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Correlation between landscape fragmentation and sandy desertification: a case study in Horqin Sandy Land, China

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Abstract The exact roles of landscape fragmentation on sandy desertification are still not fully understood, especially with the impact of different land use types in spatial dimension. Taking patch size and shape into consideration, this paper selected the Ratio of Patch Size and the Fractal Dimension Index to establish a model that reveals the association between the area of bare sand land and the fragmentation of different land use types adjacent to bare sand land. Results indicated that (1) grass land and arable land contributed the most to landscape fragmentation processes in the regions adjacent to bare sand land during the period 1980 to 2010. Grass land occupied 54 % of the region adjacent to bare sand land in 1980. The Ratio of Patch Size of grass land decreased from 1980 to 2000 and increased after 2000. The Fractal Dimension Index of grass increased during the period 1980 to 1990 and decreased after 1990. Arable land expanded significantly during this period. The Ratio of Patch Size of arable land increased from 1980 to 1990 and decreased since 1990. The Fractal Dimension Index of arable land increased from 1990 to 2000 and decreased after 2000. (2) The Ratio of Patch Size and the Fractal Dimension Index were significantly related to the area of bare sand land. The role of landscape fragmentation was not linear to sandy desertification. There were both positive and negative effects of landscape fragmentation on sandy desertification. In 1980, the Ratio of Patch Size and the Fractal Dimension Index were negatively related to the area of bare sand land, showing that the landscape fragmentation and regularity of patches contributed to the expansion of sandy desertification. In 1990, 2000, and 2010, the Ratio of Patch Size and the Fractal Dimension Index were mostly positively related to the area of bare sand land, showing the landscape fragmentation and regularity of patches contributed to the reversion of sandy desertification in this phase. The absolute values of the coefficients were the highest for grass land in the regression models, so that grass land had the most important influence on sandy desertification.

Keywords Sandy desertification · Landscape fragmentation · Horqin Sandy Land

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Introduction

As a form of land degradation through wind erosion, mainly reflecting excessive human activities and climate change in arid, semi-arid, and part of sub-humid region (UNCCD 2004), sand desertification has become one of the most severe ecological and socioeconomic problems in Northern China (Liu et al. 2008; Wang and Zhu 2001). The area of sandy desertification increased rapidly, at a rate of 1560, 2100, 2460, and 3600 km^2 a^{-1} in the 1950s, 1970s, 1980s, and 1990s, respectively (CCICCD 2002; Wang et al. 2011). By 2000, the area of sandy desertification had reached 385,700 km^2 in northern China, and the direct economic loss associated with sandy desertification was about 54.1 billion RMB per year (Zhang et al. 1996). Although the trend of sandy desertification has been reversed in some places in Northern China since 2000, the problem of sandy desertification remains unresolved (Corbane et al. 2008; Helldén and Tottrup 2008; Wang et al. 2012; Xue et al. 2013).

Understanding landscape changes is regarded as one of the key steps in revealing the processes and mechanisms of sandy desertification (Hirche et al. 2011; Luo et al. 2005; Qi et al. 2012; Rost et al. 2003). In general, landscape is defined as a heterogeneous land area composed of a cluster of interacting ecosystems (Fu and Jones 2013; Rodiek, 1988). The landscape pattern changes are strongly related to ecological processes, which are represented by the flow and transfer of matter, energy, water, biota, and information within or among ecosystems (Nagendra et al. 2004), so that consensus exists around the fact that spatial heterogeneity is strongly related to the processes of sandy desertification. Different types of landscape metrics have been examined to interpret the landscape pattern changes and their ecological functions, based on the integration of remote sensing theories, socioeconomic methods, and geographic information system (GIS) tools (Chang et al. 1998; Maestre and Escudero 2009; Salinas and Mendieta 2013; Sun et al. 2008). For instance, Sun et al. (2007, 2008) used cost-distance connectivity as the key indicator for representing the risk of desertification over the period 1977–1997. Li (1997) used a diversity index, evenness index, and contagion index to quantify the extent of sandy desertification.

Fragmentation is one of the typical landscape processes. It represents the effects of human actions and natural processes on the environment that is dissected into spatially isolated parts with changes in biophysical factors, such as biodiversity and wildlife habitat, and socioeconomic activities (Galvin et al. 2005; Nagendra et al. 2004). During the process of landscape fragmentation, the original land cover may be removed, new edge habitat may be created, and the access for human activities may be increased (Burgess 1988; Li et al. 2009). As a result, landscape fragmentation results in smaller habitat patches, decreased connectivity between patches, decreased complexity of patch shapes, a higher proportions of edge habitat, and then functional changes in ecological systems (Bar Massada et al. 2008; Fan and Myint 2014; Nams 2012).

The exact roles of landscape fragmentation to sandy desertification have been widely discussed in previous studies. Some researchers claimed that landscape fragmentation resulting from human reclamation and grazing activities could destroy the integrality of vegetation cover. The land cover changes could create higher opportunities for soil exposure to wind which contributed to land degradation and sandy desertification (Bogaert et al. 2000; Galvin et al. 2005; Jaeger 2000; Sun et al. 2005). Soil properties might be changed during the isolation of vegetative patches. This shift also could have a strong effect on the underlying soil (Mueller et al. 2007; Reynolds et al. 1999). For instance, Schlesinger et al. claimed that nutrition distribution in soil varied when arable lands were fragmented (Schlesinger et al. 1996). Studies monitoring ecosystem dynamics in arid regions also provided some evidence for the link between sandy desertification and landscape fragmentation over the long term (Hanafi and Jauffret 2008). As a result, some researchers believed that landscape fragmentation was a harbinger of sandy desertification (Maestre and Escudero 2009).

However, despite efforts at developing a theoretical framework and tools for interpreting the association between sandy desertification and landscape fragmentation, important uncertainties remain (Ci and Yang 2010; Maestre and Escudero 2009; Wang et al. 2011; Wang and Zhu 2001). There is an increased awareness that a better understanding of the interaction of landscape fragmentation and sandy desertification is needed. This paper utilizes two aspects of landscape fragmentation—patch size and the patch shape—to assess sandy desertification in Horqin Sandy Land during the period 1980 to 2010 in order to provide a better understanding about the relationship of landscape fragmentation on sandy desertification.

Materials and methods

Study area

Horqin Sandy Land is one of the four largest sandy lands in China (Alamusa et al. 2014; Bagan et al. 2010; Han et al. 2010; Li and Zhang 2015; Wu et al. 2013). It is located in a typical agricultural-pastoral region in Northern China, as shown in Fig. 1. Average annual temperature is around 3 to 7 °C, with a minimum value of −12 °C in January and a maximum value of 24 °C in July. Average annual precipitation is between 350 and 500 mm, 70 % of which falls in summer. Average annual evaporation is between 1500 and 2500 mm and average annual wind speed ranges from about 3.4 to 4.4 m s^{-1}, and the average wind velocity is about 4.2 to 5.9 m s^{-1} in spring. Traditionally, agricultural activities, like cultivating and grazing, are the main sources of income for local residents. Not surprisingly, this region is characterized by a preponderance of farm and grass lands. Because of its vulnerable ecological conditions, and the long-term effects of overgrazing, over-reclamation, and deforestation, sandy desertification frequently occurred. Sandy desertified land accounts for over 30 % of the total land area in Horqin Sandy Land. To rehabilitate desertified lands and improve regional eco-environments, some successful measures, including planting indigenous trees, shrubs, and grasses, have been implemented in parts of the Horqin Sandy Land since the mid-1970s (Yan et al. 2011; Zhang et al. 2012).

