^{\frac{1}{\varepsilon}}\right)^2}{\ln(\varepsilon)} \quad (5)$$

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

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

$$CO(t) = \sum_{i=1}^{m(t)} \sum_{j=1}^{n_i(t)} p_{ij}(t) \cdot S_{ij}(t) \quad (6)$$

where t is the variable of time; $p_{ij}(t) = \frac{A_{ij}(t)}{A}$, $A_{ij}(t)$ the area of the j th patch in the i th HLZ type and A the total

area under investigation; $S_{ij}(t) = 8 \frac{\sqrt{3} \cdot A_{ij}(t)}{(\text{Pr}_{ij}(t))^2}$, $\text{Pr}_{ij}(t)$ is the perimeter of the j th patch in the i th HLZ type and $8\sqrt{3}$ the ratio of the square of perimeter to the area of a hexagon; $0 \leq C(t) \leq 1.1$ and when all patches have the shape of hexagon (6-gon), $C(t) = 1.0$.

The mean center model is formulated as (Yue et al., 2005a),

$$x_j(t) = \sum_{i=1}^{I_j(t)} \frac{A_{ij}(t) \cdot X_{ij}(t)}{A_j(t)} \quad (7)$$

$$y_j(t) = \sum_{i=1}^{I_j(t)} \frac{A_{ij}(t) \cdot Y_{ij}(t)}{A_j(t)} \quad (8)$$

where t is the variable of time; $I_j(t)$ is patch number of land cover type j ; $A_{ij}(t)$ is area of the i th patch of land cover type j ; $A_j(t)$ is total area of land cover type j ; $(X_{ij}(t), Y_{ij}(t))$ is latitude and longitude coordinate of the geometric center of the i th patch of land cover type j ; $(x_j(t), y_j(t))$ is the mean center of land cover type j .

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

$$D_j = \sqrt{(x_j(t+1) - x_j(t))^2 + (y_j(t+1) - y_j(t))^2} \quad (9)$$

$$\theta_j = \arctg\left(\frac{y_j(t+1) - y_j(t)}{x_j(t+1) - x_j(t)}\right) \quad (10)$$

where D_j is shift distance of land cover type j in the period from t to $t+1$; $t=0, 1$ and 2 represent respectively the years of 2000, 2039 and 2069 in this paper; θ_j is the shift direction of land cover type j , which due east is 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 coordinate of the mean center of land cover type j in the years t and $t+1$. When $0^\circ < \theta_j < 90^\circ$, it is stated that land cover type j shifts towards northeast during the period from t to $t+1$; when $90^\circ < \theta_j < 180^\circ$, land cover type j shifts towards northwest; when $180^\circ < \theta_j < 270^\circ$, land cover type j shifts towards southwest; when $270^\circ < \theta_j < 360^\circ$ land cover type j shifts towards southeast.

3. Results and analyses

3.1. Spatial distribution of land cover types

In terms of land cover scenarios based on HadCM3A1FI, HadCM3A2 and HadCM3B2, which are respectively termed as scenario I, scenario II and Scenario III, spatial distribution of land cover types

would have a very apparent regional variety in China (Figs. 7, 8 and 9) because of the regional difference on spatial hydrothermal distribution, the influence of the continental monsoon climate and the human activities.

In future 100 years, the cultivated land in China would be in principle divided into two production areas, agricultural region and livestock farming region, which take the curve linking Da-Xiao Hinggan Mountains, Yulin, Lanzhou, the east Qinghai-Xizang Plateau and its southeast edge as their border (Figs. 10 and 11). Cultivated land would centrally be distributed in northeast plain, north China plain, middle and lower reaches of Yangtze river, Sichuan basin, central Shaanxi plain, Hexi corridor in Gansu province, and alluvial fan areas on the north and the south of Tianshan mountains. In addition, a great quantity of cultivated land would be scattered on hilly areas in the south of China.

The complicated terrain characteristics and heterogeneous climate lead to great difference of spatial woodland distribution. Woodland in northeast China would mainly be distributed in Da-Xiao Hinggan Mountains, Changbai Mountains and East Liaoning Basin; in southwestern China, woodland would mainly be distributed in areas of Himalaya Mountains and Hengduan Mountains in the east and south of Yalu Tsangpo river in Tibet, mountainous range around Sichuan basin, Yunnan-Guizhou plateau and most hilly areas in Guangxi. In southeastern China, woodland would mainly be distributed in the low mountainous and hilly areas such as Wuyi Mountains, Nanling ridges and Taiwan Mountains. In northwestern China, the woodland would mainly be distributed in the mountainous areas of Tianshan Mountain, Altai Mountains, Qilian Mountains, Ziwu Mountain, Helan Mountain, Liupan Mountain and Yinshan Mountain. In short, woodland in China would mainly be distributed in mountainous and hilly areas.

Grassland would mainly be distributed in western China and comparatively less in eastern China. Geographically, the grassland would mainly be distributed in Qinghai-Xizang Plateau, Inner Mongolia plateau, Loess Plateau, Tianshan Mountains, Altai Mountains and areas around Tarim Basin. In the meanwhile, some grassland would be scattered on hilly areas of Hunan, Hubei, Anhui, Fujian, Yunnan, Guizhou, Sichuan, Guangdong, Guangxi and Taiwan, which would mix with woodland.

Water areas include rivers and lakes (Yue et al., 2005b). Rivers can be divided into oceanic systems that discharge into oceans and inland ones that start in mountainous areas and disappear in conoplain or flow into inland lakes. The oceanic system can be subdivided into Pacific, Indian and Arctic drainage basins,

Fig. 7. Land cover scenarios I (Left map: land cover in 2039; Middle map: land cover in 2069; Right map: land cover in 2099).

