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Land-cover changes of biome transition zones in Loess Plateau of China

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ABSTRACT

The Holdridge life zone (HLZ) model has been improved to help classify the biome transition zone (BTZ) in China's Loess Plateau. A positive and negative transformation index of land-cover (PNTIL) was developed to quantitatively evaluate the land-cover changes in every type of BTZ. Three bioclimatic datasets, with a spatial resolution of 1 km × 1 km, were used to classify the BTZ type in Loess Plateau. These include the mean annual biotemperature (MAB), average total annual precipitation (TAP) and potential evapotranspiration ratio (PER). In 1985, 1995 and 2005 land cover data was used to analyze the changes within BTZs. The results show that there are 14 BTZ types, which account for 25.21% of the total land-cover area in Loess Plateau. From 1985 to 2005, cultivated land decreased 0.93% per decade; on average wetland and water areas, woodland and grassland increased 3.47%, 0.24% and 0.06% respectively per decade. During this period the total rate of whole BTZ land-cover transformation decreased from 28.53% to 21.91%. Overall the total positive and negative transformed areas of land cover in BTZs displayed a decreasing trend. Moreover, the results indicate that the transition zones may have exhibited a greater change and landscape diversity than the adjacent biomes in Loess Plateau from 1985 to 2005.

1. Introduction

Land-cover change directly impacts on biogeochemical cycling, soil erosion and ecological diversity (Chapin et al., 2000); it also affects the ability of biological systems to support human needs by altering ecosystem services (Vitousek et al., 1997; Yue et al., 2007). Thus, changes in land systems can, in turn, have major consequences for global change (Kalnay and Cai, 2003; Rindfuss et al., 2004; Turner et al., 2007). Furthermore, the land-cover of biome transition zones (BTZs) is expected to be among the most sensitive areas to climate change (Solomon, 1986; di Castri et al., 1988; Bestelmeyer and Wiens, 2001) and human activity. It also has a higher level of landscape species richness (gamma diversity, Whittaker, 1983) than in neighboring biomes (Neilson, 1993; Hochstrasser et al., 2002). In order to quantitatively identify, classify and convey the highly explicit changes in land-cover among the different BTZs, it is important to improve the adaptation strategies used to mitigate (and in turn even benefit from) the projected impact on land use from climate change (Rounsevell and Reay, 2009).

Since the early 1880s a continuing effort to facilitate understanding of the relationship between vegetation distribution climate and biome classification, has been under development (Schouw, 1823; Griesebach, 1872; Merriam, 1892; Clements, 1916; Koeppen and Geiger, 1930; Thornthwaite, 1931; Holdridge, 1947). This led to the Holdridge life zone (HLZ) model (Holdridge, 1967; Holdridge et al., 1971) which utilizes three bioclimatic variables: mean annual biotemperature, average total annual precipitation, and potential evapotranspiration ratio (the ratio of mean annual potential evapotranspiration to average total annual precipitation). The HLZ model relates the distribution of major biome types (termed life zones) to bioclimatic variables, and has been widely accepted for use in projecting the impact of climate change on vegetation distribution (Post et al., 1982; Belotelov et al., 1996; Peng, 2000; Chen et al., 2003; Yue et al., 2005, 2006).

The HLZ classification system is also widely used in association with satellite data, land-cover data, actual vegetation cover data, elevation, slope and other data. This enhances its function in biome mapping, diversity conservation, land-cover scenario analysis, land planning and management. For example Lugo et al. (1999) successfully used HLZ in maps of aggregated land cover classes in the United States. Powell et al. (2000) assessed the biodiversity coverage of representative protected natural areas in Costa Rica by comparing them with HLZ. Pan et al. (2003) identified 47 land cover classes in China with NOAA/AVHRR data and HLZ. Roy et al. (2006) mapped biomes in India using maps of vegetation type derived from temporal satellite data and environmental parameters. Yue et al. (2007) created scenario analysis of land-cover in China by

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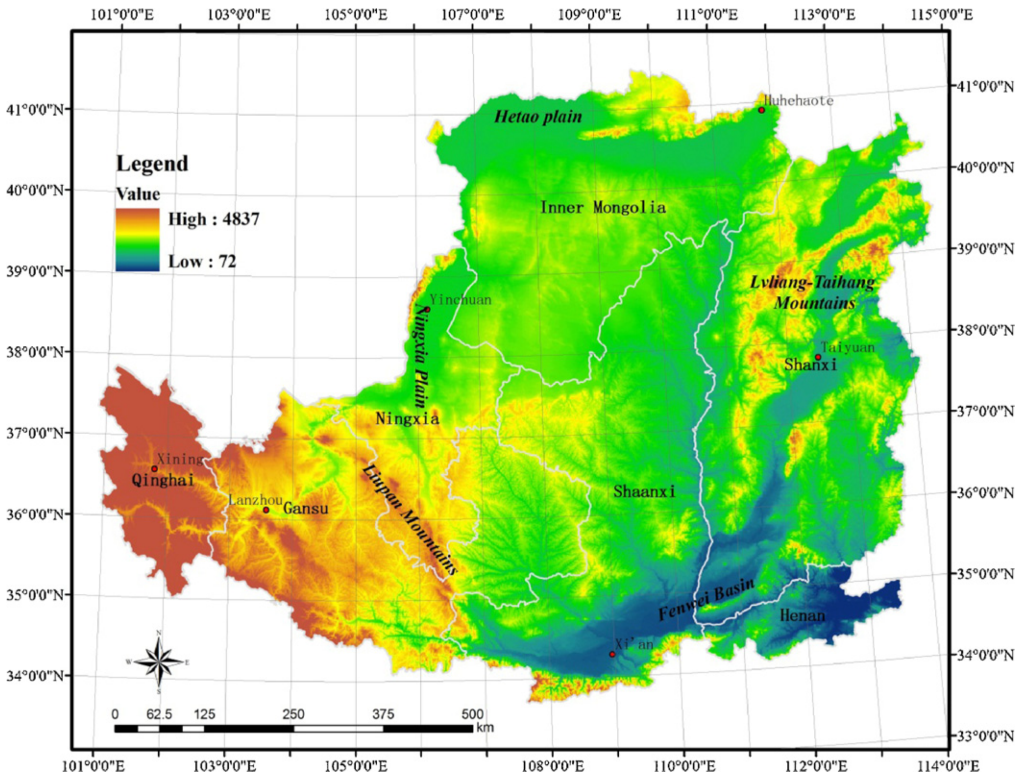

Fig. 1. A digital elevation model of Loess Plateau.

associating HLZ with land-cover data derived from Landsat TM. Feng and Chai (2008) used HLZ and statistical dynamic analysis methods to simulate the vegetation patterns in land ecosystems. In Puerto Rico Soto and Pintó (2010) defined and classified landscape units associated with elevation, slope, HLZ and geology; these can serve as basic factors for use in research, planning and land management efforts. However, these applications rarely involved the classification of the BTZ due to the lack of quality spatial bioclimatic data (Holdridge, 1967) and spatial simulation method with GIS.

Loess Plateau, located at 100°54′–114°43′E and 33°43′–41°16′N, covers an area of about 640,000 km^2 in the upper and middle reaches of China's Yellow River (Fig. 1). It is not only the largest region in Loess but also suffers the highest rates of soil erosion in China. The mean annual temperature and mean annual precipitation respectively range from 3.6 °C to 14.3 °C and from 150 mm to 750 mm. Soil erosion is the principal ecological issue in Loess Plateau. Low vegetation coverage, as a result of unsuitable land use (e.g. step slope land reclamation and overgrazing), is the leading cause of severe soil erosion in the region (Liu, 1999; Fu et al., 2004; Liu et al., 2012). Loess Plateau is therefore one of the key target areas for implementation of the “Grain-for-Green Programme” initiated by China's central government. Between 1998 and 2010 all cultivated lands with a slope over 25° were converted into woodland or grass land in order to effectively control the soil erosion (Wang et al., 2010). The project succeeded in increasing vegetation cover in Loess Plateau (Xin et al., 2008). This improved the soil nutrient levels (Qiu et al., 2009), and helped recover the soil's physical properties (Li and Shao, 2006). However, land-cover changes of the biome transition zones in Loess Plateau still need to be quantitatively analyzed.