Landscape fragmentation metrics

Landscape fragmentation, or the breakup of a continuous habitat into smaller and less connected patches, can be differentially characterized. This paper utilizes two landscape indictors to represent the characteristics of landscape fragmentation at the patch scale—the Ratio of Patch Size and the Fractal Dimension Index.

The Ratio of Patch Size is defined as the ratio of the area of specific patch i to the average area of patches in the landscape, as shown in Eq. (1). A higher Ratio of Patch Size represents a higher continuity of the same patch. It reflects the numeric characteristics of landscape fragmentation.

$$\mathrm{RPS}_i = A_i / A \tag{1}$$

where RPS_i is the Ratio of Patch Size of a specific patch i, A_i is the area of patch i, and A is the average area of patches in a whole region.

The Fractal Dimension Index is defined as two times the logarithm of patch perimeter divided by the logarithm of the area of patch i. It reflects shape complexity across a range of spatial scales and is negatively correlated to landscape fragmentation. The Fractal Dimension Index is defined as Eq. (2).

$$\mathrm{FD}_i = \frac{2\ln(0.25P_i)}{\ln A_i} \tag{2}$$

where FD_i is the Fractal Dimension Index of patch i, and P_i is the perimeter of patch i. A_i is the area of patch i.

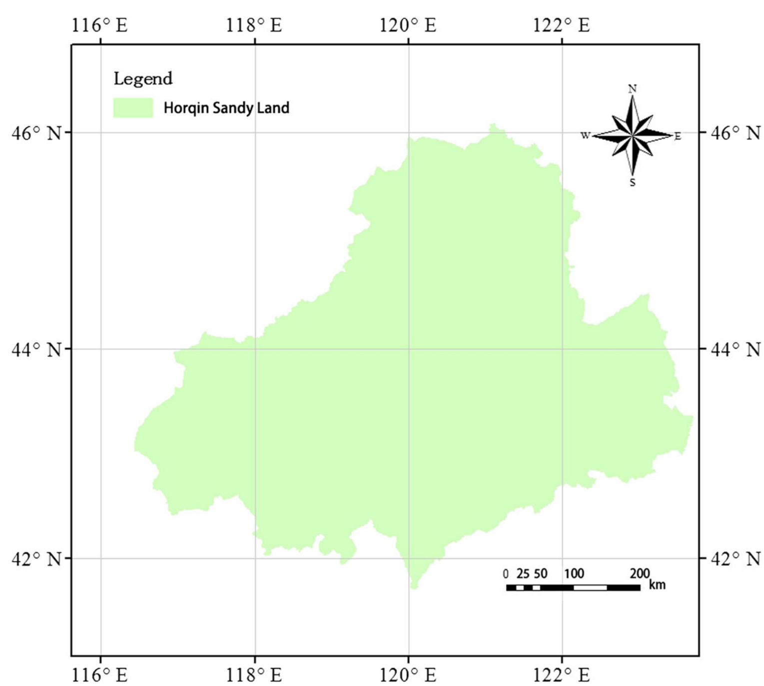


Fig. 1 The location of study area

Model for correlation analysis

Bare sand land is the critical indication for sandy desertification in a given region. The land is considered to be severely desertified when the proportion of bare sand land is high, while it is slightly desertified when the proportion of bare sand land is low. Thus, the area of bare sand land can be used to represent the extent of sandy desertification to some extent. An increase in bare sand land area indicates an expansion of sandy desertification, while a decrease in the area of bare sand land means a reversal of sandy desertification.

A basic assumption of this analysis is that fragmentation of all types of patches contributes to sandy desertification and, as a result, the area of bare sand land is indicated by the cumulative effect of landscape fragmentation across all patches adjacent to the bare sand lands, as shown in Eq. (3).

$$A_x = C_0 \cdot \prod_{i=1}^{n} \mathrm{RPS}_i^{\alpha_i} \cdot \prod_{i=1}^{n} \mathrm{FD}_i^{\beta_i} \tag{3}$$

where A_x is the area of bare sand land patch x, C_0 is the integrated efficient factor, RPS_i is the average value of the Ratio of Patch Size of the patches of the land use type i which are adjacent to the specific bare sand land patch x, FD_i is the average value of the Fractal Dimension Index of the patches of the land use type i which are adjacent to the specific bare sand land patch x, and α_i and β_i are the corresponding elasticity coefficients of RPS_i and FD_i, respectively.

To reveal the correlation between sandy desertification and landscape fragmentation, linear regression model in the form of logarithm is established, as shown in Eq. (4):

$$\ln A_0 = \ln C_0 + \sum_{i=1}^{n} (\alpha_i \cdot \ln \mathrm{RPS}_i) + \sum_{i=1}^{n} (\beta_i \cdot \ln \mathrm{FD}_i) + u \tag{4}$$

where α_i and β_i are the coefficients of corresponding $\ln\mathrm{RPS}_i$ and $\ln\mathrm{FD}_i$, respectively, and u represents the factors having influence on the area of bare sand land.

Before using the model to analyze the correlation between land use intensity and sandy desertification, a critical problem should be solved first. Generally, bare sand land is the source of sandy desertification. It may impact the adjacent patches. During the sandy desertification expansion, nearby spaces of bare sand land tend to have greater chances of being changed into sand land. Because of this condition, the spatial distribution of sandy desertification may not be random. The area of bare sand land could be spatially self-related to some extent. The regression results of Eq. (4) may be biased under the condition of the existence of spatial autocorrelation. Hence, a simultaneous autoregressive model (SAR) was estimated framed around the original model as shown in Eq. (5):

$$\ln A_x = \ln C_0 + \rho \cdot W_x \cdot \ln A_0 + \sum_{i=1}^{n} (\delta_i \cdot l\mathrm{nRPS}_i) + \sum_{i=1}^{n} (\phi_i \cdot \ln \mathrm{FD}_i) + u \tag{5}$$

where A_x is the area of bare sand land patch x, A_0 is the vector of the area of bare sand lands in the whole region of Horqin Sandy Land, W_x is the vector of spatial weights representing the spatial correlation between bare sand land patch x and any other bare sand land, and ρ is the autoregression coefficient, representing the integrated effect of spatial auto-correlation of bare sand lands.

