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Vegetation diversity and its application in sandy desert revegetation on Tibetan Plateau

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Abstract

The dry and cold Tibetan Plateau is, by its nature, sensitive to desertification, and now human impacts and overexploitation makes things worse. One of the most important things involved in combating desertification is to stabilize mobile sandy land and facilitate revegetation. A study was conducted on shifting sand dunes of Tibetan Plateau to investigate the relationships among sand control, vegetation restoration and diversity dynamics of seed plant species. It was found that a positive correlation lay between sand stabilizing shrubs (*Caragana korshinskii* and *Artemisia ordosica*) and *Leymus secalinus*, a species of dominant and perennial grass in well-restored vegetation, but a negative correlation occurred between those shrubs and *Agriophyllum arenarium* indicator of shifting dunes. Secondly, sand stabilization facilitated revegetation, and total cover and cover of *L. secalinus* rose continuously from the beginning of restoration, but diversity indices showed a complex tendency. Based on these results, it was reasoned that on alpine shifting dunes of desertified regions, continual sand drifting caused by gales was the limiting factor for plant to survival. If sand barriers were established, sand drifting would be effectively controlled, then many native plant species could colonize shifting dunes gradually, so the process of revegetation was facilitated.

Keywords: Shifting sand dune; Species diversity; Revegetation; Colonization; Limiting factor

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1. Introduction

Tibetan Plateau, the highest point in the world has been suffering from severe desertification for many years. Tibetan Plateau has 12.17% of such lands of China (Lu, 2000; Zhang, 2000; Wu and Ci, 2002). The Plateau lies mainly in the Tibetan Autonomous Region and Qinghai Province of China.

Rainfall diminishes from more than 1000 mm in southeast to 40 mm in north-west, and over more than half of the Plateau the rainfall is less than 400 mm (Wu, 1995; Zhao, 1995). Altitude is an important factor everywhere on the Plateau, and strong wind ($>17\,\mathrm{m\,s^{-1}}$) is also a serious factor in many places. Mean annual temperature usually varies from -5.8 to 3.7 °C. Active accumulated temperature above 0 °C is less than 2000 °C. Additionally, the dry and cold climates determine the poor flora of Tibetan Plateau (Wu, 1995; Lu, 2000; Lin and Tang, 2001). Such unfavorable conditions make ecosystems fragile and sensitive to desertification, and severely retard vegetation restoration.

Due to heavy grazing and excessive conversion of rangeland to cropland, extensive grasslands were stripped of their vegetation and degraded into desertified lands in the past few decades. Combating desertification is important and urgent to conserve land resource and to achieve sustainable development on the Plateau. In past years, however, studies and practices on combating desertification of China basically focused on Xinjiang, Inner Mongolia and Gansu, and relatively less work was done on the Tibetan Plateau (Yang et al., 1997; Zhang et al., 2003; Zeng et al., 2003; Lu et al., 2004).

Considering this background, specific studies are needed on Tibetan Plateau to diagnose causes of desertification and to decide on proper measures to control it. A few studies have been done on the extent and mechanism of desertification there (Yan et al., 2001; Zou et al., 2002; Zhang et al., 2003), but few researches reported on sand fixation and vegetation restoration. It must be realized that vegetation restoration is the most difficult but important thing involved in combating desertification (Snyman, 2003; Visser et al., 2004).

On the issue of vegetation restoration, some ecologists argued that vegetation should be restored naturally rather than artificially (Bradshaw, 2000; Jiang, 2002). However, vegetation restoration on shifting sand dunes essentially belongs to primary succession instead of secondary succession (Misak and Draz, 1997; Lichtner, 1998). It seems that mere natural processes cannot necessarily bring about good revegetation on shifting sand dunes dotted across the grasslands. If so, artificial measures are needed in some degree. How should people effectively facilitate revegetation on shifting sand dunes? Irrigation seems inappropriate for these arid or semi-arid regions. Therefore, people should seek more advisable and feasible methods to restore vegetation on shifting sand dunes of Tibetan Plateau (Link et al., 1994; Bowers, 1996; Jiang, 2002). An outlet is the establishment of artificial sand barriers. Because such barriers can reduce wind velocity and activity of sand, they play vital roles in the process of revegetation (Dong et al., 1993; Liu and Zhao, 2001; Qiu et al., 2004).