When quantitatively identifying and classifying the different BTZs of Loess Plateau, the location of transition zones between arid, semi-arid and semi-moist climate can be clearly recognized. Assessing the changes in land-cover between different BTZs is vital to understanding restoration efficiency and trends in land-cover change. They will also assist in providing the support for the land planning and management of Loess Plateau. In this paper, we focus on identifying the BTZs of Loess Plateau by improving the classification regulation of the HLZ model, and quantitatively explaining the land-cover changes in all BTZ types. We achieved this by developing the positive and negative transformation indexes of land-cover (PNTIL) from 1985 to 2005.

2. Materials and methods

2.1. Datasets

The bioclimatic data of Loess Plateau used includes the mean annual biotemperature, average total annual precipitation and potential evapotranspiration ratio from 1985 to 2005 (Fig. 2). The spatial resolution is 1 km × 1 km. The data has been respectively separated from the rest of China. The bioclimatic data of China was simulated by a high accuracy and speed method of surfacing modeling (HASM), which is described in detail by Yue (2010). Furthermore, the land-cover data of Loess Plateau has been extracted from the land-cover data of the rest of China in 1985, 1995 and 2005 at a spatial resolution of 1 km × 1 km. The classification of land-cover in 1985 and 1995, with an overall accuracy of 81%, is derived from the Advanced Very High Resolution Radiometer (AVHRR) sensors (Liu et al., 2003). The classification of land-cover in 2005 has an overall accuracy of 95% and is based on Landsat TM and CBERS-2 CCD data (Liu et al., 2009). Pixels are classified as cultivated land, woodland, grassland, wetland and water areas, built-up land, desert and other land.

2.2. Classification method of BTZ

The classification method of the HLZ model uses a two-dimensional array of hexagons in a triangular frame. It uses the mean annual biotemperature (MAB) in degrees centigrade, average

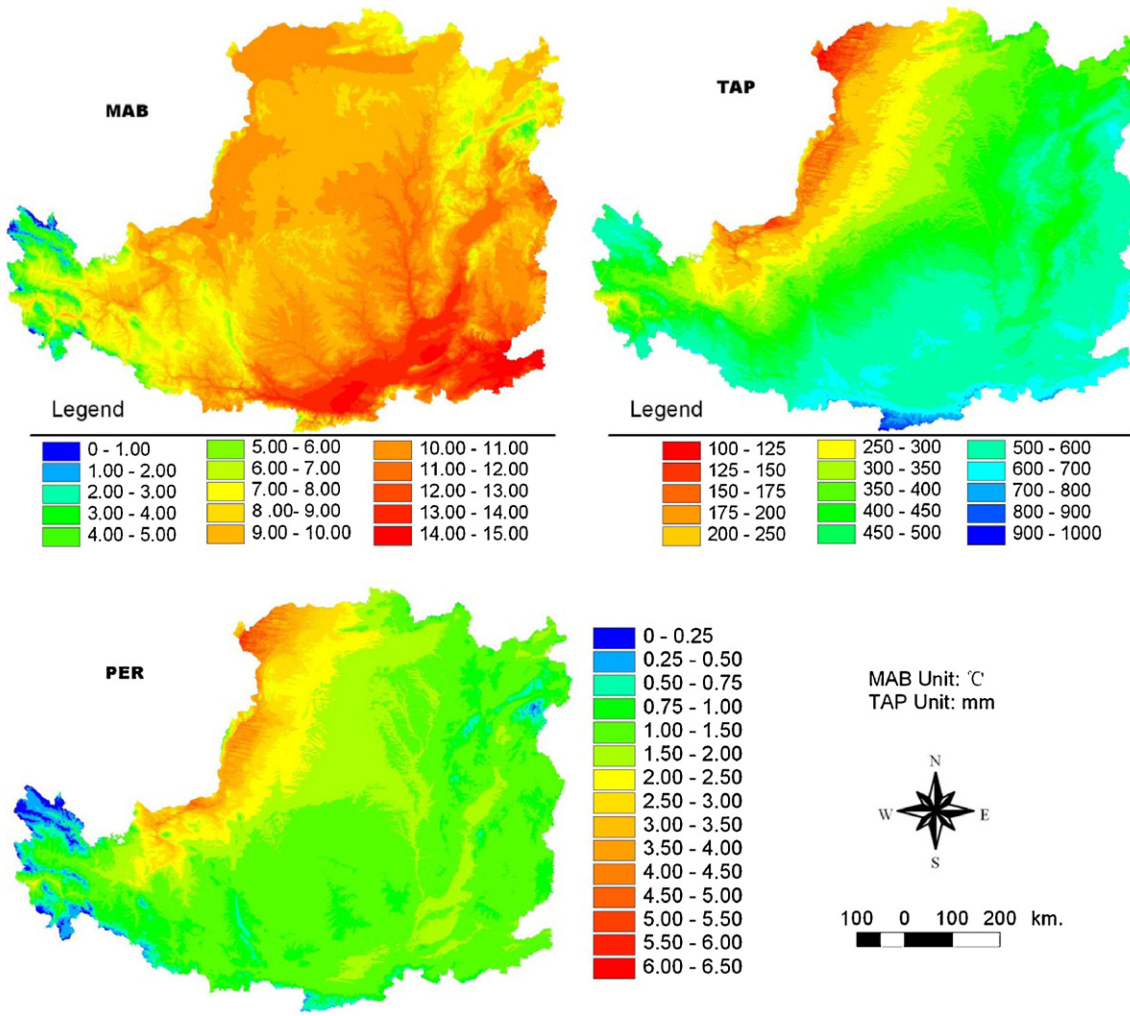

Fig. 2. MAB, TAP and PER in Loess Plateau from 1985 to 2005.

total annual precipitation (TAP) in millimeters and potential evapotranspiration ratio (PER) to formulate the relationship between climate patterns and broad-scale vegetation distribution. The various guidelines of MAB, TAP and PER mark out 6 separate triangles in each hexagon which represent transition zones (Fig. 3) (Holdridge, 1967). However, it is difficult to define which transition zone belongs to each triangle, as they lie adjacent two other biome zones hexagons (Fig. 3) shows that the three guide line sets intersect to form a series of new triangles which include the three smaller, original triangles.

Within each new triangle, two of the three bioclimatic factors correspond to its adjacent core zones. These act as the remainder from the main body of three hexagons; at least one of the factors corresponds to that of a neighboring core zone. For example the three lines of MAB (6.0 °C), TAP (250 mm) and PER (2.0) intersect to form triangle 22 that includes the three small triangles I, II and III. Within triangle 22, two of the following values, MAB > 6.0 °C, TAP < 250 mm and PER < 2.0, correspond to the remaining main body from the boreal dry scrub zone, cool temperate desert scrub zone and cool temperate steppe zone. Thus, we define each new triangle (e.g. triangle 22) as the transition zones between its adjacent three core zones and in turn calculate its classification criterion (Table 1) in terms of the logarithmical coordinate system of the HLZ model. The classification method of BTZ can be formulated as:

$$M(x, y) = \log_2\ \mathrm{MAB}(x, y) \tag{1}$$

$$T(x, y) = \log_2\ \mathrm{TAP}(x, y) \tag{2}$$

$$P(x, y) = \log_2\ \mathrm{PER}(x, y) \tag{3}$$

$$\begin{aligned} &\text{if}\ \ M(x, y) \in \{\mathrm{MAB}_{0_i}\}, T(x, y) \in \{\mathrm{TAP}_{0_i}\}\ \ \text{and}\ \ P(x, y) \in \{\mathrm{PER}_{0_i}\} \\ &\mathrm{BTZ}(x, y) = i(1, 2, 3, \ldots, 49) \end{aligned} \tag{4}$$

where MAB(x, y), TAP(x, y) and PER(x, y) are respectively represent the values of mean annual biotemperature in degrees centigrade, average total annual precipitation in millimeters and potential evapotranspiration ratio at site (x, y); BTZ(x, y) is the value of BTZ type at site (x, y); MAB_{0_i}, TAP_{0_i} and PER_{0_i} are standards of MAB logarithm, TAP logarithm and PER logarithm of the ith$(1, 2, 3, \ldots, 49)$ transition zone.