In this paper, the vector of spatial weights is defined to reflect the distance between bare sand land patch x and other bare sand lands. Closer bare sand lands have higher weight values, as shown in Eqs. (6)~(8):

$$W_x = [a_{ix}]_{1 \times m} \tag{6}$$

$$a_{ix} = \begin{cases} 0 & i = x \\ \overline{d_{ix}}/d_{ix} & i \neq x \end{cases} \tag{7}$$

$$\overline{d_{ix}} = \frac{1}{m} \sum_{p=1}^{m} d_{ix} \tag{8}$$

where m is the amount of the bare sand lands, d_{ix} is the distance between the specific bare sand land patch x *and* any other bare sand land i, and a_{ix} is the weight of bare sand land i to bare sand land patch x.

Data acquisition and processing

Most of the data in this paper were extracted from Landsat MSS/TM/ETM images of 1980, 1990, 2000, and 2010, as shown in Table 1. All spectral data were

Table 1 The satellite remote sensing data being used in this paper

Year	Type	WRS	Path/row
1980	Landsat MSS	WRS1	128/29,128/30, 128/31,129/29, 129/30, 129/31, 130/28,130/29, 130/30 130/31, 131/28,131/29,131/30,131/31,132/28,132/29,132/30,132/31
1990/2000/2010	Landsat TM/ETM	WRS2	119/29,119/30, 119/31,120/29, 120/30, 120/31, 121/28,121/29, 121/30 121/31, 122/28,122/29,122/30,122/31,123/28,123/29,123/30,123/31

collected in summer or autumn, mainly in September. First, radio metric calibration, geometric correction, and cloud removal were conducted for all of these images. Then, they were geo-referenced to the WGS_1984 UTM Projected Coordinate System with a geometric precision of 0.5 pixels. Finally, geometric corrections and classifications were carried out. Field surveys were conducted in Tongliao City of Horqin Sandy Land in 2009, to better identify the objects from the satellite images. Seven land use types were identified including irrigated cultivated land, dry farmland, forestry, grassland, resident land, surface water, and bare sand land. The indicators of the proportion of bare sand land can be computed on the basis of resulting classification. The landscape fragmentation indicators were also calculated using satellite imagery.

Results

The changes of bare sand land

The area of bare sand land could reflect the extent of sandy desertification, and the distribution of bare sand land represented the regional land cover characteristics spatially. Figure 2 showed the changes of bare sand land during 1980–2010 in Horqin Sandy Land. Sandy desertification was more serious in 1990, while it was much better in 2010.

The spatial distribution of bare sand lands varied much during 1980–2010. There were 45,263 bare sand land patches with an average area of 0.17 km^2 and a maximum area of 9.7×10^2 km^2 in 1980, most of which were mainly concentrated in the center of Horqin Sandy Land. In 1990, the patch number of bare sand land patches increased to 292,233, which was more than six times the amount present in 1980. The average patch size of bare sand land was 0.16 km^2 in 1990, similar to that in 1980. The maximum patch area of bare sand land was 1.1×10^4 km^2, much larger than that in 1980. The maximum patch of sand land was approximately one fourth of the total area of bare sand land. This implied some smaller patches combined to form larger ones while new small patches of sand land emerged. In general, the fragmentation of bare sand lands was strengthened.

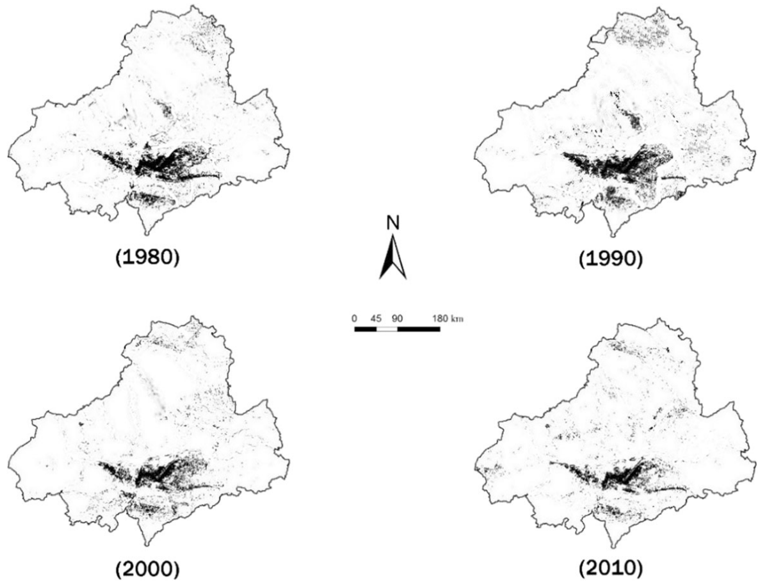
In 2000, the number of sand land patches decreased to 58,819. The maximum area of the bare sand land patches was 1.9×10^2 km^2, much smaller than that in 1980 or 1990. The average area of the sand land patches was 6.9×10^{-2} km^2. As both the number of sand land patches and the average area decreased greatly across the entire study area, sandy desertification had reversed by 2000.

In 2010, the number of sand land patches continued to decrease to a total of 45,263. The maximum patch area of sand land was 9.7×10^2 km^2, greater than that in 2000. The average patch size increased to 0.17 km^2 in 2010. This finding suggested that some patches of bare sand land were reversed and turned into another land use type, while other sand land patches expanded. Both the expansion and reversal of sandy desertification occurred over this period.

General landscape fragmentation changes in Horqin Sandy Land

Based on the land use classification, the landscape fragmentation indicators were calculated, as shown in Figs. 3 and 4. In 1980, the maximum and minimum values of the Ratio of Patch Size were 1.1×10^5 and 2.5×10^{-3}, respectively. More than 95 % of all patches (95.6 %) were smaller than the average area. Only less than 5 % of all patches had greater area than the average, but they covered 1.4×10^5 km^2 or 88.3 % of the entire landscape. It implied that the bigger patches could have the most dominant effect on the landscape pattern and functions. The Fractal Dimension Index ranged from 1.2014 to 1.6037,

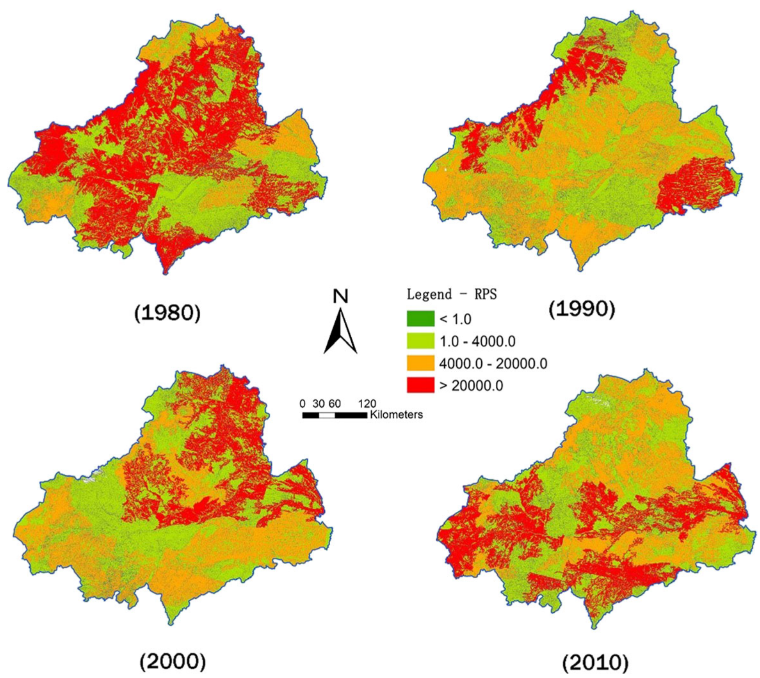
Fig. 2 The bare sand land in Horqin Sandy Land



with an average value of 1.3141. Of all patches, 56.9 % had a Fractal Dimension Index value greater than the average, implying that most patches were in relatively more irregular shape.