With development of restoration ecology and understanding of principles of biodiversity, it is realized that species composition and diversity are fundamental characteristics of ecosystems (Chapin et al., 1992; Hooper and Vitousek, 1997; ESA, 1999; Burke, 2001), and vegetation diversity should be considered in the course of vegetation restoration (ESA, 1999; Burke, 2001). Therefore, if diversity dynamics is linked to vegetation restoration, some crucial constraints to revegetation in mobile sandy lands may be discovered. Unfortunately, few studies were done on this subject, especially in those areas of Tibetan Plateau. Due to this research background, investigation and studies were carried out on naturally and artificially restored vegetation on sand dunes of Gonghe Basin, one of the typical and main desertified regions of Tibetan Plateau (Yang et al., 1997; Zeng et al., 2003). The purposes of this study are: (1) to understand diversity dynamics of seed plant species in the process of vegetation restoration; (2) to reveal relationships among diversity dynamics, vegetation restoration and sand fixation; and (3) to seek the limiting factor to rehabilitation on shifting sand dunes of Tibetan Plateau.

2. Materials and methods

2.1. Study site

The study site is located at Gonghe Basin, in north-eastern Tibetan Plateau, between 35°27′N and 36°56′N latitude and between 98°20′E and 101°22′E longitude (Fig. 1). Gonghe Basin is well known for Longyangxia, the highest reservoir and hydropower station along the upper reaches of the Yellow River (Zhao et al., 2002). Gonghe Basin's elevations are above 2400 m; and the mean annual temperature is between 1.0 and 5.2 °C. Air temperature can sometimes drop to below 0 °C even in summer. The annual precipitation ranges from 158.6 to 619.6 mm, occurring usually in growing season from June to August. The annual potential evaporation is above 1528 mm. Gales can occur in every season. Zonal vegetation is typical steppe and desert steppe (Zhou et al., 1987; Dong et al., 1993). Steppe potentially lies in most part of the Basin, and its dominant species are *Stipa krylovii*, *Orinus thoroldii*, *Stipa breviflora*, *and Artemisia frigida*, etc. Desert steppe appears in some north-west places of the basin, and it consists of *Stipa breviflora*, *Heterocappus altaicus*, *Poa annua*, *Carex duriuscula*, *Leymus secalinus*, and other species.

Shazhuyu, in the north-west of the basin, has typical sandy lands of Tibetan Plateau and was seriously affected by sandy desertification. Landform principally results from wind erosion and sand deposition. Averagely, 50.6 days per year have winds with speeds higher than 17.2 m s^{-1} (Dong et al., 1993). Unfavorable natural conditions make grasslands there susceptible to desertification and hamper revegetation in sandy land.

Since 1958, Sand Control Experimental Station established by Government of Qinghai Province has focused on control of sandy desertification and to restore vegetation at Shazhuyu. On the severe conditions of wind blowing and sand drifting, physical sand barriers persist too few years to guarantee good vegetation restoration, and planting or seeding without physical sand barriers does not succeed in restoring vegetation either. Therefore, researchers introduced the integrative methods: while physical barriers were established, sand stabilizing shrubs such as *Caragana korshinskii* or *Artemisia ordosica* were seeded or transplanted. Due to application of such methods, vegetation has been restored on some dunes, and the dunes have been fixed. On these dunes, total cover and cover of *L. secalinus* are obviously higher than on bare dunes. *L. secalinus*, a perennial grass of the Gramineae family with powerful rootstocks, is regarded as an indicator of well-restored vegetation (WRV) in sandy land of Gonghe Basin because of good growth reflected from high cover, height about 30–80 cm and persistence. However, the remaining dunes unprotected from winds are still shifting not only because total plant cover is less than 10%, but also because dominant species are annual grasses such as indigenous *Agriophyllum arenarium*, rather than perennial plants. In the south of the experimental