Fig. 8. Land cover scenarios II (Left map: land cover in 2039; Middle map: land cover in 2069; Right map: land cover in 2099).

Fig. 9. Land cover scenarios III (Left map: land cover in 2039; Middle map: land cover in 2069; Right map: land cover in 2099).

Fig. 10. Major maintains and rivers in China.

accounting for 64% of the total land area in China. The inland system includes a few perennial rivers and has large tracts with no runoff, accounting for 36% of the total land area in China (Zhao, 1986). Five major lake regions can be identified, which are the northeast lake region, the northwest lake region, the Qinghai-Xizang lake region, the eastern lake region and the southwest lake region. They include 2800 natural lakes approximately, each with an area greater than 1 km² and many reservoirs that are artificial lakes.

Built-up land mainly be distributed in the areas near rivers or valleys, with abundant water resources, convenient traffic, fertile soil and plentiful products, which are determined by characteristics of urban development. Because of joint affection of various factors such as geographical features and social-economic conditions, in eastern China, built-up land would mainly be distributed in Northeast Plateau, North China Plain, Plain in the middle and lower reaches of Yangtze River, Yangtze River Delta and Pearl River Delta in the future 100 years. In western China, built-up land would mainly be distributed in Sichuan Basin, central Shaanxi plain, Hetao Plain in Ningxia, Hexi

Corridor in Gansu and Xinjiang Oasis. In mountainous, hilly and plateau areas, built-up land would mainly be distributed in provincial and prefectural capitals and other administrative areas.

Nival areas would mainly occur in mountainous ridges in Tianshan Mountains, Qilian Mountains, Kunlun Mountains, Himalaya Mountains and Hengduan Mountains. Deserts would mainly occur in Junggar Basin, Tarim Basin, Qaidam basin, Inner Mongolia Plateau. Bare rocks would mainly be distributed in Qinghai-Xizang Plateau, the east of Turpan Basin, and Karst area in the southwest China. Desertification land would mainly be distributed in outside areas of deserts and inside areas of meadows in northwestern China.

3.2. Area changes of land cover types

Land cover types, of which area would increase in all the periods from 2000 to 2039, from 2039 to 2069, and from 2069 to 2099 under all the three scenarios, include built-up land and desertification land. Area of woodland type would increase in all the three periods under all the scenarios except a decrease in the period from 2069 to

Fig. 11. Provinces and provincial capitals in China.

2099 under scenario I. Land cover types, of which area would decrease in all the three periods, include cultivated land, grassland and nival area. Area of water area type would decrease in all the three periods under all the three scenarios except an increase in the period from 2069 to 2099 under scenario I. During the period from 2000 to 2039, area of wetland type would decrease under all the three scenarios; from 2039 to

2069, area of wetland would increase under scenarios I and II, but decrease under scenario III; from 2069 to 2099, the one would increase under scenarios I and III, but decrease under scenario II. Under scenarios I and II, area of desert would increase during all the three periods; under scenario III, area of desert would decrease during the period from 2000 to 2039, but increase during other two periods. Under scenario III,

Table 2

Area change of land cover types under scenario I (units: million hectares)

Land cover type	2000–2039		2039–2069		2069–2099	
	Area	Change rate per decade (%)	Area	Change rate per decade (%)	Area	Change rate per decade (%)
Cultivated land	–10.40	–1.25	–0.10	–0.02	–2.80	–0.47
Woodland	30.33	3.08	14.35	1.73	–2.17	–0.25
Grassland	–15.12	–1.58	–2.55	–0.38	–12.51	–1.88
Built-up land	0.06	0.38	0.09	0.82	0.12	1.02
Water area	–1.38	–2.76	–1.14	–3.44	1.31	4.40
Wetland	–0.79	–3.50	0.24	1.67	0.37	2.41
Nival area	–0.48	–1.51	–1.28	–5.71	–0.09	–0.47
Desert	–1.57	–0.72	–2.06	–1.29	–10.09	–6.57
Bare rock	–4.67	–2.40	–11.70	–8.88	6.90	7.14
Desertification land	4.03	0.82	4.15	1.09	18.97	4.81

Table 3

Area change of land cover types under scenario II (units: million hectares)

Land cover type	2000–2039		2039–2069		2069–2099	
	Area	Change rate per decade (%)	Area	Change rate per decade (%)	Area	Change rate per decade (%)
Cultivated land	–9.1071	–1.0958	–0.6482	–0.1088	–0.9979	–0.1680
Woodland	18.1233	1.8412	19.1106	2.4110	13.7246	1.6147
Grassland	–6.4003	–0.6678	–18.9823	–2.7132	–12.7870	–1.9897
Built-up land	0.0329	0.2218	0.0256	0.2281	0.2974	2.6314
Water area	–0.8419	–1.6907	–0.1885	–0.5413	–0.0816	–0.2382
Wetland	–0.7863	–3.4703	0.4126	2.8193	–0.0830	–0.5229
Nival area	–0.3925	–1.2372	–0.2819	–1.2465	–0.6065	–2.7859
Desert	–2.2136	–1.0094	–1.4169	–0.8977	–4.7304	–3.0800
Bare rock	–4.0956	–2.1079	0.4787	0.3587	–2.5499	–1.8906
Desertification land	5.6811	1.1536	1.4903	0.3857	7.8143	1.9991

area of bare rock would decrease during all the three periods; under scenario II, area of bare rock would decrease during the periods from 2000 to 2039 and from 2069 to 2099, but increase during the period from 2039 to 2069 (Tables 2–4). Woodland would have the greatest increasing rate that would be 2.34% per decade; bare rock would have the biggest decreasing rate that would be 2.38% per decade.