In 1990, the landscape was divided into smaller patches and the extent of landscape fragmentation increased, with a maximum patch area of 1.3×10^4 km^2 and minimum patch area of 5.8×10^{-4} km^2. These patch sizes were much smaller than those in 1980. The values of the Ratio of Patch Size ranged from 1.7×10^{-3} to 3.8×10^4. The gap between the maximum and the minimum values was narrowed, indicating that the extent of landscape fragmentation increased and the effect of bigger patches on the landscape was decreased. However, at

Fig. 3 The Ratio of Patch Size in Horqin Sandy Land



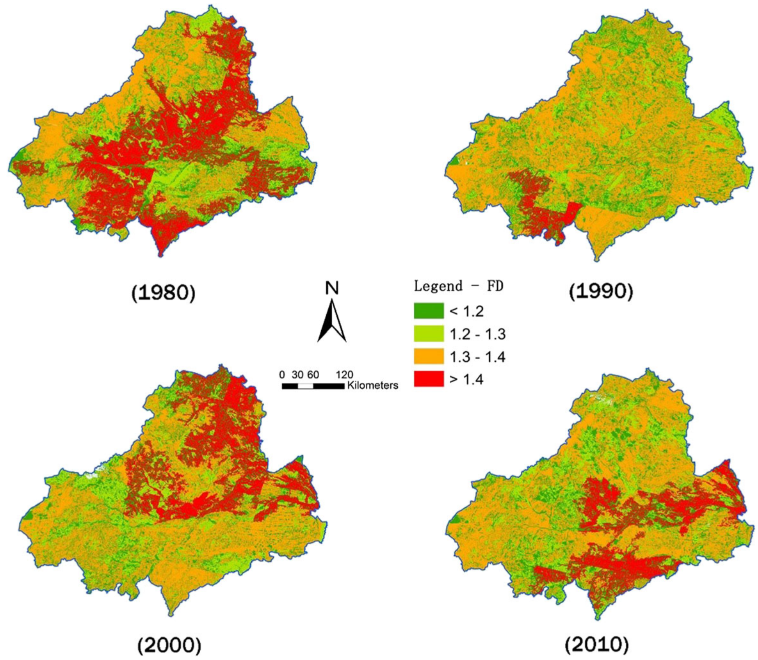


Fig. 4 The Fractal Dimension Index in Horqin Sandy Land

the same time, about 4.7 % of all patches had larger area than the average, and they covered 88.7 % of the whole landscape, while the smaller patches occupied only 11.3 % of the whole landscape. This situation was similar to that in 1980, indicating that all patches, including bigger ones and smaller ones, were fragmentized at a similar level, so that the area percentage of bigger patches and that of smaller patches remained similar to that in 1980. The Fractal Dimension Index ranged from 1.1798 to 1.5829, which was less than that in 1980, indicating the patches had more regular shape in 1990. Of all patches, 47.5 % had higher Fractal Dimension Index value than the average, while the other 52.5 % patches had lower Fractal Dimension Index value. The patch number slightly decreased to 431,749, reflecting a slight recovery of fragmentation. The maximum patch area was much larger than that in 1990, while the average patch area slightly increased to 0.35 km^2. Similarly, the Ratio of Patch Size ranged from 1.6×10^{-3} to 8.9×10^4, reflecting the further recovery of landscape fragmentation in 2000. The average fractal index was 1.3259. Patches (51.2 %) had lower Fractal Dimension Index value than the average. In 2010, the patch number continued to decrease, showing that the aggregation of the patches in the whole landscape. The minimum value of the Ratio of Patch Size was similar to that in 2000, and the maximum value was relatively larger. Some large patches were divided into smaller ones, while some relatively small patches were gathered together into bigger ones. Both fragmentation and aggregation were strengthened during the period 2000 to 2010. The average fractal index value was 1.3289, which was similar to that in 1990 and that in 2000.

In spatial dimension, the Ratio of Patch Size in the center and the east was higher than that in other part of Horqin Sandy Land in 1980. It obviously decreased in most parts of Horqin Sandy Land in 1990, while it slightly increased again in the center and the north during the period 1990–2000. After 2000, the Ratio of Patch Size decreased in the north but increased in the south. These patches with the highest value of Fractal Dimension Index were concentrated in the middle part of Horqin Sandy Land, indicating a relative high level of landscape fragmentation in this area.

Landscape fragmentation changes around bare sand lands

The characteristics of the patches adjacent to bare sand land were presented in Table 2. In 1980, 42,866 patches, 10 % of all, were adjacent to bare sand land patches. They covered 1.1×10^5 km^2, accounting for 69.9 % of the entire landscape. The average area of the patches adjacent to bare sand land was 2.6 km^2, much higher

Table 2 Characteristics of patches adjacent to bare sand land

Year	Patch number	RPS		FD	
		Minimum	Maximum	Average	Std
1980	42,866	1.4×10^{-3}	1.4×10^{4}	1.3233	0.028
1990	34,137	3.1×10^{-4}	4.6×10^{3}	1.3425	0.040
2000	21,785	2.0×10^{-4}	7.1×10^{4}	1.3395	0.041
2010	12,623	7.4×10^{-5}	1.9×10^{3}	1.3386	0.045

than that of all patches in Horqin Sandy Land. The maximum patch area was 3.8×10^{4} km^2, which was also the biggest of all patches, indicating that the biggest patches were in the region adjacent to bare sand land. The Ratio of Patch Size ranged from 1.4×10^{-3} to 1.4×10^{4}, indicating patches adjacent to the bare sand land were less fragmented. The Fractal Dimension Index ranged from 1.2014 to 1.5523 showing that the adjacent patches were in more regular shapes.

In 1990, the number of patches adjacent to the bare sand land decreased to 34,137. The average area of the patches adjacent to the bare sand land increased slightly to 2.9 km^2, much larger than that of all patches in Horqin Sandy Land. The maximum area of these patches was 1.3×10^{4} km^2, same as that of all patches in Horqin Sandy Land. It implied that the aggregation of patches occurred adjacent to the bare sand land, while the fragmentation was strengthened across the entire landscape. The Ratio of Patch Size ranged from 3.1×10^{-4} to 4.6×10^{3}. The Fractal Dimension Index ranged 1.1940 to 1.5932. The average value of the Fractal Dimension Index of the adjacent patches was higher than that of other patches. It was also higher than that of the adjacent patches in 1980. It implied that the patches adjacent to the bare sand land became more irregular than 1980.