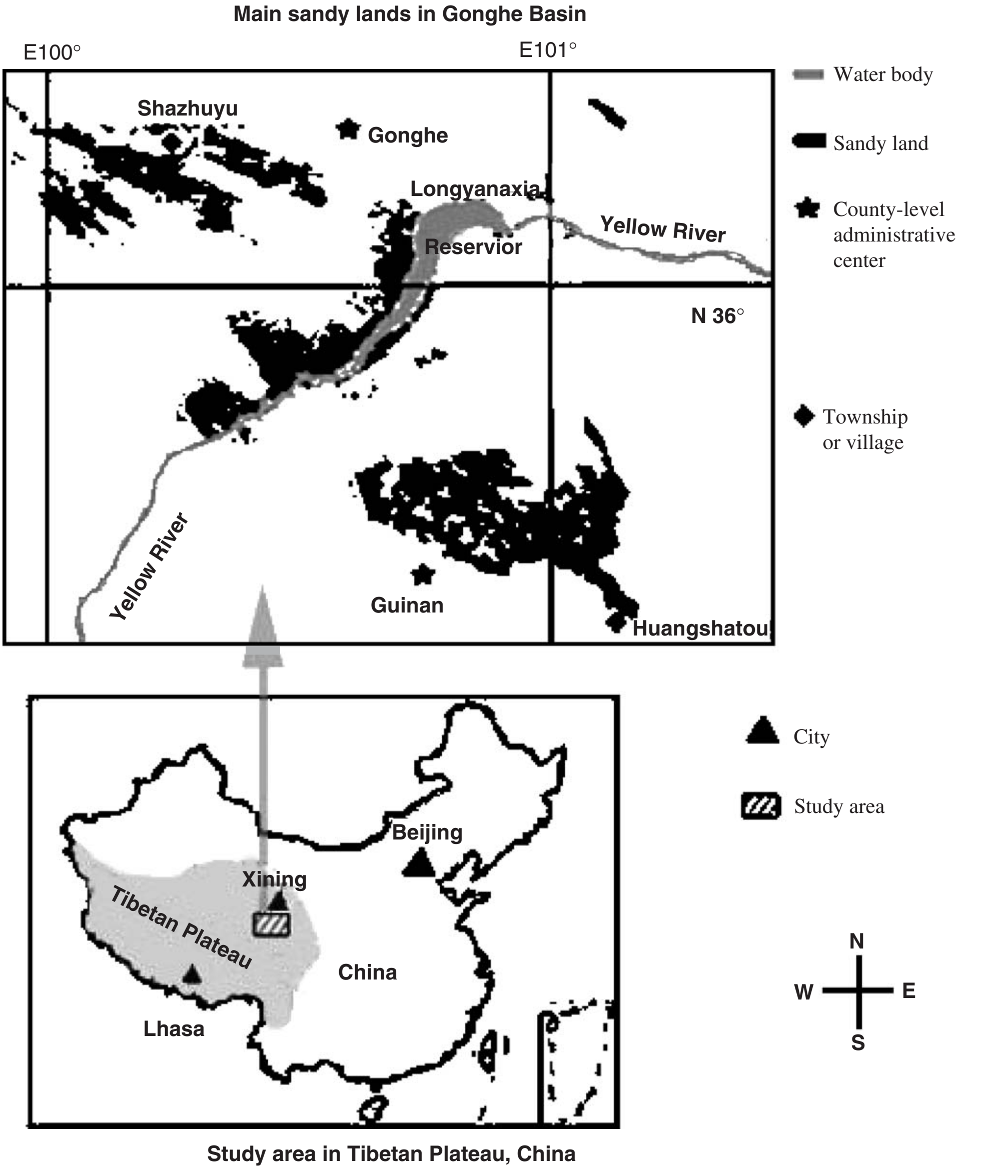

Fig. 1. Main sandy lands in Gonghe Basin. Study site was located at Shazhuyu a township of Gonghe County, Qinghai Province, China.