In terms of the three scenarios of land cover, most land cover types would have similar change trends during the period from 2000 to 2099. Area of woodland would increase by 42.4984 million hectares under scenario I, 50.9585 million hectares under scenario II and 79.219 million hectares under scenario III. Desertification land would increase by 27.1433, 14.9857 and 4.2709 million hectares under scenarios I, II and III respectively. Built-up land would increase by 0.2679, 0.3559 and 0.5474 million hectares under scenarios I, II and III respectively. Grassland, cultivated land and nival area, which would continuously shrink in all the three

periods from 2000 to 2039, from 2039 to 2069 and from 2069 to 2099, would decrease respectively by 30.1825, 13.3035 and 1.8434 million hectares under scenario I, 38.1696, 10.7532 and 1.2809 million hectares under scenario II, and 42.3194, 20.0045 and 1.8873 million hectares under scenario III (Tables 5–7).

The land cover types that would have a greater transformation include cultivated land, woodland, grassland and desertification land. The cultivated land that would have been transformed would be mainly converted into woodland and the converting rate would become smaller and smaller gradually during the period from 2000 to 2099. The transformed woodland would be mainly converted into grassland. Most transformed grassland would be converted into woodland and a considerable part of the transformed grassland would be converted into desertification land. The transformed desertification land would mainly be converted into woodland and grassland (Tables 8–16).

Table 4

Area change of land cover types under scenario III (units: million hectares)

Land cover type	2000–2039		2039–2069		2069–2099	
	Area	Change rate per decade (%)	Area	Change rate per decade (%)	Area	Change rate per decade (%)
Cultivated land	–12.5179	–1.5062	–4.4783	–0.7645	–3.0083	–0.5256
Woodland	40.6009	4.1246	18.0856	2.1028	20.5325	2.2456
Grassland	–17.3510	–1.8104	–11.2941	–1.6939	–13.6743	–2.1606
Built-up land	0.1708	1.1513	0.0901	0.7741	0.2865	2.4057
Water area	–1.8839	–3.7833	–0.8936	–2.8194	–0.6227	–2.1462
Wetland	–1.2442	–5.4912	–0.4840	–3.6498	0.0094	0.0796
Nival area	–0.5556	–1.7513	–0.6185	–2.7953	–0.7132	–3.5183
Desert	–0.4983	–0.2272	1.7800	1.0921	2.9914	1.7772
Bare rock	–7.9193	–4.0759	–5.0308	–4.1248	–6.0301	–5.6423
Desertification land	1.1985	0.2434	2.8436	0.7624	0.2288	0.0600

Table 5

Land cover scenario I (units: million hectares)

	2000	2039	2069	2099	Area change	Change rate per decade (%)
Cultivated land	207.7798	197.3766	197.2751	194.4763	−13.3035	−0.64
Woodland	246.088	276.415	290.76	288.5864	42.4984	1.73
Grassland	239.6064	224.4831	221.9328	209.4239	−30.1825	−1.26
Built-up land	3.7088	3.7658	3.8587	3.9767	0.2679	0.72
Water area	12.4488	11.0736	9.9293	11.2399	−1.2089	−0.97
Wetland	5.6645	4.8706	5.1148	5.4843	−0.1802	−0.32
Nival area	7.9311	7.4511	6.1755	6.0877	−1.8434	−2.32
Desert	54.8258	53.2572	51.1949	41.1048	−13.721	−2.50
Bare rock	48.5742	43.9075	32.2088	39.1041	−9.4701	−1.95
Desertification land	123.123	127.1499	131.3005	150.2663	27.1433	2.20

Table 6

Land cover scenario II (units: million hectares)

	2000	2039	2069	2099	Area change	Change rate (%)
Cultivated land	207.7798	198.6727	198.0245	197.0266	−10.7532	−0.52
Woodland	246.088	264.2113	283.3219	297.0465	50.9585	2.07
Grassland	239.6064	233.2061	214.2238	201.4368	−38.1696	−1.59
Built-up land	3.7088	3.7417	3.7673	4.0647	0.3559	0.96
Water area	12.4488	11.6069	11.4184	11.3368	−1.112	−0.89
Wetland	5.6645	4.8782	5.2908	5.2078	−0.4567	−0.81
Nival area	7.9311	7.5386	7.2567	6.6502	−1.2809	−1.62
Desert	54.8258	52.6122	51.1953	46.4649	−8.3609	−1.52
Bare rock	48.5742	44.4786	44.9573	42.4074	−6.1668	−1.27
Desertification land	123.123	128.8041	130.2944	138.1087	14.9857	1.22

3.3. Ecotope diversity and patch connectivity of land cover

Ecotope diversity of land cover would have a decreasing trend, while patch connectivity would increase generally. Scenario I shows that, on an average, the decrease rate of the ecotope diversity would be 0.1604%

per decade and the increase rate of the patch connectivity would be 2.1591% per decade. Under scenario II, ecotope diversity would monotonically decrease and patch connectivity would monotonically increase; the decreasing rate of ecotope diversity would be 0.1176% per decade and the increasing rate of patch connectivity would be 2.1402% per decade. Under scenario III, the

Table 7

Land cover scenario III (units: million hectares)