In 2000, the patches adjacent to the bare sand land decreased to 21,785, while the patches of bare sand land decreased, and the total area of the patches adjacent to the bare sand land was 9.6×10^{4} km^2. At the same time, the average area of the patches adjacent to the bare sand land was 4.4 km^2. The Ratio of Patch Size ranged from 2.0×10^{-4} to 7.1×10^{4}. Fragmentation adjacent to bare sand land in 2000 was much less than that in 1990. The extent of fragmentation adjacent to the bare sand land was also less than that across the whole landscape. The Fractal Dimension Index ranged from 1.1942 to 1.5391, with an average value of 1.3395. The average value of Fractal Dimension Index was less than in 1990. And the same time, the Fractal Dimension Index of 55 % patches was less than the average among the adjacent patches of bare sand land. It implied that the patches were in more irregular shapes in 2000 than those in 1990.

In 2010, the patches adjacent to bare sand land decreased to 12,623, much less than that in 2000. However, the total area of the adjacent patches was 9.9×10^{4} km^2, higher than in 2000. The average area of the adjacent patches was larger. The Ratio of Patch Size ranged from 7.4×10^{-5} to 1.9×10^{3}. The difference between the minimum and maximum values of the Ratio of Patch Size was more significant. The Fractal Dimension Index ranged from 1.2008 to 1.5282, with an average value of 1.3386. The Fractal Dimension Index was similar to that in 2000.

Generally, the patches adjacent to bare sand land were relatively larger than others. They had higher value of the Ratio of Patch Size, lower value of the Fractal Dimension Index. And, land use changes occurred more frequently in the region adjacent to bare sand land.

The landscape fragmentation of different land use types around bare sand land

In general, during the period from 1980 to 2010, the area of surface water kept declining across the entire Horqin Sandy Land, so that the area of surface water adjacent to the bare sand land decreased rapidly. The area of wood land increased in Horqin Sandy Land but decreased in the region adjacent to bare sand land. As shown in Table 3, grass land, arable land, and wood land were the main land use types in the region adjacent to bare sand lands. Bare land, surface water, and resident land accounted for less than 3 % of this region. In 1980, grass land occupied 54 % of the total area of this region, while arable land covered only 17.9 %. The average area of grassland patches was 4.3 km^2, higher than that of arable land, which was 2.5 km^2. Grass land also had the longest

Table 3 The landscape fragmentation of different land use types around bare sand land

Year	Indicator	Water	Bare land	Grass land	Arable land	Wood land	Resident
1980	Patch number	524	15,947	13,142	7518	1575	1479
	Area (km^2)	574.1	2282.9	57,523.5	19,121.3	26,860.7	174.9
	Perimeter (km)	1773.4	25,429.1	229,074.9	141,723.4	66,477.5	2359.9
	RPS	0.4132	0.0540	1.6510	0.9594	6.4328	0.0446
	FD	1.3124	1.3202	1.3235	1.3318	1.3196	1.3202
	Patch number	189	6088	15,329	5170	2140	5221
	Area (km^2)	191.3	1172.9	44,127.5	27,211.2	26,190.9	788.8
1990	Perimeter (km)	7652.8	11244.1	175,287.0	112,870.1	96,234.7	11,136.6
	RPS	0.3466	0.0660	0.9858	1.8024	4.1912	0.0517
	FD	1.3320	1.3328	1.3451	1.3466	1.3361	1.3450
	Patch number	421	3665	10,580	3060	819	3240
	Area (km^2)	130.1	758.6	31,334.0	49,096.9	13,591.2	956.0
2000	Perimeter (km)	7826.9	7539.6	138,557.4	198,239.7	56,840.0	10,105.3
	RPS	0.0702	0.0470	0.6730	3.6460	3.7711	0.0671
	FD	1.3280	1.3279	1.3407	1.3469	1.3471	1.3411
	Patch number	25	3145	3043	3096	717	2617
	Area (km^2)	13.7	846.0	40,005.2	46,722.1	9631.9	1551.3
2010	Perimeter (km)	30.5	8030.5	185,608.9	142440.7	32,467.7	13,899.1
	RPS	0.3499	0.0344	1.5807	2.2391	1.7168	0.0758
	FD	1.2848	1.3330	1.3389	1.3365	1.3368	1.3471

edge among all land use types. The total edge of the grass land patches was 2.29×10^5 km. Grass land could have more chance to be affected by bare sand land, since most of its edge was shared with bare sand land. As a result, grass land would dominantly impact the landscape changes and the sandy desertification process in the region around bare sand land, because of the scale effect and the edge effect of patches. In the same region, the area of wood land was 2.7×10^4 km^2, while the area of arable land was 1.9×10^4 km^2. However, the average value of the Ratio of Patch Size of wood land was 6.4328. It was greater than that of any other land use type, including grass land, whose average value of the Ratio of Patch Size was 1.6509. It showed that grass land and wood land were relatively unbroken in 1980. Arable land had lower value of the Ratio of Patch Size of arable land and higher value of the Fractal Dimension Index than grass land and wood land. It implied that arable land was tend to be fragmentized and would have more irregular shape than grass land and wood land.

In 1990, arable land, grass land, and wood land were still the dominant land use types in the region adjacent to bare sand land. Arable land expanded quickly over the 1980 to 1990 period. The area of arable land increased by 42.3 % since 1980. The total area of arable land increased to 2.7×10^4 km^2, which was 50.2 % of the whole region adjacent to bare sand land, while the area of grass land decreased to 4.4×10^4 km^2, which covered 44.3 % of this whole region. Simultaneously, the average area of arable land obviously increased to 5.2 km^2, which was 206.9 % of that in 1980. The total area of wood land was similar to that in 1980, but the average area of wood land significantly decreased from 17.1 to 12.2 km^2. The Ratio of Patch Size of all land use types except arable land was lower in 1990 than that in 1980, suggesting some of the patches were divided into smaller ones. The average Fractal Dimension Index of all land use types was higher than that in 1980, respectively, suggesting the shape of the patches was more irregular.

In 2000, the area of grass land adjacent to bare sand land decreased to 3.1×10^4 km^2, while the area of arable land increased to 4.9×10^4 km^2. Arable land covered 51.2 % of the region around bare sand land. The grassland only covered 32.7 % of this region. This indicated that cultivation was still the dominant human activity during this period. The Ratio of Patch Size of arable land was 3.6460, reflecting the increase of the average area of the arable land. The Ratio of Patch Size of grass land decreased to 0.6730, implying that grass land was seriously fragmented and divided into small patches. The Fractal Dimension Index of grass land slightly decreased to 1.2407, while the Fractal Dimension Index of arable land increased slightly to 1.3469, showing the increasing of the extent of irregularity of arable land patches. The Ratio of Patch Size of wood land kept decreasing during the period 1990 to 2000, and the Fractal Dimension Index of wood land increased to 1.3471. During this period, grass land and wood land contributed to the landscape fragmentation, while arable land mainly contributed to the aggregation of small patches.