area, shifting sand dunes were fenced for about 45 years, but man-made sand barriers were never established there. These dunes restored their vegetations naturally but slowly all the time, and total cover is seldom higher than 10%, so that they are thought to be still at natural restoration stage (NRS). Inside the NRS, where artificial sand barriers were established to stabilize drifting sand and to promote vegetation restoration, the corresponding vegetation was called artificial sand fixation vegetation (AFV). AFV was dominated by *Caragana korshinskii* or *Artemisia ordosica* (Zhou et al., 1987). Further north but adjacent to the AFV, vegetation was called WRV, which was dominated by *L. secalinus* population.

2.2. Fieldwork

From August to September 2002, fieldwork was conducted at Shazhuyu. In order to understand vegetation variation in study area, two sampling methods were used in the survey.

The first method was the line transect method. Two independent transect sampling lines in width of 1 m were made from NRS to WRV in the experimental area. The first line was 665 m long, and the second was 520 m long. Both of them were subdivided into many continuous 5-m intervals. The line 665 m long included 133 contiguous plots of $5 \times 1\,m^2$ in size, and the line 520 m long included 104 such plots. For each interval, species composition and cover of every species were recorded in detail.

The other method was to survey with quadrats. All vegetation on sand dunes was classified into four types according to their habitats and histories of sand control (Table 1). Type 1 and Type 2, respectively, corresponded to the earlier and later stages of AFV. Every type was recorded with three independent or random quadrats ($5 \times 5\,m^2$). In each quadrat, total cover, species composition and cover of each species were recorded.

2.3. Analyses of transect data

Agriophyllum arenarium was regarded as an indicator species of NRS because it adapted well to shifting sand dunes (Zhou et al., 1987). *C. korshinskii* and *A. ordosica* were artificially planted to fix drifting sand, so they were viewed as sound indicator species of AFV. *L. secalinus* was taken to represent WRV mainly owing to its high cover or absolute dominance.

With the help of SAS 6.12, we worked out canonical correlation coefficients of the frequency on either sampling line between two of the three groups of indicator species. Thus, their relationships can be detected (Tang, 1986; Zhang, 1995; Gao, 2001). Presence/absence data were used for analysis.

We also studied the effects of *C. korshinskii* and *A. ordosica* on plant species richness and Shannon–Wiener index. Both transect lines were cut into three stages according to their own indicator species: NRS, AFV, and WRV. Every stage included from eight to more than 100 intervals. For each interval, we calculated Shannon–Wiener index (H) and richness ratio of plant species (S). Ratio of plant species richness was derived from the

Table 1
Classification of vegetations on controlled sand dunes of Shazhuyu

Restored vegetation	Measures used for sand control	Length of time being controlled	Number of quadrats
Type 1	Fenced but without sand barriers for about 45 years	Not controlled	1,2,3
Type 2	Controlled with physical sand barriers, and meanwhile shrubs were sowed or planted for future sand fixation	For 2–6 years	4,5,6
Type 3	Same as above	For 18 years or so	7,8,9
Type 4	Same as above	For 45 years or so	10,11,12

species number (not individual number of each species) at each interval divided by the largest species number at certain interval on the same line. Then, for each stage, we computed average Shannon–Wiener index (H) and average plant species richness ratio (S) of all intervals belonging to the same stage.