2.3. Transformation index of land-cover in BTZ

In terms of the BTZ, data generated by the above method (Fig. 4) as well as the land-cover data of Loess Plateau and the land-cover data of BTZ in Loess Plateau in 1985, 1995 and 2005 (Fig. 5) are respectively calculated by using the spatial analysis tool of ArcGIS. For evaluating the land-cover transform trends of Loess Plateau's BTZ, we divided them into positive transformation and negative transformation (Table 2) with regard to the capacity of different land-cover type to provide ecosystem services (Burkhard et al., 2009; Kimmins et al., 2010). A positive and negative transformation

Table 1
The classification criterion of biome transition zones.

Code	Name of transition zone	MAB (°C)	TAP (mm)	PER
1	Transition zone between aeolian area and nival area (Aeolian-Nival)	>0.375	<125	<0.25
2	Transition zone between aeolian area, periglacial area and nival area (Aeolian-Peri-Nival)	<0.75	>125	>0.25
3	Transition zone between Aeolian area, frigorideserta and periglacial area (Aeolian-Fri-Peri)	>0.75	<125	<0.50
4	Transition zone between periglacial area and nival area (Peri-Nival)	>0.75	<250	<0.25
5	Transition zone between frigorideserta, periglacial area and alpine cold steppe (Fri-Peri-AlpColdSte)	<1.50	>125	>0.50
6	Transition zone between periglacial area, nival area and alpine cold meadow (Peri-Nival-AlpColdMea)	<1.50	>250	>0.25
7	Transition zone between alpine cold desert, alpine cold steppe and frigorideserta (AlpColdDes-AlpColdSte-Fri)	>1.50	<125	<1.00
8	Transition zone between alpine cold steppe, alpine cold meadow and periglacial area (AlpColdSte-AlpColdMea-Peri)	>1.50	<250	<0.50
9	Transition zone between alpine cold meadow, alpine rain tundra and nival area (AlpColdMea-AlpRainTundra-Nival)	>1.50	<500	<0.25
10	Transition zone between alpine cold desert, alpine cold steppe and boreal dry scrub (AlpColdDes-AlpColdSte-BorealDryScr)	<3.00	>125	>1.00
11	Transition zone between alpine cold steppe, alpine cold meadow and boreal moist forest (AlpColdSte-AlpColdMea-BorealMoistFor)	<3.00	>250	>0.50
12	Transition zone between alpine cold meadow, alpine rain tundra and boreal wet forest (AlpColdMea-AlpRainTundra-BorealWetFor)	<3.00	>500	>0.25
13	Transition zone between boreal desert, boreal dry scrub and alpine cold desert (BorealDes-BorealDryScr-AlpColdDes)	>3.00	<125	<2.00
14	Transition zone between boreal dry scrub, boreal moist forest and alpine cold steppe (BorealDryScr-BorealMoistFor-AlpColdSte)	>3.00	<250	<1.00
15	Transition zone between boreal moist forest, boreal wet forest and alpine cold meadow (BorealMoistFor-BorealWetFor-AlpColdMea)	>3.00	<500	<0.50
16	Transition zone between boreal wet forest, boreal rain forest and alpine rain tundra (BorealWetFor-BorealRainFor-AlpRainTundra)	>3.00	<1000	<0.25
17	Transition zone between boreal desert, boreal dry scrub and cool temperate desert scrub (BorealDes-BorealDryScr-CoolTemDesScr)	<6.00	>125	>2.00
18	Transition zone between boreal dry scrub, boreal moist forest and cool temperate steppe (BorealDryScr-BorealMoistFor-CoolTemSte)	<6.00	>250	>1.00
19	Transition zone between boreal moist forest, boreal wet forest and cool temperate moist forest (BorealMoistFor-BorealWetFor-CoolTemMoistFor)	<6.00	>500	>0.50
20	Transition zone between boreal wet forest, boreal rain forest and cool temperate wet forest (BorealWetFor-BorealRainFor-CoolTemWetFor)	<6.00	>1000	>0.25
21	Transition zone between cool temperate desert, cool temperate desert scrub and boreal desert (CoolTemDes-BorealRainFor-CoolWetFor)	>6.00	<125	<4.00
22	Transition zone between cool temperate desert scrub, cool temperate steppe and boreal dry scrub (CoolTemDesScr-CoolTemSte-BorealDryScr)	>6.00	<250	<2.00
23	Transition zone between cool temperate steppe, cool temperate moist forest and boreal moist forest (CoolTemSte-CoolTemMoistFor-BorealMoistFor)	>6.00	<500	<1.00
24	Transition zone between cool temperate moist forest, cool temperate wet forest and boreal wet forest (CoolTemMoistFor-CoolTemWetFor-BorealWetFor)	>6.00	<1000	<0.50
25	Transition zone between cool temperate wet forest, cool temperate rain forest and boreal rain forest (CoolTemWetFor-CoolTemRainFor-BorealRainFor)	>6.00	<2000	<0.25
26	Transition zone between cool temperate desert, cool temperate desert scrub and warm temperate desert (CoolTemDes-CoolTemDesScr-WarmTemDes)	<12.00	>125	>4.00
27	Transition zone between cool temperate desert scrub, cool temperate steppe and warm temperate thorn steppe (CoolTemDesScr-CoolTemSte-WarmTemThornSte)	<12.00	>250	>2.00
28	Transition zone between cool temperate steppe, cool temperate moist forest and warm temperate dry forest (CoolTemSte-CoolTemMoistFor-WarmTemDryFor)	<12.00	>500	>1.00
29	Transition zone between cool temperate moist forest, cool temperate wet forest and warm temperate moist forest (CoolTemMoistFor-CoolTemWetFor-WarmTemMoistFor)	<12.00	>1000	>0.50
30	Transition zone between cool temperate wet forest, cool temperate rain forest and warm temperate wet forest (CoolTemWetFor-CoolTemRainFor-WarmTemWetFor)	<12.00	>2000	>0.25
31	Transition zone between warm temperate desert, warm temperate desert scrub and cool temperate desert (WarmTemDes-WarmTemDesScr-CoolTemDes)	>12.00	<125	<8.00
32	Transition zone between warm temperate desert scrub, warm temperate thorn steppe and cool temperate desert scrub (WarmTemDesScr-WarmTemThornSte-CoolTemDesScr)	>12.00	<250	<4.00
33	Transition zone between warm temperate thorn steppe, warm temperate dry forest and cool temperate steppe (WarmTemthornSte-WarmTemDryFor-CoolTemSte)	>12.00	<500	<2.00
34	Transition zone between warm temperate dry forest, warm temperate moist forest and cool temperate moist forest (WarmTemDryFor-WarmTemMoistFor-CoolTemMoistFor)	>12.00	<1000	<1.00
35	Transition zone between warm temperate moist forest, warm temperate wet forest and cool temperate wet forest (WarmTemMoistFor-WarmTemWetFor-CoolTemWetFor)	>12.00	<2000	<0.50
36	Transition zone between warm temperate wet forest, warm temperate rain forest and cool temperate rain forest (WarmTemWetFor-WarmTemRainFor-CoolTemRainFor)	>12.00	<4000	<0.25
37	Transition zone between subtropical desert, subtropical desert scrub and tropical desert scrub (SubtroDes-SubtroDesScr-TroDesScr)	<24.00	>125	>8.00
38	Transition zone between subtropical desert scrub, subtropical thorn steppe and tropical thorn forest (SubtroDesScr-SubtroThornSte-TroThornFor)	<24.00	>250	>4.00
39	Transition zone between subtropical thorn woodland, subtropical dry forest and tropical very dry forest (SubtroThornWood-SubtroDryFor-TroVeryDryFor)	<24.00	>500	>2.00
40	Transition zone between subtropical dry forest, subtropical moist forest and tropical dry forest (SubtroDryFor-SubtroMoistFor-TroDryFor)	<24.00	>1000	>1.00
41	Transition zone between subtropical moist forest, subtropical wet forest and tropical moist forest (SubtroMoistFor-SubtroWetFor-TroMoistFor)	<24.00	>2000	>0.50