	2000	2039	2069	2099	Area change	Change rate (%)
Cultivated land	207.7798	195.2619	190.7836	187.7753	−20.0045	−0.96
Woodland	246.088	286.6889	304.7745	325.307	79.219	3.22
Grassland	239.6064	222.2554	210.9613	197.287	−42.3194	−1.77
Built-up land	3.7088	3.8796	3.9697	4.2562	0.5474	1.48
Water area	12.4488	10.5649	9.6713	9.0486	−3.4002	−2.73
Wetland	5.6645	4.4203	3.9363	3.9457	−1.7188	−3.03
Nival area	7.9311	7.3755	6.757	6.0438	−1.8873	−2.38
Desert	54.8258	54.3275	56.1075	59.0989	4.2731	0.78
Bare rock	48.5742	40.6549	35.6241	29.594	−18.9802	−3.91
Desertification land	123.123	124.3215	127.1651	127.3939	4.2709	0.35

Table 8

Transformation of land cover types under scenario I during the period from 2000 to 2039 (units: million hectares)

2000	2039										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2000
Cultivated land	197.3766	7.7686	1.1778	0.1098				0.0943	0.0010	1.2517	207.7798
Woodland		241.2882	4.1087	0.0018					0.0809	0.6084	246.0880
Grassland		22.8763	212.0237					0.1731	0.1877	4.3456	239.6064
Built-up land		0.0537	0.0018	3.6486				0.0006		0.0041	3.7088
Water area		0.8645	0.3965	0.0056	11.0736			0.0181		0.0905	12.4488
Wetland		0.7470	0.0466			4.8706				0.0003	5.6645
Nival area		0.0928	0.1883				7.4511		0.0005	0.1984	7.9311
Desert		0.0435	0.1014					52.2364		2.4445	54.8258
Bare rock		0.9001	3.3259					0.0206	43.6081	0.7195	48.5742
Desertification land		1.7803	3.1124					0.7141	0.0293	117.4869	123.1230
Total in 2039	197.3766	276.4150	224.4831	3.7658	11.0736	4.8706	7.4511	53.2572	43.9075	127.1499	949.7504

Table 9

Transformation of land cover types under scenario I during the period from 2039 to 2069 (units: million hectares)

2039	2069										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2039
Cultivated land	191.2007	4.3679	0.3580	0.0212						1.4288	197.3766
Woodland	4.9042	251.2823	17.2971	0.1313	0.4258	0.5383	0.0002	0.0185	0.0923	1.7250	276.4150
Grassland	0.3256	28.5985	188.1030	0.0247	0.0010	0.0009	0.0001		0.1602	7.2691	224.4831
Built-up land	0.1098	0.0246	0.0009	3.5987	0.0056					0.0262	3.7658
Water area		0.7424	0.7843	0.0004	9.4151					0.1314	11.0736
Wetland		0.2251	0.0692			4.5756				0.0007	4.8706
Nival area		0.1728	0.7308				6.0870		0.0242	0.4363	7.4511
Desert	0.0943	0.0113	0.3034	0.0806	0.0181			49.0273	0.0206	3.7016	53.2572
Bare rock		2.4597	9.2782						31.3995	0.7701	43.9075
Desertification land	0.6405	2.8754	5.0079	0.0018	0.0637		0.0882	2.1491	0.5120	115.8113	127.1499
Total in 2069 period	197.2751	290.7600	221.9328	3.8587	9.9293	5.1148	6.1755	51.1949	32.2088	131.3005	949.7504

monotonically decreasing rate of ecotone diversity would be 0.246% per decade and the monotonically increasing rate of patch connectivity would be 3.8258%

per decade (Table 17). In short, climate change would generally cause ecotone diversity to become less and patch connectivity more.

Table 10

Transformation of land cover types under scenario I during the period from 2069 to 2099 (units: million hectares)

2069	2099										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2069
Cultivated land	190.0675	4.3396	0.0022	0.1240				0.0696		2.6722	197.2751
Woodland	3.0463	251.3929	27.5030	0.1374	1.0030	0.3888	0.2364	0.0185	3.0283	4.0054	290.7600
Grassland	0.4337	31.4917	173.7341	0.0727	0.6975	0.0007	0.3178	0.0666	5.7598	9.3582	221.9328
Built-up land	0.0033	0.1110	0.0204	3.5932				0.0500		0.0808	3.8587
Water area		0.0797	0.0420	0.0002	9.4694			0.0025		0.3355	9.9293
Wetland		0.0181				5.0946				0.0021	5.1148
Nival area		0.0231	0.2369				5.3771		0.0103	0.5281	6.1755
Desert		0.0007	0.0982	0.0099				39.3522		11.7339	51.1949
Bare rock		0.2610	1.1960	0.0006					29.5792	1.1720	32.2088
Desertification land	0.9255	0.8686	6.5911	0.0387	0.0700	0.0002	0.1564	1.5454	0.7265	120.3781	131.3005
Total in 2099 period	194.4763	288.5864	209.4239	3.9767	11.2399	5.4843	6.0877	41.1048	39.1041	150.2663	949.7504

Table 11

Transformation of land cover types under scenario II during the period from 2000 to 2039 (units: million hectares)

2000	2039										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2000
Cultivated land	198.6727	6.6827	1.2492	0.0311				0.0364		1.1077	207.7798
Woodland		241.7957	3.4795	0.0584					0.0752	0.6792	246.0880
Grassland		14.0931	220.8783					0.0728	0.1515	4.4107	239.6064
Built-up land		0.0494	0.0012	3.6422						0.0160	3.7088
Water area		0.4550	0.3314		11.6069			0.0008		0.0547	12.4488
Wetland		0.7407	0.0451			4.8782				0.0005	5.6645
Nival area		0.0006	0.1871				7.5386		0.0047	0.2001	7.9311
Desert		0.0158	0.1457	0.0100				51.6670		2.9873	54.8258
Bare rock		0.0403	3.2140					0.0559	44.2100	1.0540	48.5742
Desertification land		0.3380	3.6746					0.7793	0.0372	118.2939	123.1230
Total in 2039	198.6727	264.2113	233.2061	3.7417	11.6069	4.8782	7.5386	52.6122	44.4786	128.8041	949.7504