2.4. Analyses of quadrat data

With the software Canoco for Windows 4.5, correspondence analysis (CA) was performed to ordinate all quadrats and species (Greig-Smith, 1983; Ter Braak, 1985; Zhang, 1995). Data used for ordination were cover of every species. After that, changes of some main characteristics and α diversity indices were studied. Total cover and cover of *L. secalinus* were tested on their difference among four types with one-way ANOVA. Analyzed α diversity indices included Patrick index (D_p), Margalef index (D_m), Shannon–Wiener index (H) and Pielou evenness index (E) (Pielou, 1975; Ma, 1994; Zhang, 1995; Hegazy et al., 1998). Formulae are as follows:

$$D_p = S, \tag{1}$$

where S is species number in each quadrat;

$$D_m = (S - 1)/\ln N, \tag{2}$$

where S is species number in each quadrat, and N is sum of all covers of species;

$$H = -\Sigma P_i \ln P_i, \tag{3}$$

where P_i is proportion of cover of the ith species to sum of all covers of species in the same quadrat;

$$E = H/\ln S, \tag{4}$$

where H is Shannon–Wiener index and S is species number in each quadrat.

3. Results

3.1. From sampling lines

Canonical correspondence analysis indicated that the first group (*A. arenarium*) was negatively correlated with the second group (*C. korshinskii* and *A. ordosica*) and the third group (*L. secalinus*), but the second group positively correlated with the third group (Table 2, $p<0.01$).

The stages NRS and WRV showed significantly lower average plant species richness ratios (S) and average diversity measured by the Shannon–Wiener index (H) (Fig. 2, $p<0.05$).

3.2. From quadrats

An ordination plot generated by CA displayed the relationships between quadrats and species (Fig. 3). Distances between quadrats in the same vegetation type were usually less than between those in different types. As transitional stage from Type 1 to Type 3, however, Type 2 was exceptional for their large intra-type distances. Sand stabilizing shrubs *C. korshinskii* and *A. ordosica* mainly distributed in Type 3, and yet *L. secalinus*

Table 2
Canonical correlation coefficients derived from sampling lines

Sampling line	*A. arenarium* vs. *C. korshinskii* and *A. ordosica*		*A. arenarium* vs. *L. secalinus*		*C. korshinskii* and *A. ordosica* vs. *L. secalinus*	
	Negative	Probability	Negative	Probability	Positive	Probability
Line 1	0.518	0.0001**	0.779	0.0001**	0.468	0.0001**
Line 2	0.534	0.0001**	0.513	0.0001**	0.347	0.0018**

Note: (1) $^{*}p<0.05$; $^{**}p<0.01$.
(2) The values came from correlation coefficients between first principal components, but negative or positive relationship was reasoned from the correlations between original independent variables and the first principal component.

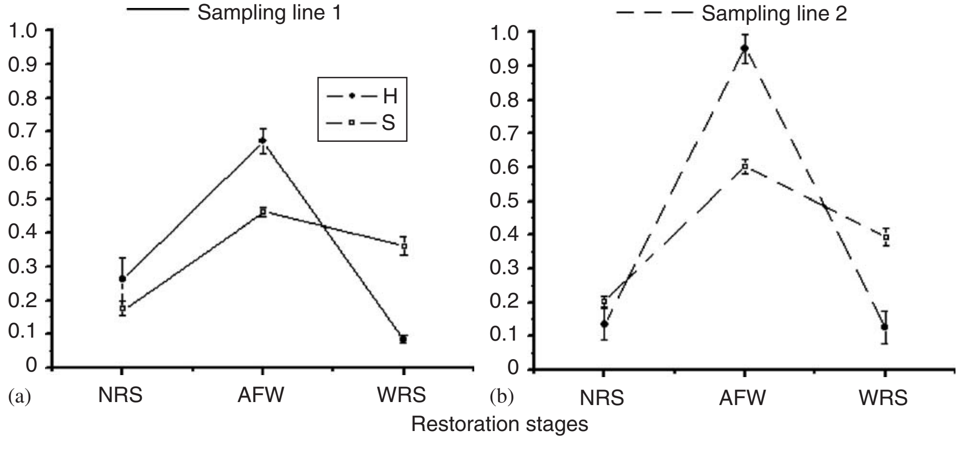

Fig. 2. Changes of species richness (*S*) and Shannon–Wiener index (*H*) along sampling lines in experimental area of sand control at Shazhuyu. NRS: natural restoration stage; AFV: artificial sand fixation vegetation; WRV: well-restored vegetation.

tended to center in Type 4. *A. arenarium* dominated Type 1 whose species is the poorest. Additionally, Type 2 was surrounded by the richest species.