Table 1 (*Continued*)

Code	Name of transition zone	MAB (°C)	TAP (mm)	PER
42	Transition zone between subtropical wet forest, subtropical rain forest and tropical wet forest (SubtroWetFor-SubtroRainFor-TroWetFor)	<24.00	>4000	>0.25
43	Transition zone between tropical desert, tropical desert scrub and subtropical desert (TroDes-TroDesScr-SubtroDes)	>24.00	<125	<16.00
44	Transition zone between tropical desert scrub, tropical thorn woodland and subtropical desert scrub (TroDesScr-TroDesThornwood-SubtroDesScr)	>24.00	<250	<8.00
45	Transition zone between tropical thorn woodland, tropical very dry forest and subtropical thorn woodland (TroThornWood-TroVeryDryFor-SubtroThornWood)	>24.00	<500	<4.00
46	Transition zone between tropical very dry forest, tropical dry forest and subtropical dry forest (TroVeryDryFor-TroDryFor-SubtroDryFor)	>24.00	<1000	<2.00
47	Transition zone between tropical dry forest, tropical moist forest and subtropical moist forest (TroDryFor-TroMoistFor-SubtroMoistFor)	>24.00	<2000	<1.00
48	Transition zone between tropical moist forest, tropical wet forest and subtropical wet forest (TroMoistFor-TroWetFor-SubtroWetFor)	>24.00	<4000	<0.50
49	Transition zone between tropical wet forest, tropical rain forest and subtropical wet forest (TroWetFor-TroRainFor-SubtroWetFor)	>24.00	<8000	<0.25

index of land-cover (PNTIL) was developed to quantitatively evaluate the land-cover transformation trends of BTZ; within which the positive transformation indicates that the land-cover change is beneficial and reduces the eroding, overgrazing and drought-ravaged in Loess Plateau, and to improve the capacity of ecosystem services. Conversely negative transformation shows the land-cover change will increase the possibility of soil erosion of Loess Plateau. The PNTIL in each BTZ type is formulated as:

$$\mathrm{LCTR}_{i,k} = \left(\frac{\Delta S_{i,k}}{S_i}\right) \times \frac{1}{t} \times 100 \tag{5}$$

where $\mathrm{LCTR}_{i,k}$ is the k direction transformation rate of land-cover in ith BTZ type; $k=1$, 2, are respectively the positive and negative transformation rates of land-cover in the investigation area; t is the variable of time; S_i is the area of land-cover in ith BTZ type; $\Delta S_{i,k}$ is the k direction transformation area of land-cover in ith BTZ type.

2.4. Indices of ecological diversity and patch connectivity

The ecological diversity index can be used to formulate aspects of uniformity and richness in ecological diversity; this is formulated as (Yue, 2010; Yue et al., 2005, 2011).

$$D(t)_i = \frac{\ln\left(\sum_{j=1}^{m(\varepsilon_i)} (P_{i_j}(t))^{1/2}\right)^2}{\ln \varepsilon_i} \tag{6}$$

where $D(t)$ and $m(\varepsilon_i)$ are respectively the ecological diversity and total number of land-cover patches of the ith BTZ type; $P_{i_j}(t)$ is probability of the jth land-cover type by ith BTZ type; $\varepsilon_i = 1/(e + A_i)$, A_i is the area of the ith BTZ type measured in km^2, and e equals 2.71828.

To express the average movement efficiency of migrants or propagules in patches of any region under investigation (Risser

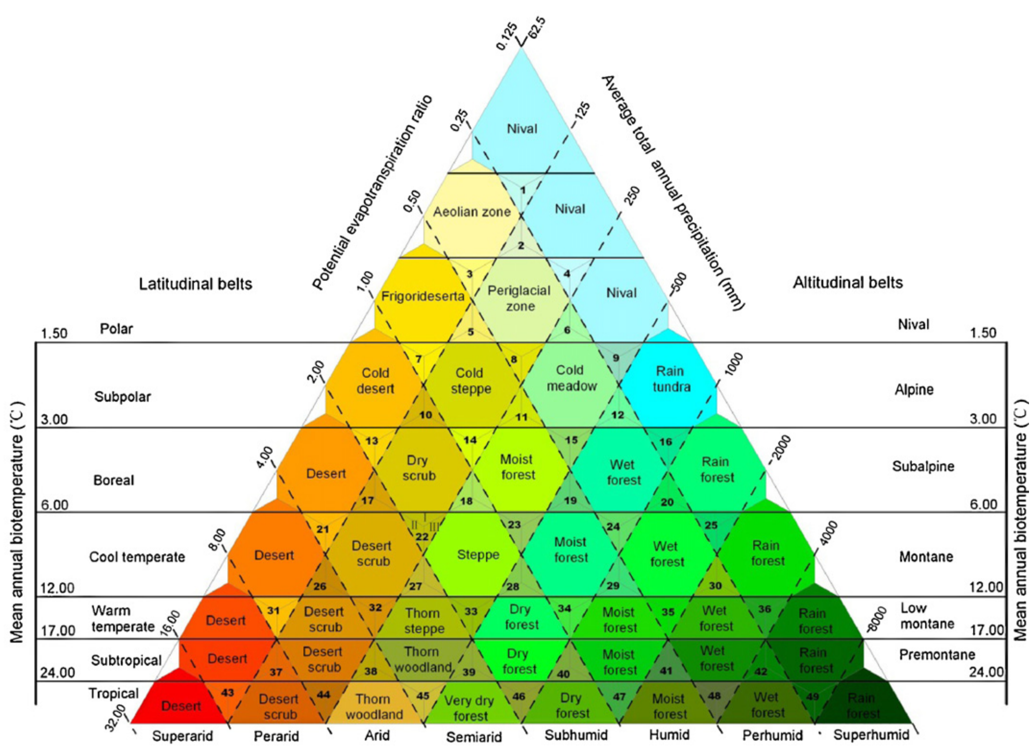

Fig. 3. The modified conceptual model of HLZ (developed by Holdridge, 1947).