Table 12

Transformation of land cover types under scenario II during the period from 2039 to 2069 (units: million hectares)

2039	2069										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2039
Cultivated land	191.9417	5.5480	0.4562	0.0357						0.6911	198.6727
Woodland	5.2461	243.1319	13.9488	0.0563	0.4364	0.6547	0.0005	0.0158	0.0504	0.6704	264.2113
Grassland	0.3336	27.6005	196.1269	0.0183	0.2835	0.0386	0.1375	0.0418	2.8611	5.7643	233.2061
Built-up land	0.0008	0.0838	0.0018	3.6475						0.0078	3.7417
Water area		0.8223	0.0230	0.0024	10.6714					0.0878	11.6069
Wetland		0.2801	0.0008			4.5973					4.8782
Nival area		0.1734	0.0774				7.0360		0.0055	0.2463	7.5386
Desert	0.0364	0.0361	0.1705		0.0008			49.2876	0.0559	3.0249	52.6122
Bare rock		2.0678	0.1585						41.8237	0.4286	44.4786
Desertification land	0.4659	3.5780	3.2599	0.0071	0.0263	0.0002	0.0827	1.8501	0.1607	119.3732	128.8041
Total in 2069 period	198.0245	283.3219	214.2238	3.7673	11.4184	5.2908	7.2567	51.1953	44.9573	130.2944	949.7504

3.4. Mean center shift of land cover types

The mean center of cultivated land would wander about Nanyang of Henan province in the southwest of

North China Plain (Fig. 12). Under scenario I (Table 18), during the period from 2000 to 2039 the mean center of cultivated land would shift about 38 km towards southeast; during the periods from 2039 to 2069 and

Table 13

Transformation of land cover types under scenario II during the period from 2069 to 2099 (units: million hectares)

2069	2099										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2069
Cultivated land	193.2173	2.9073	0.0060	0.0315				0.0002		1.8622	198.0245
Woodland	2.4257	262.8130	12.9198	0.2207	0.6085	0.0525	0.0999	0.0315	1.2613	2.8890	283.3219
Grassland	0.5813	23.4715	182.5477	0.0135	0.0063	0.0008	0.0060	0.0514	0.1588	7.3865	214.2238
Built-up land	0.0239	0.0489	0.0178	3.6358	0.0020					0.0389	3.7673
Water area		0.5058	0.0211	0.0007	10.6440					0.2468	11.4184
Wetland		0.1338				5.1545				0.0025	5.2908
Nival area		0.2225	0.2993				6.3818		0.0200	0.3331	7.2567
Desert		0.0466	0.0831	0.1099				44.4663		6.4894	51.1953
Bare rock		3.9175	0.7169						39.7368	0.5861	44.9573
Desertification land	0.7784	2.9796	4.8251	0.0526	0.0760		0.1625	1.9155	1.2305	118.2742	130.2944
Total in 2099 period	197.0266	297.0465	201.4368	4.0647	11.3368	5.2078	6.6502	46.4649	42.4074	138.1087	949.7504

Table 14

Transformation of land cover types under scenario III during the period from 2000 to 2039 (units: million hectares)

2000	2039										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2000
Cultivated land	195.2619	10.0545	1.2927	0.0581				0.2145		0.8981	207.7798
Woodland		239.3115	6.0446	0.1756					0.0357	0.5206	246.0880
Grassland		30.8602	205.0071	0.0005				0.3855	0.0805	3.2726	239.6064
Built-up land		0.0611	0.0026	3.6373				0.0009		0.0069	3.7088
Water area		1.1600	0.6478	0.0002	10.5649			0.0088		0.0671	12.4488
Wetland		1.1773	0.0667			4.4203				0.0002	5.6645
Nival area		0.1260	0.3317				7.3755		0.0005	0.0974	7.9311
Desert		0.0440	0.1105					52.2936		2.3777	54.8258
Bare rock		1.3876	5.4665					0.0634	40.5254	1.1313	48.5742
Desertification land		2.5067	3.2852	0.0079				1.3608	0.0128	115.9496	123.1230
Total in 2039	195.2619	286.6889	222.2554	3.8796	10.5649	4.4203	7.3755	54.3275	40.6549	124.3215	949.7504

Table 15

Transformation of land cover types under scenario III during the period from 2039 to 2069 (units: million hectares)

2039	2069										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2039
Cultivated land	189.0787	2.4989	0.9295	0.2010	0.0080			0.3506		2.1952	195.2619
Woodland	0.6178	282.7075	2.5833	0.0861	0.0201			0.0046	0.0394	0.6301	286.6889
Grassland	0.4660	15.8541	200.2371	0.0506	0.0017		0.0001	0.2999	0.0618	5.2841	222.2554
Built-up land	0.0521	0.1630	0.0019	3.6305	0.0002			0.0049		0.0270	3.8796
Water area	0.0373	0.3725	0.3527	0.0005	9.6336			0.0360		0.1323	10.5649
Wetland	0.0972	0.3453	0.0404			3.9361				0.0013	4.4203
Nival area		0.0743	0.2738				6.7553	0.0003		0.2718	7.3755
Desert	0.2224	0.0431	0.4009					47.4018	0.0338	6.2255	54.3275
Bare rock		0.9769	3.7287					0.0743	35.4464	0.4286	40.6549
Desertification land	0.2121	1.7389	2.4130	0.0010	0.0077	0.0002	0.0016	7.9351	0.0427	111.9692	124.3215
Total in 2069	190.7836	304.7745	210.9613	3.9697	9.6713	3.9363	6.7570	56.1075	35.6241	127.1651	949.7504

from 2069 to 2099, towards northeast and shift distances about 44 km and 36 km respectively. Under scenario II (Table 19), during the periods from 2000 to 2039 and

from 2069 to 2099, the mean center would shift towards southeast and shift distances be about 47 km and 17 km respectively; from 2039 to 2069 towards northeast and