The results of one-way ANOVA about total cover and cover of *L. secalinus* indicated that either of them was likely to be significantly different from that of another vegetation type ($p<0.001$). Changes of vegetation were expressed in two figures (Figs. 4 and 5). Total cover, Patrick index, Margalef index, Shannon–Wiener index and Pielou index were all very low in Type 1, in which the annual plant *A. arenarium* was dominant, and *L. secalinus* was absent. In Type 2, total cover rose dramatically, and meanwhile Patrick index, Margalef index, Shannon–Wiener index and Pielou index all reached their maximums, but *L. secalinus* was still absent. In Type 3, total cover rose to a higher degree, and cover of *L. secalinus* began increasing, but Patrick index, Margalef index, Shannon–Wiener index and Pielou index appeared to drop. In Type 4, *L. secalinus* population was in great cover and held strong dominance, but Patrick index, Margalef index, Pielou and Shannon–Wiener index all went to low levels again. Here, the diversity dynamics was somewhat similar to that in Fig. 2.

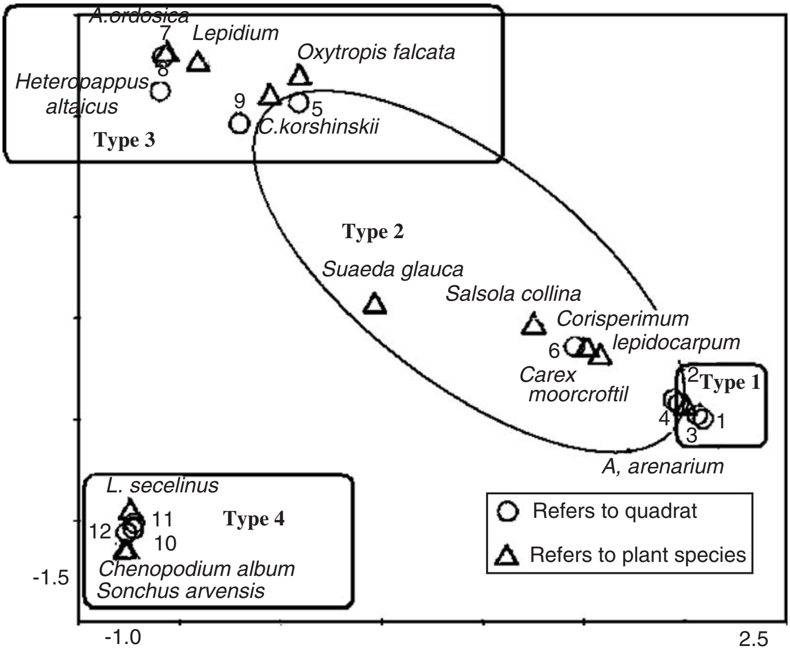

Fig. 3. CA-based ordination plot. The horizontal axis of the plot contributed 0.528 to total variance and the vertical axis contributed 0.244. Quadrat classification here was consistent with Table 1. Type 1: quadrats 1, 2, 3; type 2: quadrats 4, 5, 6; type 3: quadrats 7, 8, 9; type 4; quadrats 10, 11, 12.

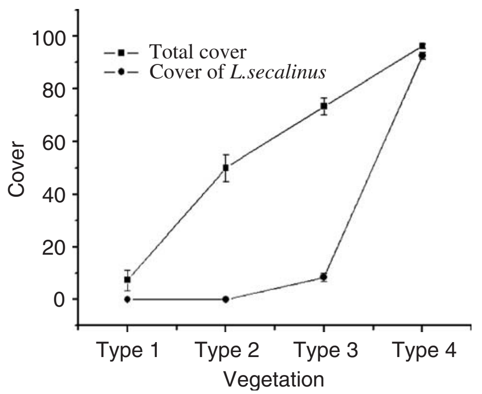

Fig. 4. Changes in total covers, cover of *L. secalinu* in the process of vegetation restoration.