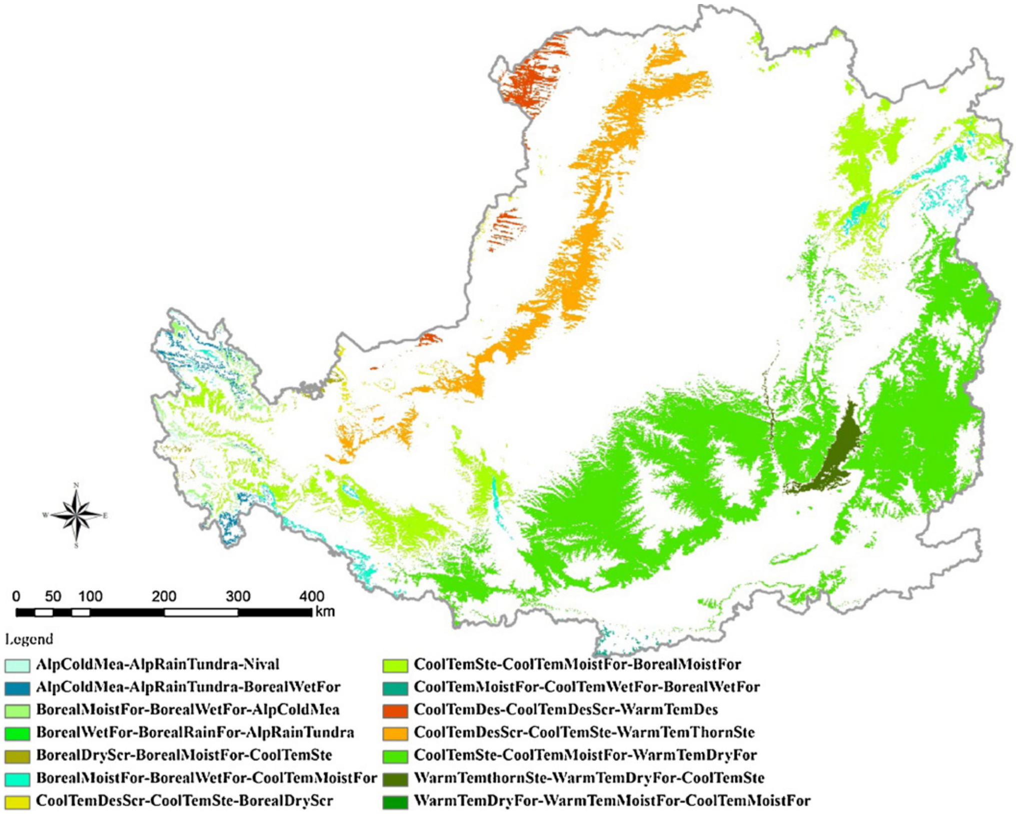

Fig. 4. Average spatial distribution of BTZs in Loess Plateau from 1985 to 2005.

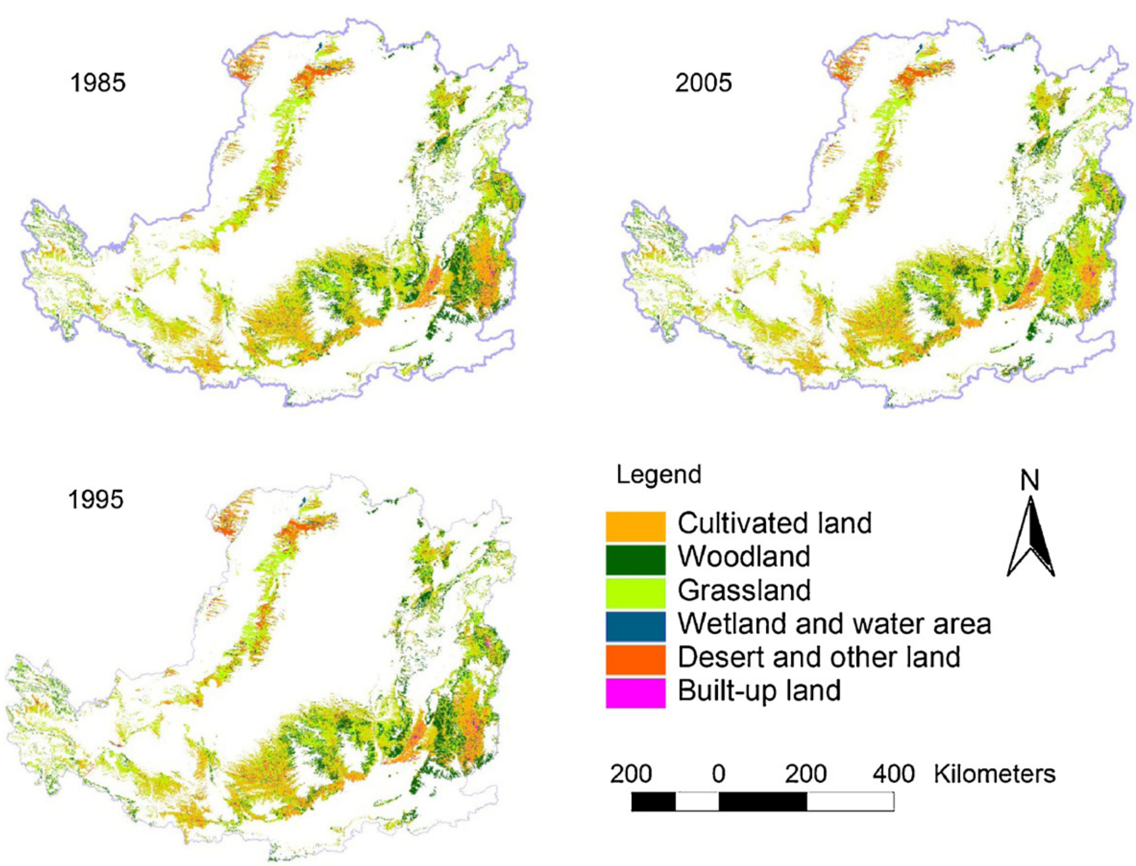

Fig. 5. Land-cover spatial distribution in BTZ of Loess Plateau across different periods.

Table 2
Regulations to define the transform direction of land-cover in Loess Plateau's BTZ.

Land-cover type	Original type	Transformed type	Transform direction
Cultivated land (I)	I	II	+
	I	III	+
	I	IV	+
	I	V	−
	I	VI	−
Woodland (II)	II	I	−
	II	III	−
	II	IV	−
	II	V	−
	II	VI	−
Grassland (III)	III	I	−
	III	II	+
	III	IV	+
	III	V	−
	III	VI	−
Wetland and water area (IV)	IV	I	−
	IV	II	+
	IV	III	−
	IV	V	−
	IV	VI	−
Desert and other land (V)	V	I	+
	V	II	+
	V	III	+
	V	IV	+
	V	VI	+
Built-up land (VI)	VI	I	+
	VI	II	+
	VI	III	+
	VI	IV	+
	VI	V	−

"+" and "−" respectively express the positive transformation and negative transformation of land-cover.

et al., 1984), patch connectivity index can be formulated as (Yue et al., 2005, 2006; Fan, 2005).

$$CO_i = \sum_{f=1}^{m_i(t)} \sum_{g=1}^{n_{i_f}(t)} P_{i_{fg}}(t) \cdot S_{i_{fg}}(t) \tag{7}$$

where $m_i(t)$ is the total number of land-cover types in each ith BTZ type; $n_{i_f}(t)$ is the total number of land-cover patches of each fth land-cover type within the ith BTZ type; $P_{i_{fg}}(t)$ is the proportional area of gth land-cover patches in the total area of the fth land-cover type in the ith BTZ type; $S_{i_{fg}}(t) = 8\sqrt{3} \cdot A_{i_{fg}} / Pr^2_{i_{fg}}$, $A_{i_{fg}}$ and $Pr^2_{i_{fg}}$ are respectively the area and the perimeter of the gth land-cover patch of the fth land-cover type in the ith BTZ type, coefficient $8\sqrt{3}$ is the ratio of the square of perimeter to the area of a hexagon, $0 \le CO_i \le 1$; t is the variable of time.