Table 16

Transformation of land cover types under scenario III during the period from 2069 to 2099 (units: million hectares)

2069	2099										
	Cultivated land	Woodland	Grassland	Built-up land	Water area	Wetland	Nival area	Desert	Bare rock	Desertification land	Total in 2069
Cultivated land	187.1116	1.9350	0.2992	0.1040	0.0373	0.0972		0.1737		1.0256	190.7836
Woodland	0.0517	301.5362	2.1513	0.2113	0.0013			0.0015	0.0287	0.7925	304.7745
Grassland	0.5419	18.7455	187.6167	0.0014	0.0011		0.0001	0.1090	0.1138	3.8318	210.9613
Built-up land		0.0092	0.0006	3.9387				0.0016		0.0196	3.9697
Water area		0.3099	0.2672		9.0089			0.0066		0.0787	9.6713
Wetland		0.0677	0.0195			3.8485				0.0006	3.9363
Nival area		0.0815	0.3887				6.0437		0.0121	0.2310	6.7570
Desert	0.0338	0.0207	0.1690					53.3213	0.0144	2.5483	56.1075
Bare rock		1.3192	4.4218					0.1349	29.3962	0.3520	35.6241
Desertification land	0.0363	1.2821	1.9530	0.0008				5.3503	0.0288	118.5138	127.1651
Total in 2099 period	187.7753	325.3070	197.2870	4.2562	9.0486	3.9457	6.0438	59.0989	29.5940	127.3939	949.7504

shift distance about 59 km. Under scenario III (Table 20), the mean center would shift towards southeast in all the three periods and the shift distance be about 40 km, 26 km and 18 km during the periods from 2000 to 2039, from 2039 to 2069 and from 2069 to 2099 respectively.

The mean center of woodland would wander about the area from Yichang of Hubei province to Wanxian county of Chongqing. Under scenario I, the mean center would shift about 20 km towards northwest during the period from 2000 to 2039; about 256 km towards southwest from 2039 to 2069, and about 60 km towards northeast from 2069 to 2099. Under scenario II, the mean center shift about 78 km towards northeast during the period from 2000 to 2039, about 306 km towards southwest from 2039 to 2069, and about 69 km towards northwest from 2069 to 2099. Under scenario III, the mean center would shift 45 km, 60 km and 73 km towards southwest during the periods from 2000 to 2039, from 2039 to 2069 and from 2069 to 2099 respectively.

The mean center of grassland would wander about the area around Qinghai Lake. In terms of all the three scenarios the mean center would almost shift towards the southwest during the period from 2000 to 2039, towards northeast except towards northwest under scenario III during the period from 2039 to 2069, and towards southeast from 2069 to 2099.

The mean center of built-up land would wander about the juncture of Anhui, Henan and Hubei. In terms of scenario I, the mean center would respectively shift 26 km and 178 km towards southwest during the periods from 2000 to 2039 and from 2069 to 2099, 59 km towards northwest from 2039 to 2069. In terms of scenario II, the mean center would shift 60 km towards southeast during the period from 2000 to 2039, 7 km and 225 km towards

northwest from 2039 to 2069 and from 2069 to 2099. In terms of scenario III, the mean center would shift 139 km towards southeast, 123 km and 54 km towards southwest during the periods from 2000 to 2039, from 2039 to 2069, and from 2069 to 2099 respectively.

The mean center of water area would wander about upper reaches of Weihe River in the south of Gansu. In terms of scenarios I and II, the mean center would shift towards southeast, northeast and southwest respectively during the periods from 2000 to 2039, from 2039 to 2069 and from 2069 to 2099. In terms of scenario III, the mean center would respectively shift 170 km, 106 km and 111 km towards southeast during the periods from 2000 to 2039, from 2039 to 2069 and from 2069 to 2099.

The mean center of wetland would wander about Tongliao in Northeast Plain. Under scenario I, the mean center would shift 23 km towards southeast from 2000 to 2039, 112 km towards northeast from 2039 to 2069, and 38 km towards southwest from 2069 to 2099. Under scenario II, the one would shift 41 km towards southwest from 2000 to 2039, 78 km and 32 km towards northeast from 2039 to 2069 and from 2069 to 2099. Under scenario III, the one shift 44 km towards southeast from 2000 to 2039, 40 km towards northeast from 2039 to 2069, and 10 km towards southeast from 2069 to 2099.

The mean center of nival areas would wander about the juncture of Kunlun Mountains and Arjin Mountains. Under all the three scenarios during all the three periods, the mean center would almost shift towards southwest except towards northwest during the period from 2000 to 2039 under scenario III.

The mean center of desert would be wander about the eastern area of Tarim Basin. Under scenario I, the mean center would shift 20 km towards northeast from 2000 to 2039, 38 km towards northeast from 2039 to 2069, and 146 km towards southwest from 2069 to 2099. Under scenario II, the one would shift 34 km towards northwest from 2000 to 2039, 3 km towards southwest from 2039 to 2069, and 110 km towards southwest from 2069 to 2099. Under scenario III, the one would shift 25 km towards northeast from 2000 to 2039, and 76 km and 21 km towards southeast from 2039 to 2069 and from 2069 to 2099 respectively.