4. Discussion and conclusions

4.1. Changes of vegetation diversity

In the process of revegetation induced by sand fixation, plant species richness, Shannon–Wiener index and some other diversity indices rose rapidly to their peak values

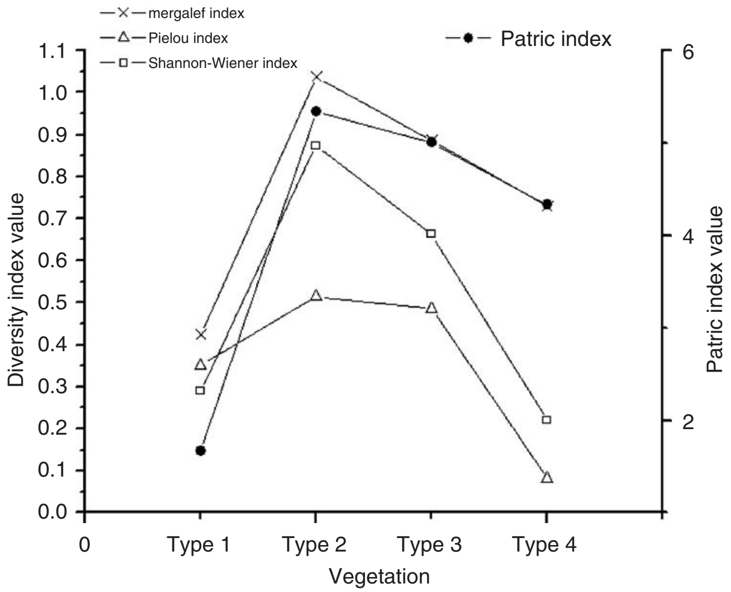

Fig. 5. Changes in the Patrick index, Margalef index, Shannon–Wiener index and Pielou index of restored vegetation types 1–4.

in a short time, but soon after they tended to drop, and finally they reached their second lowest levels.

How should we understand these changes? At the stage of NRS or vegetation of Type 1, sand drifting caused by gales made it impossible for plant species to establish, with the exception of a few annual species such as *A. arenarium*, and, as a result, plant richness and Shannon–Wiener index remained rather low. However, after physical sand barriers were established and *C. korshinskii* and *A. ordosica* were planted, sand was effectively stopped from drifting (Wolfe and Nickling, 1993; Liu and Zhao, 2001; Yan et al., 2001; Li et al., 2003; Joseph and Hupy, 2004; Qiu et al., 2004), and then more native plant species could establish than before (Fort and Richards, 1998; Burke, 2001; Liu and Zhao, 2001). Moreover, because total cover was not very high at the stage of AFV, inter-specific competition was probably not too intense for many species to coexist. Therefore, species richness and Shannon–Wiener index increased in this situation. At the stage of WRV, probably due to intense inter-specific competition resulting from overwhelming dominance of *L. secalinus*, some other species were eliminated or decreased in individual number or cover, and led to low species richness and Shannon–Wiener index (Connell, 1978; Li et al., 2003). It was reported that succession on coastal sand dunes followed a similar trend (Lichtner, 1998).

The intermediate disturbance hypothesis was an important explanation for the high species diversity or the coexistence of species in ecological communities, and lots of studies had confirmed it on local scales (Connell, 1978; Sousa, 1984; Roxburgh et al., 2004; Johst and Andreas, 2005). The results of this study also fit this hypothesis.

4.2. Changes of total cover and cover of *L. secalinus*

Total cover and cover of *L. secalinus* increased throughout the process of vegetation restoration, and they reached maximums finally in best-restored vegetation. Such changes were different from those of species diversity.

This study suggests that total cover and cover of *L. secalinus* are the two best indices to evaluate degree of vegetation restoration or desertification because they exhibited steady changes in the process of restoration. On the other hand, species diversity should not be viewed as sound index to evaluate vegetation restoration because it did not change steadily in the process of revegetation, that is, diversity was high at the intermediate stage but low at initial or later stages, including the well-restored stage.