3. Results

3.1. Spatial distribution of BTZs in Loess Plateau

The BTZ simulation results show that there was an average of 14 BTZ types in Loess Plateau between 1985 and 2005 (Fig. 4). The BTZ that was most often represented was the transition zone between cool temperate desert scrub, cool temperate steppe and warm temperate thorn steppe (CoolTemSte-CoolTemMoistFor-WarmTemDryFor), transition zone between cool temperate steppe, cool temperate moist forest and boreal moist forest (CoolTemSte-CoolTemMoistFor-BorealMoistFor), and transition zone between cool temperate desert scrub, cool temperate steppe and warm temperate thorn steppe (CoolTemDesScr-CoolTemSte-WarmTemThornSte). They respectively cover 60.86%, 14.83% and 13.32% of the total area of BTZs in Loess Plateau. CoolTemSte-CoolTemMoistFor-WarmTemDryFor was mainly distributed in the mountainous and hilly regions along the north bank of the Weihe River and the south of the Lvliang-Taihang Mountains. CoolTemSte-CoolTemMoistFor-BorealMoistFor was mainly distributed in the north of Lvliang-Taihang, Qilian and Liupanshan mountains. CoolTemDesScr-CoolTemSte-WarmTemThornSte was mainly distributed in the eastern Ordos Plateau and northwestern Shanbei Plateau. The transition zone between cool temperate desert, cool temperate desert scrub and warm temperate desert (CoolTemDes-CoolTemDesScr-WarmTemDes), accounted for 2.44% of the total area of BTZs in Loess Plateau and were distributed across the northwestern Ordos Plateau, the border area of Inner Mongolia Plateau and the central area of Ningxia plain. Transition zone between boreal moist forest, boreal wet forest and cool temperate moist forest (BorealMoistFor-BorealWetFor-CoolTemMoistFor), covered 2.22% of the total area of BTZs, they were distributed in the high altitude areas of Lvliang-Taihang, Qilian and Liupanshan mountains. Transition zone between warm temperate thorn steppe, warm temperate dry forest and cool temperate steppe (WarmTemthornSte-WarmTemDryFor-CoolTemSte) accounted for 2.37% of the total area of BTZs and were distributed in the Fen-Wei Basin located in the south of Lvliang-Taihang Mountains. The remaining BTZs, which only cover 3.95% of the total area of BTZs in Loess Plateau, were scattered in Qilian Mountains, and include transition zone between alpine cold meadow, alpine rain tundra and nival area (AlpColdMea-AlpRainTundra-Nival), transition zone between alpine cold meadow, alpine rain tundra and boreal wet forest (AlpColdMea-AlpRainTundra-BorealWetFor), transition zone between boreal moist forest, boreal wet forest and alpine cold meadow (BorealMoistFor-BorealWetFor-AlpColdMea), transition zone between boreal wet forest, boreal rain forest and alpine rain tundra (BorealWetFor-BorealRainFor-AlpRainTundra), transition zone between boreal dry scrub, boreal moist forest and cool temperate steppe (BorealDryScr-BorealMoistFor-CoolTemSte), transition zone between boreal moist forest, boreal wet forest and cool temperate moist forest (CoolTemDesScr-CoolTemSte-BorealDryScr), transition zone between cool temperate moist forest, cool temperate wet forest and boreal wet forest (CoolTemMoistFor-CoolTemWetFor-BorealWetFor), and finally transition zone between warm temperate dry forest, warm temperate moist forest and cool temperate moist forest (WarmTemDryFor-WarmTemMoistFor-CoolTemMoistFor).

3.2. Changes of land-cover area in BTZs

With regard to the results gained by analyzing the land-cover areas of BTZs in Loess Plateau in 1985, 1995 and 2005 (Fig. 5 and Table 3), grassland, cultivated land and woodland were the major land-cover types and respectively covered 40.25%, 32.99% and 20.22% of the average total area of BTZs between 1985 and 2005. The area of every land-cover type in all BTZs (except cultivated land) displayed an increasing trend between 1985–1995 and 1995–2005. The areas of built-up land, wetland and water area, and desert and other land showed a continuous increasing trend which respectively rose 9.61%, 3.47% and 0.84% per decade. Moreover, the areas of woodland, grassland and cultivated land exhibited a fluctuating change over the period. Areas of woodland decreased in the first decade and then increased in the second decade, with an overall increase of 0.24% per decade. Areas of grassland increased in the first decade and then decreased in the second decade, with an average growth of 0.06% per decade. Areas of cultivated land decreased in the first decade and then increased in the second decade, and generally decreased 0.93% overall per decade.

Table 3
Changes of land-cover area between BTZs and their adjacent biomes in Loess Plateau (unit: km^2).

Land-cover type	Transition zones				Adjacent biomes			
	1985	1995	2005	Decadal change rate (%)	1985	1995	2005	Decadal change rate (%)
Cultivated land	52,343	49,428	51,374	−0.93	154,975	154,377	153,344	−0.53
Wood land	32,076	27,421	32,231	0.24	60,693	58,389	62,997	1.90
Grassland	63,859	71,245	63,936	0.06	199,619	204,063	196,847	−0.69
Wetland and water area	1440	1476	1540	3.47	8292	7628	8328	0.22
Desert and other land	6166	6223	6269	0.84	36,264	35,020	36,445	0.25
Built-up land	2779	2870	3313	9.61	10,980	11,346	12,862	8.57

3.3. Transformation of land-cover in BTZs

Analyses on the land-cover transformation in all types of BTZ between 1985–1995 and 1995–2005 (Table 4) show that the transformed area (45,271 km^2) of land-cover during the first decade was less than (34,759 km^2) the second decade. The total transformation rates were 28.53% (comprise 13.71% positive transformation and 14.85% negative transformation) and 21.91% (comprise 11.44% positive transformation and 10.47% negative transformation) for the periods 1985–1995 and 1995–2005 respectively.

During the first decade, The WarmTemDryFor-WarmTemMoistFor-CoolTemMoistFor area mainly covered by wood land, in which the transformed area of land-cover was only 7 km^2, but displayed the largest transformation rate (33.33%) of all the BTZ types. CoolTemSte-CoolTemMoistFor-WarmTemDryFor area had the largest area of transformation (31,647 km^2) and the second highest transformation rate (30.80%). On the other hand, the WarmTemthornSte-WarmTemDryFor-CoolTemSte area had the lowest transformation rate (15.30%), and a transformed area of 575 km^2. The CoolTemSte-CoolTemMoistFor-

Table 4
Land-cover transformation of each BTZ type in Loess Plateau (unit: km^2).

BTZ type	Total area	From 1985 to 1995						From 1995 to 2005						Decadal change rate (%)
		Total transform		Positive transform		Negative transform		Total transform		Positive transform		Negative transform		
		Area	Rate (%)	Area	Rate (%)	Area	Rate (%)	Area	Rate (%)	Area	Rate (%)	Area	Rate (%)	
AlpColdMea-AlpRainTundra-Nival	255	50	19.61	17	6.67	33	12.94	40	15.69	21	8.24	19	7.45	−1.96
AlpColdMea-AlpRainTundra-BorealWetFor	2004	542	27.05	295	14.72	297	14.82	409	20.41	187	9.33	222	11.08	−3.32
BorealMoistFor-BorealWetFor-AlpColdMea	2325	480	20.65	244	10.49	236	10.15	387	16.65	193	8.3	194	8.34	−2.00
BorealWetFor-BorealRainFor-AlpRainTundra	10	3	30	1	10	2	20	0	0	0	0	0	0	
BorealDryScr-BorealMoistFor-CoolTemSte	584	103	17.64	60	10.27	43	7.36	105	17.98	45	7.71	60	10.27	0.17
BorealMoistFor-BorealWetFor-CoolTemMoistFor	3525	750	21.28	321	9.11	429	12.17	657	18.64	397	11.26	260	7.38	−1.32
CoolTemDesScr-CoolTemSte-BorealDryScr	660	139	21.06	67	10.15	72	10.91	141	21.36	61	9.24	80	12.12	0.15
CoolTemSte-CoolTemMoistFor-BorealMoistFor	23,522	6438	27.37	3019	12.83	3419	14.54	5022	21.35	2716	11.55	2307	9.81	−3.01
CoolTemMoistFor-CoolTemWetFor-BorealWetFor	442	73	16.52	35	7.92	38	8.6	8	1.81	1	0.23	7	1.58	−7.36
CoolTemDes-CoolTemDesScr-WarmTemDes	3877	826	21.31	348	8.98	478	12.33	849	21.9	498	12.84	351	9.05	0.30
CoolTemDesScr-CoolTemSte-WarmTemThornSte	21,135	3618	17.12	1742	8.24	1876	8.88	3761	17.8	1861	8.81	1900	8.99	0.34
CoolTemSte-CoolTemMoistFor-WarmTemDryFor	96,545	31,665	32.8	15,240	15.79	16,425	17.01	22,762	23.58	11,976	12.4	10,790	11.18	−4.61
WarmTemthornSte-WarmTemDryFor-CoolTemSte	3758	577	15.35	367	9.77	210	5.59	616	16.39	197	5.24	420	11.18	0.52
WarmTemDryFor-WarmTemMoistFor-CoolTemMoistFor	21	7	33.33	3	14.29	4	19.05	2	9.52	2	9.52	0	0	−11.91