The mean center of bare rock would wander about the around area of Kekexili Mountain in Qinghai-Xizang Plateau. Under scenario I, the mean center would shift 15 km towards northwest from 2000 to 2039, 28 km towards southwest from 2039 to 2069, and 54 km towards southeast from 2069 to 2099. Under scenario II, the one would shift 12 km towards southwest from 2000 to 2039, 12 km towards northwest from 2039 to 2069, and 9 km towards northeast from

Table 17
Ecotope diversity and patch connectivity

Scenarios	Period	Diversity	Connectivity
HadCM3A1FI	2000	0.0935	0.0528
	2039	0.0928	0.0687
	2069	0.0917	0.0701
	2099	0.092	0.0642
	Increased ratio per decade	−0.1604	2.1591
HadCM3A2	2000	0.0935	0.0528
	2039	0.0929	0.0624
	2069	0.0928	0.0661
	2099	0.0924	0.0641
	Increased ratio per decade	−0.1176	2.1402
HadCM3B2	2000	0.0935	0.0528
	2039	0.0924	0.0697
	2069	0.0918	0.071
	2099	0.0912	0.073
	Increased ratio per decade	−0.2460	3.8258

Fig. 12. Shift trend of mean center of land cover types in China (Left map: Scenario I; Middle map: Scenario II; Right map: Scenario III).

Table 18
Shift trend of the mean center under scenario I

Land cover type	2000–2039		2039–2069		2069–2099	
	Distance (km)	Direction	Distance (km)	Direction	Distance (km)	Direction
Cultivated land	38.3827	287.81°	43.7309	44.40°	36.3724	5.47°
Woodland	20.4859	123.48°	256.2602	227.36°	60.2040	86.84°
Grassland	54.7277	225.72°	124.7824	61.32°	80.0148	343.80°
Built-up land	25.6433	212.17°	58.9676	175.43°	177.9427	266.92°
Water area	128.7035	357.19°	195.5907	6.72°	197.0785	194.49°
Wetland	22.8663	289.37°	111.5089	58.65°	37.9343	229.43°
Nival area	11.3650	234.50°	25.7471	222.66°	116.5167	270.66°
Desert	20.3248	42.61°	37.9435	156.50°	145.7545	247.51°
Bare rock	15.0415	149.93°	28.1945	184.93°	53.9005	273.03°
Desertification land	110.9973	287.53°	93.2249	281.28°	157.8782	92.71°

Table 19
Shift trend of the mean center under scenario II

Land cover type	2000–2039		2039–2069		2069–2099	
	Distance (km)	Direction	Distance (km)	Direction	Distance (km)	Direction
Cultivated land	46.5404	274.34°	59.3802	54.54°	16.5264	340.79°
Woodland	78.1206	25.12°	305.8616	228.24°	68.7200	106.78°
Grassland	112.1583	212.25°	219.4164	41.51°	23.2976	336.89°
Built-up land	60.3967	274.76°	7.1556	155.81°	225.3487	169.04°
Water area	65.7434	351.57°	56.0458	18.99°	18.7554	265.56°
Wetland	40.9152	263.08°	77.7505	66.25°	32.1454	48.15°
Nival area	18.4164	263.97°	20.0544	261.20°	56.9311	263.35°
Desert	32.7392	107.86°	3.1286	323.86°	110.0835	269.38°
Bare rock	12.5083	183.61°	12.2299	127.59°	9.1083	39.87°
Desertification land	125.2159	285.99°	29.8726	228.32°	141.0112	85.25°

2069 to 2099. Under scenario III, the one would respectively shift 31 km and 23 km towards northwest from 2000 to 2039 and from 2039 to 2069, and 48 km towards southwest from 2069 to 2099.

The mean center of desertification land would wander about the northwest of Qaidam basin. During the period

from 2000 to 2039, the mean center would respectively shift 111 km, 125 km and 141 km towards southeast under scenarios I, II and III. From 2039 to 2069, the one would shift 93 km towards southeast under scenario I, 30 km towards southwest under scenario II, and 14 km towards northwest under scenario III. From 2069 to

Table 20
Shift trend of the mean center under scenario III

Land cover type	2000–2039		2039–2069		2069–2099	
	Distance (km)	Direction	Distance (km)	Direction	Distance (km)	Direction
Cultivated land	40.4861	288.14°	24.5506	326.00°	17.6988	342.30°
Woodland	45.1047	202.81°	59.8017	206.83°	73.0859	194.89°
Grassland	68.7917	199.08°	42.5383	152.29°	9.8802	330.50°
Built-up land	138.7902	294.62°	122.9710	223.38°	53.6349	202.16°
Water area	169.9664	354.13°	105.9959	356.35°	111.4750	358.56°
Wetland	43.8508	293.82°	40.2609	36.60°	10.4989	352.90°
Nival area	25.1487	133.53°	17.8007	241.86°	23.9020	229.60°
Desert	24.4768	35.55°	75.9650	321.27°	21.3177	306.87°
Bare rock	31.4136	147.31°	23.3175	141.45°	48.4996	216.60°
Desertification land	140.8968	280.97°	14.4511	125.04°	93.5899	79.66°

2099, the one would shift 158 km towards northwest under scenario I, and respectively 141 km and 94 km towards northeast under scenarios II and III.