4.3. Rehabilitation and its limiting factor

Even if species diversity is unsuitable to evaluate degree of vegetation restoration, it is important to understand mechanism of vegetation restoration on shifting sand dunes. Diversity rising at the initial stage suggests that sand drifting be the limiting or key factor to start vegetation restoration on shifting sand dunes, perhaps not merely in Gonghe Basin. This knowledge is important for us to accelerate vegetation restoration in desertified regions. During rehabilitation of desertified lands, if physical and biological sand barriers are established, sand drifting is controlled, and consequently revegetation is facilitated evidently.

Our conclusion about the limiting factor seems to conflict with the traditional thought that water is always the prime constraint to plant growth in arid or semi-arid areas (Ronny et al., 1996). In fact, it is not. As far as shifting sand dunes are concerned, their actual annual evapo-transpiration is normally less than annual precipitation, and then much rainfall can be accumulated inside bare dunes year by year (Wang et al., 2002). When revegetation begins, the first process for plant species is to colonize shifting sand dunes. However, plant dispersal, germination, and some other processes essential to colonization are hampered because of sand drifting. Therefore, compared with sand drifting, it is somewhat groundless to say soil water is the limiting factor to vegetation restoration on shifting dunes. Nevertheless, after many species have completed their colonization and vegetation has developed to an advanced stage with high total cover, sand drifting will become impossible and soil water is decreased or reduced (Link et al., 1994; Qian et al., 1999; Xiao et al., 2003). Consequently, the limiting factor will naturally transfer from drifting sand to water availability in this changed situation. Further studies are necessary to test this speculation about limiting factor to vegetation restoration.

4.4. How to restore degraded vegetation

Natural process was highlighted recently in restoration ecology (Katoh et al., 1998; Bradshaw, 2000; BWG/CCICED, 2001; Jiang, 2002), but does it mean that human-induced vegetation restoration is good for nothing? It may not be the case (Misak and Draz, 1997; Burke, 2001; Liu and Zhao, 2001). All communities can keep themselves in relative balance (Yodzis, 1981; Charles, 1985), so that if they are not damaged too badly, they can restore themselves rapidly and economically through natural processes (Katoh et al., 1998; Jiang, 2002). However, if they are destroyed too badly to restore themselves, human assistance seems necessary (Okoli and Balafoutas, 1998; Zhang, 2001; Snyman, 2003; Visser et al., 2004). This study provided a good example. Despite protection for many years, vegetation of shifting dunes could not pass through the threshold of restoration, and poor vegetation-covered dunes were always shifting. However, sand barriers could carry vegetation though the threshold easily. Hence, a wiser strategy of vegetation restoration is to adopt proper methods according to the degree of land deterioration. If drylands were deprived of only vegetation and soil was still conserved, vegetation restoration relying on natural processes would be advisable. On the contrary, in the case of shifting dunes, vegetation restoration should be initiated by artificial sand control, and only in this way can perfect combination between natural process and human assistance lead to effective and rapid rehabilitation.

4.5. Opinions on role of *L. secalinus* in succession

Because *L. secalinus* was dominant at some later stage of restoration, especially in the best-restored vegetation, it is possibly the best-adapted species on fixed sand dunes of Gonghe Basin. Additionally, it was often found to be dominant elsewhere in controlled sandy lands of the basin. Therefore, *L. secalinus* must play an important role in the process of vegetation restoration in sandy lands of Gonghe Basin, and it may be dominant species at certain stage of vegetation restoration, but this hypothesis needs further supports. Since the zonal vegetation is mainly dominated by *Stipa krylovii* in this basin (Zhou et al., 1987; Dong et al., 1993), vegetation succession should eventually result in domination of this species, but it is uncertain whether this will happen or not because soil genesis that usually takes many centuries will be involved in this process (McAuliffe, 1994).

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