WarmTemDryFor area mainly covered by cultivated land, in which there was the greatest positively transformed area (15,240 km^2) and the highest positively transformed rate (15.79%). The BorealWetFor-BorealRainFor-AlpRainTundra area mainly covered by grassland, in which there was the least positively and negatively transformed area (respectively, 1 km^2 and 2 km^2). The CoolTemSte-CoolTemMoistFor-WarmTemDryFor area was the largest negatively transformed area (16,425 km^2). The WarmTemthornSte-WarmTemDryFor-CoolTemSte area had the lowest negative transformation rate (5.59%). In general, the positive transformation rates were greater than the negative rates in all the BTZ types except the BorealMoistFor-BorealWetFor-AlpColdMea, BorealDryScr-BorealMoistFor-CoolTemSte and WarmTemthornSte-WarmTemDryFor-CoolTemSte areas.

During the second decade, we saw the largest transformed area (22,762 km^2) and the highest transformation rate (23.58%) in the CoolTemSte-CoolTemMoistFor-WarmTemDryFor area. The CoolTemSte-CoolTemMoistFor-WarmTemDryFor area was the greatest positively transformed area (11,976 km^2) as well as the largest negatively transformed area (10,790 km^2). The CoolTemDes-CoolTemDesScr-WarmTemDes area had the largest positive transformation rate (12.84%); CoolTemDesScr-CoolTemSte-BorealDryScr area had the largest negatively transformed rate (12.1%), while there was not any transformation in the BorealWetFor-BorealRainFor-AlpRainTundra area.

Comparing the transformed area of land-cover in the first decade with the transformed area in the second decade (Table 4) shows that the land-cover of most BTZ types generally had a decreasing transformation trend, and the decrease rate of negative transformation was generally higher than the increase rate of positive transformation in all BTZ types during the two decades. The results show that the total area of all BTZs was 158,663 km^2, accounting for 25.21% of the entire Loess Plateau area (Table 5) during the period 1985–2005. This means that there is over one fourth of land-cover in Loess Plateau belongs to the climate transition zone. There were 14 BTZ types in Loess Plateau, with the top three types, CoolTemSte-CoolTemMoistFor-WarmTemDryFor, CoolTemSte-CoolTemMoistFor-BorealMoistFor and CoolTemDesScr-CoolTemSte-WarmTemThornSte covering 88.99% of all BTZs, and the other 11 BTZ types covering only 11.01%.

Furthermore, comparing the transition zones with adjacent biomes (Table 5) shows that the total transformation rate of land-cover in all transition zones was 28.53% and 21.91% respectively during the two decades from 1985 to 1995 and 1995 to 2005, which is more than 22.87% and 17.66% of all of the adjacent biomes. In addition, discounting the first decade, the transformation rate of cultivated land, woodland, grassland, wetland, water area, desert and other land types including built-up land in all transition zones is higher than in all the adjacent biomes during the two decades.

3.4. Ecological diversity and patch connectivity of land-cover in BTZs

The results (Table 6) from the operating diversity index and the patch connectivity index for data corresponding to Fig. 5 show that the ecological diversity of the entire BTZs area generally increased (0.27% per decade), while patch connectivity showed a continuously increasing trend (1.01% per decade) during the two decades. However, the ecological diversity and patch connectivity of each BTZ type showed a fluctuating transformation trend during the two decades. Ecological diversity increased continuously in the CoolTemMoistFor-CoolTemWetFor-BorealWetFor area and the CoolTemDes-CoolTemDesScr-WarmTemDes area. It increased and then decreased in the seven BTZ types of AlpColdMea-AlpRainTundra-Nival, AlpColdMea-AlpRainTundra-BorealWetFor,

Table 5
The transformation of each land-cover type in BTZs and adjacent biomes (unit: km^2).

Zone type	Land-cover type	Total area in 1985	From 1985 to 1995						Total area in 1995	From 1995 to 2005						Total area in 2005
			Total change		Positive change		Negative change			Total change		Positive change		Negative change		
			Area	Rate (%)	Area	Rate (%)	Area	Rate (%)		Area	Rate (%)	Area	Rate (%)	Area	Rate (%)	
Whole BTZs	Cultivated land	52,343	15,952	30.48	14,826	28.32	1126	2.15	49,428	9364	18.94	8160	16.51	1207	2.44	47,992
	Wood land	32,076	11,009	34.32	0	0.00	11,009	34.32	27,421	4554	16.61	0	0.00	4555	16.61	39,249
	Grassland	63,859	15,479	24.24	4644	7.27	10,835	16.97	71,245	18,272	25.65	7858	11.03	10,416	14.62	52,460
	Wetland and water area	1440	586	40.69	35	2.43	551	38.26	1476	452	30.62	38	2.57	414	28.05	1596
	Desert and other land	6166	1125	18.25	1125	18.25	0	0.00	6223	1247	20.04	1247	20.04	0	0.00	6438
	Built-up land	2779	1120	40.30	1112	40.01	8	0.29	2870	870	30.31	852	29.69	18	0.63	10,928
Adjacent biomes	Cultivated land	154,975	36,237	23.38	32,213	20.79	4024	2.60	154,377	26,044	16.87	22,008	14.26	4036	2.61	153,344
	Wood land	60,693	15,017	24.74	0	0.00	15,017	24.74	58,389	9596	16.43	0	0.00	9596	16.43	62,997
	Grassland	199,619	41,577	20.83	9215	4.62	32,362	16.21	204,063	36,639	17.95	11,369	5.57	25,270	12.38	196,847
	Wetland and water area	8292	3284	39.60	219	2.64	3065	36.96	7628	2252	29.52	141	1.85	2111	27.67	8328
	Desert and other land	36,264	7569	20.87	7569	20.87	0	0.00	35,020	5782	16.51	5782	16.51	0	0.00	36,445
	Built-up land	10,980	4013	36.55	3935	35.84	78	0.71	11,346	2843	25.06	2761	24.33	82	0.72	12,862

Table 6
Ecological diversity and patch connectivity of land-cover in BTZs and adjacent biomes (unit: km^2).