In 2010, the total area and average area of grass land significantly increased. The average area of grass land was 13.2 km^2, much higher than that in 2000. The Ratio of Patch Size of the grass land increased dominantly to 1.5807. The total area of arable land decreased by 4.8 %. It covered 47.3 % of the region around bare sand land. The average area of arable land decreased by 5.9 %. The Ratio of Patch Size of arable land decreased to 2.2391 from 3.646 in 2000. It implied that most arable land patches were divided into smaller patches. The total area of word land kept decreasing and the Ratio of Patch Size of wood land was much lower than that in 2000. At the same time, the Fractal Dimension Index of arable land, grass land, and wood land decreased slightly to 1.3368, 1.3389, and 1.3368, respectively. The result showed that the patches of all land use types had more regular shape in 2010.

SAR model results and analysis

In order to analyze the association between the area of bare sand land and fragmentation adjacent to the bare sand land patches, regression models of SAR were tested. Four regression models were established for the correlation between the area of bare sand land and the landscape fragmentation in 1980, 1990, 2000, and 2010, respectively, as shown in Table 4. All four models could be accepted, and the adjusted R^2 and F values were satisfactory. The F values of the regression models were 411.5, 6791.3, 5167.7, and 2230.5, respectively, with significance levels below 1 %. The values of adjusted R^2 were 0.195, 0.826, 0.809, and 0.740.

In 1980, most of the independent variables had significant influence on the area of bare sand land. The estimated coefficient of the Ratio of Patch Size of surface water was at a significance level beyond 5 %, while that of arable land was at a significance level below 5 %. The estimated coefficients of the Ratio of Patch Size of all other land use types were at a significance level below 1 %. The area of bare sand land was negatively related to the Ratio of Patch Size. It implied that the smaller patches adjacent to bare sand land would be easiest to contribute to the expansion of the sand land, so that the landscape fragmentation could help to accelerate the expansion of sandy desertification. The coefficient of RPS of grass land was −0.242, the absolute value of which was the highest among all land use types, so that grass land had the most important influence on the expansion of bare sand land. At the same time, the area of bare sand land was also negatively related to the Fractal Dimension Index. Lower Fractal Dimension Index represented the higher regularity of patches, so that the regularity of the patches adjacent to the bare sand land was positively related to the area of bare sand land. It implied that the regularity of the patch shape would contribute to the expansion of sandy desertification during this phase. The coefficient of FD of grass land was −12.061, the absolute value of which was the highest among all land use types, showing that the shape of grass land patches also had the dominant influence on the sandy desertification expansion. Besides grass land, bare land and surface water also had significant influence on the area of bare sand land. Compared to the Ratio of Patch Size, the Fractal Dimension Index had more influence on the area changes of bare sand land. The absolute value of FD of any land use type was higher than the corresponding absolute value of RPS. The effect of the spatial auto-correlation of bare sand land was also significant. The spatial auto-correlation term of the SAR model of year 1980 was positively related to the area of bare sand land at a significance level below 1 %. It implied that the area of bare sand land could increase when sandy desertification was serious in the whole region. Any bare sand land patch could contribute to the expansion of other bare sand land patches.

In 1990, the coefficient of spatial auto-correlation term was at a significance level beyond 5 %, while the coefficients of all other independent variables were at a significance level below 1 %. This implied that the effect of the autoregressive process of the dependent variable, the area of bare sand land, was not dominant during this period. The area changes of bare sand land

Table 4 The regression models of the SAR models

Regressor		1980 (n=25,570)			1990 (n=21,457)			2000 (n=18,341)			2010 (n=11,787)		
		Coefficient	T	Sig	Coefficient	T	Sig	Coefficient	T	Sig	Coefficient	T	Sig
Const		5.381	25.861	0.000	11.866	139.342	0.000	11.273	109.005	0.000	11.882	55.382	0.000
RPS	Surface water	0.006	0.307	0.759	0.102	8.453	0.000	0.141	12.850	0.000	−0.389	−2.674	0.008
	Bare land	−0.028	−5.496	0.000	0.233	70.744	0.000	0.199	53.717	0.000	0.205	35.811	0.000
	Grass land	−0.242	−56.611	0.000	0.506	156.689	0.000	0.456	133.592	0.000	−0.445	−91.436	0.000
	Arable land	−0.013	−2.033	0.042	0.244	80.339	0.000	0.278	88.578	0.000	0.289	54.478	0.000
	Wood land	−0.061	−6.569	0.000	−0.161	−47.648	0.000	−0.082	−11.810	0.000	0.159	16.420	0.000
	Resident	−0.164	−10.550	0.000	0.165	36.724	0.000	0.214	49.721	0.000	0.200	36.209	0.000
FD	Surface water	−3.301	−4.225	0.000	−3.917	−6.917	0.000	0.759	1.486	0.137	9.266	0.862	0.389
	Bare land	−5.823	−33.802	0.000	−0.384	−1.979	0.048	1.197	5.051	0.000	0.716	1.953	0.051
	Grass land	−12.061	−66.220	0.000	6.388	32.333	0.000	5.708	25.813	0.000	8.982	31.025	0.000
	Arable land	−1.205	−6.714	0.000	1.401	6.889	0.000	2.887	13.132	0.000	2.791	8.183	0.000
	Wood land	0.843	2.674	0.008	0.642	3.125	0.002	0.682	1.757	0.079	−0.253	−0.503	0.615
	Resident	−1.050	−2.014	0.044	1.073	4.335	0.000	1.100	4.329	0.000	−0.040	−0.116	0.908
Sample		25,569			21,456			18,340			11,786		
F		411.5			6791.3			5167.7			2230.5		
Sig		0.000			0.000			0.000			0.000		
Adjust R^2		0.195			0.826			0.809			0.740		

could be mainly induced by the landscape processes adjacent to the bare sand land. Different than in 1980, the coefficients of the Ratio of Patch Size of most land use types were positively related to the area of bare sand land, except that of wood land, suggesting the area expansion of the patches adjacent to the bare sand land contributed to the expansion of bare sand land. Among all land use types, grass land still had the most important influence on the area of bare sand land. The coefficient of the Ratio of Patch Size of grass land was 0.506, which meant that the area of bare sand land increased by 0.50 % when the Ratio of Patch Size of the grass land increased by 1 %. The Ratio of Patch Size of arable land and that of bare land also had dominant impact on the area of bare sand land as well. The estimated coefficient of the Ratio of Patch Size of arable land and that of bare land were 0.244 and 0.233, respectively, reflecting that the area of bare sand land would increase by 0.24 and 0.23 % when the area of the patches of arable land and bare land increased by 1 %, respectively. The Fractal Dimension Index of grass land, arable land, wood land, and resident was positively related to the area of bare sand land, while that of surface water and bare land were negatively related to the area of bare sand land. Among all land use types, the Fractal Dimension Index of grass land, whose coefficient was 6.388, had the most dominant impact. The absolute values of the coefficients of FD were higher than those of RPS, showing that patch shape still had greater influence on sandy desertification than patch size. The correlation between landscape processes was to some extent different to that in 1980.