4. Conclusions and discussion

4.1. Conclusions

In the future 100 years, cultivated land would gradually decrease, especially the one distributing in the north and the south of Tianshan Mountain, Hexi Corridor of Gansu, Loess Plateau, and the south of Inner Mongolia Plateau. The mean center of cultivated land would shift towards east in general. Woodland area would increase greatly with temperature and precipitation in China. Woodland and grassland in hilly areas would have an expanding trend with decrease of cultivated land. These results simulated in terms of climate scenarios coincide with consequences expected by the Grain-for-Green policy (Feng et al., 2005). In other words, climate change would favor the implementation of Grain-for-Green policy in China.

With temperature rise, precipitation and evapotranspiration increase in considerable area of China, nival area would shrink, ecotope diversity would decrease and desertification area would expand at a comparatively slow rate. Desertification land in peripheral areas of Tarim Basin and Junggar Basin would spread out with the irregular circle shape. Desertification in Inner Mongolia Plateau would extend towards the east and the southeast. Desertification in Loess Plateau would become more serious.

In short, ecosystems in China would have a pattern of beneficial cycle after efficient ecological conservation and restoration. However, if human activities would exceed regulation capacity of ecosystems themselves, the ecosystems in China might be deteriorated more seriously. Ecological conservation and restoration is a long-term and complex project. It involves undeveloped local governments and millions of farmers living in ecological vulnerable areas. Government investment and financial subsidy are not enough. It is necessary to establish a set of policies to ensure the ecological conservation and restoration. Especially in desertification areas, various economic activities must be subject to strictly judicial control.

4.2. Discussion

How climatic changes might affect land cover is one of overarching questions of land use and land cover change project (LUCC), a core project of the Interna-

tional Geosphere–Biosphere Programme (IGBP) and the International Human Dimensions of Global Environmental Change Programme (IHDP). Land cover dynamics and its diagnostic models are one of LUCC's focuses (<http://www.geo.ucl.ac.be/LUCC/lucc.html>). Various models for simulating land cover scenarios have been developed. For instances, the published SRES land cover scenarios assumes that everywhere within a major world region changes occur at the same rate. The land cover changes under A1, B1 and B2 marker scenarios are highly uncertain. The A2 marker scenario did not include land cover change, so changes under the A1 scenario were assumed to apply also to A2. The SRES land cover scenarios do not include the effect of climate change on future land cover (Arnell et al., 2004).

SRES A2 and B2 scenarios of IPCC were downscaled in a probabilistic cellular automata model (PCAM) to define the narrative scenario conditions of future urban land use change. The results of the modeling experiments illustrated the spectrum of possible land cover scenarios of New York Metropolitan Region for the years 2020 and 2050 (Solecki and Oliveri, 2004).

CLUE was developed within a framework of conversion of land use and its effects under assumptions that there is a dynamic equilibrium between the total population and the agricultural production and land cover changes occur only when biophysical and human demands can not be met any more through existing land use (Veldkamp and Fresco, 1996; Verburg and Veldkamp, 2001).

The input–output (I–O) model was used to develop land cover scenarios in China, which was not spatially explicit and did not consider possible impacts of climate changes (Hubacek and Sun, 2001). Socio-economic changes are linked to different types of land via an explicit representation of land requirement coefficients associated with specific economic activities. The strong biophysical linkages are mainly manifested in the derivation of regional differences of the land requirement coefficients and the typical I–O technical coefficients by means of Agro-Ecological Zone (FAO/IIASA, 1993).

A spatially explicit stochastic methodology (SESM) was developed for simulating land use changes at a watershed level without the need to describe the complex relationships between biophysical, economic and human factors (Luijten, 2003). Its transition probabilities were based on observed frequencies of actual conversions between forest, pasture and scrub in the period 1946–1970. Land use changes were simulated on a grid cell basis, in which each grid cell acts independently. Three

explorative scenarios for the year 2025 were developed under assumptions of Business as Usual (BU), Ecological Watershed (EW), and Corporate Farming (CF).

A land use change modeling kit (LUCK) was developed for scenario generation in a grid-based discretization-mode on catchment scale, which represents the spatial distribution of land cover types in the landscape (Niehoff et al., 2002). The potential conversion of land cover types of each grid is based on an evaluation of the characteristics of each grid as well as on its neighborhood relationships. Because land cover changes happen successively, LUCK tries to simulate the dynamics by an iterative procedure.

All these typical models above can be distinguished into 4 categories: statistical models, stochastic models, dynamic models and integrated models. They all have drawbacks. The published SRES land cover scenarios has an assumption problem. PCAM puts more emphasis on urban ecosystem. CLUE emphasizes agricultural ecosystem. I–O can only address the question at what rates changes are likely to progress (quantity of change), but ignores the question where land cover changes are likely to take place (location of change). SESM limits its application on watershed scale.

SMLC is a stochastic model of land cover change, dealing with both the location and quantity issues in an integrated way (Veldkamp and Lambin, 2001). It has no need to integrate with other simulation modules. It is comparatively simple to construct transition probability matrixes between HLZ types and land cover types, which avoids the discontinuity between past and future as appeared in the SRES land cover scenarios. On the basis of the combination of current spatial pattern of land cover types with climatic change trend and scenarios, SMLC is able to generate reliable projections into the future and, in backward mode, to the past, which is the ultimate objective of the LUCC project developing means for projecting land covers. SMLC could be conveniently used on any spatial scales because of the availability of rich LUCC data and IPCC data (<http://ipcc-ddc.cru.uea.ac.uk>).

However, SMLC severely simplifies the land cover system and focuses primarily on climatic attributes. It is required to incorporate data on a wide range of social, economic and political factors, which is the focal point of our further research works on SMLC.

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