Type	Ecological diversity			Patch connectivity		
	1985	1995	2005	1985	1995	2005
AlpColdMea-AlpRainTundra-Nival	0.2081	0.2113	0.2038	0.6797	0.7087	0.6997
AlpColdMea-AlpRainTundra-BorealWetFor	0.1339	0.1339	0.1296	0.6729	0.6571	0.6450
BorealMoistFor-BorealWetFor-AlpColdMea	0.1391	0.1427	0.1426	0.5890	0.5878	0.5864
BorealWetFor-BorealRainFor-AlpRainTundra	0.2558	0.2311	0.2311	0.7071	0.6366	0.6663
BorealDryScr-BorealMoistFor-CoolTemSte	0.2059	0.2043	0.2056	0.5110	0.4888	0.5127
BorealMoistFor-BorealWetFor-CoolTemMoistFor	0.1431	0.1438	0.1423	0.4083	0.3466	0.5421
CoolTemDesScr-CoolTemSte-BorealDryScr	0.1942	0.2056	0.1988	0.2543	0.1783	0.6255
CoolTemSte-CoolTemMoistFor-BorealMoistFor	0.1296	0.1290	0.1306	0.4598	0.4348	0.4702
CoolTemMoistFor-CoolTemWetFor-BorealWetFor	0.1049	0.1200	0.1273	0.5022	0.6086	0.5042
CoolTemDes-CoolTemDesScr-WarmTemDes	0.1899	0.1900	0.1911	0.5608	0.5823	0.4805
CoolTemDesScr-CoolTemSte-WarmTemThornSte	0.1404	0.1396	0.1426	0.3169	0.2958	0.3050
CoolTemSte-CoolTemMoistFor-WarmTemDryFor	0.1130	0.1128	0.1143	0.3557	0.4094	0.3778
WarmTemthornSte-WarmTemDryFor-CoolTemSte	0.1439	0.1545	0.1460	0.6738	0.6399	0.2170
WarmTemDryFor-WarmTemMoistFor-CoolTemMoistFor	0.3132	0.3781	0.3718	0.6287	0.4761	0.6516
Whole BTZs	0.1231	0.1225	0.1237	0.3819	0.3829	0.3896
Adjacent biomes	0.1168	0.1162	0.1177	0.2585	0.2567	0.2658

BorealMoistFor-BorealWetFor-AlpColdMea, BorealMoistFor-BorealWetFor-CoolTemMoistFor, CoolTemDesScr-CoolTemSte-BorealDryScr, WarmTemthornSte-WarmTemDryFor-CoolTemSte and WarmTemDryFor-WarmTemMoistFor-CoolTemMoistFor, and decreased and then increased in the other BTZ types. Furthermore, patch connectivity decreased continuously in the transition zones of AlpColdMea-AlpRainTundra-BorealWetFor, BorealMoistFor-BorealWetFor-AlpColdMea and WarmTemthornSte-WarmTemDryFor-CoolTemSte, increased and then decreased in the AlpColdMea-AlpRainTundra-Nival, the CoolTemMoistFor-CoolTemWetFor-BorealWetFor, the CoolTemDes-CoolTemDesScr-WarmTemDes and the CoolTemSte-CoolTemMoistFor-WarmTemDryFor BTZ types, and decreased and then increased in the other BTZ types.

4. Discussion and conclusions

The HLZ model fails to take into consideration physiological changes (Yue et al., 2005), and its accuracy is somewhat lower than in mechanistic models. It cannot display the transient response of vegetation (Yates et al., 2000) so is of little use for land planning and management at regional or biome scales (Herrick et al., 2006). However, the HLZ model is nonetheless a well-established correlative climate–vegetation model, effective when dealing with minimal data on MAB, TAP and PER, and has been used widely to achieve various objectives (Lugo et al., 1999). Because ecological potential depends mainly on climate in the long term (decades to centuries) (Herrick et al., 2006), the HLZ model can be a useful tool for identifying ecological units (life zones) (Lugo et al., 1999). Furthermore, biotemperature is defined as the mean of unit-period temperatures with substation of zero for all unit-period values below 0 °C and above 30 °C, which is a measurement of only the heat which is effective in plant growth (Holdridge, 1967; Holdridge et al., 1971). Precipitation as a climatic determinant of the life zones (Holdridge, 1967), different life zone types have different responses to the changes in precipitation patterns, and the responses of vegetation production to changes in precipitation pattern differ by both vegetation type and precipitation amount (Fang et al., 2005), but the increased precipitation promotes plant growth of temperate biomes (Lane et al., 1998; Knapp et al., 2002). Potential evapotranspiration is the amount of water that would be transpired under constantly optimal conditions of soil moisture and plant cover (Holdridge, 1967; Yue et al., 2005). The PER provides an index of biological humidity conditions (Yue et al., 2005). Thus, the classification method of BTZ can be used to identify the BTZs of Loess Plateau with MAB, TAP and PER in decadal level (from 1985 to 2005). In addition use of the land-cover data in 1985, 1995 and 2005 provides an effective means of assessing landscape levels in all BTZ type.

In both the transition zones and adjacent biomes in Loess Plateau, the area of cultivated land showed a decreasing trend, while the area of woodland and grassland showed an increasing trend during the two decades. The driving force of these changes came mainly from the implementation of the Grain-for-Green Programme, which required that all cultivated land with a slope over 25° be converted into woodland or grass land as a means of effectively controlling soil erosion (Wang et al., 2010). This meant that the area of returning cropland to forestry and afforestation on barren hills, for instance, went up 1.738 and 2.291 million hectares in Loess Plateau between 1999 and 2003 respectively (Jiao et al., 2005).

By the end of 2002, there were 113,500 silt dams and more than 4 million small erosion control projects (e.g. embankments, flood pools, water cellars, etc.) built in Loess Plateau (Xu, 2004). The precipitation showed a decreasing trend from 1956 to 2005 in Loess Plateau (Xin et al., 2009). The increasing trend of wetland and water area in Loess Plateau is mainly due to the erosion control project carried out during the last two decades and in terms of the results obtained by analyzing land-cover transformation in all transition zones and adjacent biomes, wetland and water area showed the highest transformation rate of all land-cover types during this period, demonstrating that wetland and water area is more sensitive than other land-cover types to climate change and human activities. It is therefore necessary to concentrate on maintaining and improving the efficiency of established erosion control projects when it comes to the government implementing policies to protect and restore ecosystem in Loess Plateau.

The results show that the increasing ratios of built-up land were 9.61% and 8.57% per decade respectively in transition zones and adjacent biomes in Loess Plateau during the period 1985–2005. This increase in built-up land mainly occurred around urban areas, indicating that urban expansion was a major contributor to the increase of built-up land in Loess Plateau during the two decades therefore urban planning should be prioritized where it comes to Loess Plateau.

The ecological diversity and patch connectivity of land-cover in all transition zones generally shows an increasing trend during the period 1985–2005, with the same change trend in all adjacent biomes. What's more, the ecological diversity and patch connectivity of land-cover in all transition zones is higher than that of adjacent biomes, which indicates that transition zones have higher ecological diversity and patch connectivity than adjacent biomes. However, higher ecological diversity of land-cover landscape in transition zones predicates more landscape fragmentation than adjacent biomes. Furthermore, land-cover landscape with higher ecological diversity may help the survival of more species in transition zones, but it is worth noting that the ecosystem of transition zones is more unstable than other biomes because the land-cover landscape is more susceptible to climate change and human activities.

In this paper, the transition zones can be classified using the improved HLZ model in Loess Plateau, and the total positive and negative transformation of land-cover in transition zones and adjacent biomes can be identified by using the PNTIL method. However, the major driving forces which led to the series transformation included urban expand, industry development, road construction, population increase, the Grain-for-Green Programme, the erosion control project, nature reserve establishments and climate change. We focused on researching and discussing every factor affecting land-cover change as well as which of these factors were major driving forces in our further research on PNTIL. Our results provide a solid preliminary assessment of land-cover changes, indicating that transition zones are more affected by climate change and human activities, as well as higher landscape diversity than adjacent biomes in Loess Plateau.

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