In 2000, the correlation between landscape fragmentation processes and sandy desertification was similar to that in 1990. The spatial auto-correlation term was positively related to the area of bare sand land, implying that the expansion of bare sand land could impact the area of bare sand land at other spots. At the same time, the Ratio of Patch Size and the Fractal Dimension Index were positively related to the area of bare sand land at a significance level below 1 %, except that the Ratio of Patch Size of wood land was negatively related to the area of bare sand land at a significance level below 1 %. It implied that the increase of the area of wood land helped to decrease the area of bare sand land, while the expansion of arable land and grass land would help to accelerate the expansion of the area of bare sand land during this period. The increase of the Fractal Dimension Index, representing the increase of irregularity of the patches, would also increase the area of bare sand land. However, as a fact, the Fractal Dimension Index of all kinds of patches decreased in 2000. As a result, the decrease of the Fractal Dimension Index led to the decrease of area of bare sand land. Therefore, although the correlation between the landscape fragmentation process and sandy desertification was similar to that in 1990, the fragmentation process took two different roles: (1) the increase of patch area led to the expansion of sandy desertification, and (2) an increase in the extent of regularity led to the recovery of sandy desertification. Among all land use types, grass land had the most dominant impact on sandy desertification. The coefficient of the Ratio of Patch Size and that of the Fractal Dimension Index of grass land were 0.456 and 5.708, respectively, implying the area of bare sand land increased by 0.46 % when the Ratio of Patch Size of grass land increased by 1 %, and it decreased by 5.71 % when the Fractal Dimension Index of grass land decreased by 1 %. The results showed that the decrease of the Fractal Dimension Index, which meant the increase of the extent of regularity of the patches, greatly contributed to the recovery of sandy desertification in 2000, although the increase of the area of arable land, grass land, and resident, which represented the enhancing of the human activities, helped to accelerate the expansion of sandy desertification.

In 2010, the coefficient of spatial auto-correlation term and the coefficient of the Fractal Dimension Index of surface water were at a significance level beyond 5 %, while the coefficients of all other independent variables were at a significance level below 1 %. This implied that the effect of the autoregressive process of the dependent variable, the area of bare sand land, was not significant. The bare sand land itself had less influence on the changes of sandy desertification during this period. Since the area of bare sand land was much smaller than before, and the patch number of bare sand land was less than before, any bare sand land patch had less influence in accelerating the expansion of other bare sand land. During this period, the area and patch number of surface water decreased rapidly. Therefore, surface water also had less influence on the landscape changes and the process of sandy desertification. The Ratio of Patch Size of all land use types except grass land was positively related to the area of bare sand land. The coefficient of the Ratio of Patch Size of grass land was −0.445. The area of bare sand land would increase by 0.45 % when the Ratio of Patch Size of grass land decreased by 1 %. It implied that the aggregation of grass land patches during this period would help to alleviate the extent of sandy desertification, and the fragmentation of grass land patches would help to accelerate the sandy desertification expansion. The Fractal Dimension Index of grass land and arable land was positively related to the area of bare sand land. The absolute values of the coefficients of the Fractal Dimension Index of grass land and arable land were relative higher than those of other land use types, implying that grass land and arable land had dominant impact on sandy desertification. Compared to that in 2000, the role of arable land on the changes of bare sand land was obviously strengthened. The decrease of Fractal Dimension Index of grass land and arable land led to the decrease of the area of bare sand land in 2010.

Discussion

Influence of land use on landscape fragmentation

Patch size is an important factor to the ecological function of specific landscape pattern. A bigger patch may contain more species and have relative more complicated structure and functions. Materials and energy cycling may be more active in bigger patches, so that bigger patches may be more stable in providing ecological services during the ecological processes. The vegetation coverage is quite different between land use types. The components in any patch are therefore different. Nutrient cycling and water infiltration within and between the patches of different land use types will be bound to specific landscape pattern that is decided by the composition of mosaics of all land use types.

Patch shape is also an important factor to the ecological function of specific landscape pattern. In particular, the edge effect of the patches is vital in some vulnerable circumstances. In the edge regions of the patches, interaction of the materials and energy is quite active between the adjacent patches, especially between different land use type patches. The edges may also be the impediment for the translocation of the materials and the species. In sandy desertified lands, the edge regions of the patches are relatively more vulnerable to be eroded by wind, because the vegetation coverage in these regions is often changed and the soil is tended to be exposed because of different utility of the land. For any specific patch, the shape is more complex and irregular when the patch edge is longer and the patch area is smaller. The complexity of the patches may be impacted by both natural processes and anthropogenic processes.

Human activities will greatly interrupt the ecological services of the patches of specific land use types. The regions adjacent to bare sand land are sensitive to the changes of human activities. Sandy desertification mainly occurs in arable land and grass land, and the ecological restoration projects are designed according to the distribution of sandy desertification, so that bare sand land is spatially related to the distribution of arable land, grass land and wood land to some extent. As the main sources of family income, grazing and cultivation are the main types of agricultural activities of local residents. Livestock production and cereal cultivation are often depicted as major causes of land use changes and landscape pattern changes. Traditionally, nomadism was the dominant production mode for local residents. With heavy livestock intensity, grass land was fragmented with changes in vegetative cover, loss of soil nutrients, and decrease of surface heterogeneity. The results of this study suggested that Ratio of Patch Size of grass land continued to decrease from 1980 to 2000, showing that some bigger patches were divided into smaller ones, and the shape of these grass land patches became more irregular during this period. Since 2000, the limitation on grazing, such as the strategy of Grazing Prohibition Policy, was complemented. It helped to decrease both the human activities and the livestock pressures on grass land, so that the average patch area of grass land increased and the grass land patches became more regular. The landscape fragmentation processes were reversed.

As the grazing requires higher investment, some local families cannot afford the high cost of the grazing production. There is also higher risk of the investment on the grazing than on the cultivation. Cultivation becomes a very important way of making money for local residents. During some historical periods, reclamation frequently occurred, resulting in the expansion of arable land with the increasing of the patch area and the strengthening of the regularity of the patch shape of arable land. From 1980 to 2000, the number of arable land patches decreased significantly, while the total area of arable land highly increased. The expansion of arable land was the dominant process in the whole landscape. After 2000, some arable land-related ecological strategies were implemented in Horqin Sandy Land, including the strategy of Green for Grain, which asked local residents to turn some newly reclaimed farms back into grass land or wood land. Under these conditions, the total area of arable slightly decreased from 2000 to 2010. The shape of the arable land patches turned slightly more irregular.

Wood land also greatly contributes to the landscape changes. During some historic periods, the trees were widely cut for firewood in Horqin Sandy Land. These human activities also contributed to the expansion of sandy desertification. In recent several decades, to bring sandy desertification under control and reduce its influence on grasslands and farmlands, ecological restoration strategies were implemented in this region, including the strategies of Grain for Green Project, the Beijing and Tianjin Sandstorm Source Controlling Project, the Three-North Shelterbelt Project, etc. These projects pushed forward the afforestation, so that the total area of wood land obviously increased in the whole region of Horqin Sandy Land during the period 1980 to 2010. Generally, the ecological restoration projects were implemented adjacent in some seriously sandy desertified regions. Along with the reversion of sandy desertification from 1980 to 2010, the area of bare sand land in the seriously sandy desertified regions was obviously decreased. The proportion of the less sandy desertified regions increased, where the proportion of wood land was lower than that in the seriously sandy desertified regions. As a result, the proportion of wood land in the region adjacent to bare sand land decreased in temporal dimension.

It is interesting to find that surface water had less influence on the bare sand land. As water is the fluid of all life, the ecosystem around surface water provides a high stock of natural capital and the basis for life and economic development. Water use is important to the ecological balance in northern China. In historical period, surface water supported the human activities, cultivation, and grazing, with more than 95 % of the population and more than 90 % of social wealth in northern China, although it covers relatively smaller portion of the land than other land use types. Hence, the geographical distribution of surface water also contributed to the landscape fragmentation. However, the role of surface was eliminated along with the depletion of surface water. This phenomenon reveals that the way of using natural resources has been changed. The impact of human activities may have different influence on sandy desertification since recent years.

As a result, interaction between ecological factors and human activities frequently deeply impacts the landscape structure. Human activities may have two major influences on the landscape fragmentation: (1) the loss of nutrients from the upper layers of soil coupled to disturbance of vegetative cover and (2) changes in the landscape pattern with differences in patch size and patch shapes, which can result in various compositions of the landscape structures and also the functions.

Feedbacks of landscape fragmentation process

Landscape fragmentation has significant influence on the ecological functions. Soil is regarded as spatially homogeneous mass with specific vegetation cover. Land use is an important factor that has significant influence on land cover changes. Under the pressures of land use changes which are caused by anthropogenic activities such as human trampling, farming practices, and grazing activities, the vegetation cover tends to be destroyed and the soil is easy to be exposed to wind. The land cover changes with nutrient loss can result in increased landscape heterogeneity and landscape fragmentation.

Generally, it is believed that landscape fragmentation is positively related to the expansion of sandy desertification. In previous studies, researchers claimed landscape fragmentation noticeably affected the ecological functions. Small patches with irregular shape have relatively longer edges, which refer to the boundary between the adjacent patches and habitats. The patch edge is the interface of the water, sediment, and nutrient exchange between the vegetation and bare ground in arid and semi-arid ecosystems. It is vulnerable to the climatic conditions in arid-semi-arid areas. The changes of the landscape pattern may also interrupt the exchange of materials and energy between the patches and provide more opportunities for the soil to be exposed to wind and eroded under specific climatic conditions. Thus, fragmentation processes associated with the division of the landscape into smaller and irregular shapes could expose soil to higher risk of biomass loss and higher risk of sandy desertification. The landscape fragmentation is a fundamental ecological process for the expansion of sandy desertification.

The findings in this paper partially supported the views of previous studies. In 1980, the Ratio of Patch Size of any land use type was negatively related to the area of bare sand land, and the Fractal Dimension Index of most land use types was negatively related to the area of bare sand land, too. The landscape fragmentation, with smaller and more irregular patches, helped to accelerate the expansion of sandy desertification. The fragmentation of grass land and the expansion of arable land dominantly contributed to the process of sandy desertification.

Furthermore, this paper also found that there was also negative feedback along with the process of landscape fragmentation in Horqin Sandy Land during the period from 1980 to 2010. And, the negative feedback of landscape fragmentation varied between land use types. Empirical studies have demonstrated soil nutrients and water infiltration generally appear to have positive feedbacks involving litter deposition and wind erosion. The patches of different land use types have different vegetative coverage. The presence of perennial vegetation increases the infiltration of water into the soil and decreases the erosional capability of soil. While vegetative cover is lost during sandy desertification, the landscape results in higher heterogeneity with different patches of the nutrients. Hence, land use and its changes could lead to changes in landscape heterogeneity with different nutrients and water infiltration. In arable lands, the original ground vegetation can be destructed during the reclamation processes, while in grass lands, livestock's crunching and trampling do harm to the vegetation coverage of grassland and change the properties of soil's crust layer.

For grass land, it was recovered under some ecological restoration projects during 1990 to 2010, especially after 2000. The average patch area of grass land increased while the patch shape became more regular, with the releasing of grazing pressure and the decreasing of sandy desertification risk. Hence, the Ratio of Patch Size of grass land was negatively related to the area of bare sand land and the Fractal Dimension Index of grass land was positively related to the area of bare sand land in 2010.

As for arable land, it significantly expanded while the proportion of grass land decreased. Therefore, the expansion of arable land dominated the landscape fragmentation processes and mostly influenced sandy desertification. The average patch size adjacent to bare sand land tended to increase, and the Fractal Dimension Index decreased, so that the landscape became more homogeneous and less fragmented. Smaller patches were combined into larger ones. The expansion of arable land represented heavier pressure of human activities on land. Therefore, the aggregation of arable land patches would bring more risk of sandy desertification.

As a result, during the period 1990 to 2010, land use and land cover changes occurred frequently along with the combination of different patches. The synergistic effect of the landscape fragmentation of all kinds of land use types deeply influenced the risk of the soil being exposed to wind erosion increased. Therefore, landscape fragmentation presented either positive or negative effect on sandy desertification during different periods.

Conclusion

Landscape fragmentation may be related to the sandy desertification processes. This paper used the Ratio of Patch Size and the Fractal Dimension Index to represent landscape fragmentation and established a model to reveal the association between the area of bare sand land and fragmentation of different land use types adjacent to bare sand land. Results indicated that grass land and arable land contributed the most to landscape fragmentation processes in the regions adjacent to bare sand land during the period 1980 to 2010. Grass land occupied 54 % of the region adjacent to bare sand land in 1980. The Ratio of Patch Size of grass land decreased from 1980 to 2000 and increased after 2000. The Fractal Dimension Index of grass increased during the period 1980 to 1990 and decreased after 1990. Arable land expanded significantly during this period. The Ratio of Patch Size of arable land increased from 1980 to 1990 and decreased since 1990. The Fractal Dimension Index of arable land increased from 1990 to 2000 and decreased after 2000.

The Ratio of Patch Size and the Fractal Dimension Index were significantly related to the area of bare sand land. The role of landscape fragmentation was not linear to sandy desertification. There were both positive and negative effects of landscape fragmentation on sandy desertification: (1) in 1980, the Ratio of Patch Size and the Fractal Dimension Index were negatively related to the area of bare sand land, showing that the landscape fragmentation and regularity of patches contributed to the expansion of sandy desertification; and (2) in 1990, 2000, and 2010, the Ratio of Patch Size and the Fractal Dimension Index were mostly positively related to the area of bare sand land, showing the landscape fragmentation and regularity of patches contributed to the reversion of sandy desertification in this phase. The absolute values of the coefficients were the highest for grass land in the regression models.

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