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Effects of different restoration measures and sand dune topography on short- and long-term vegetation restoration in northeast China

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ABSTRACT

Our study investigated the effects of different restoration measures and sand dune topography on vegetation restoration in the Horqin Sandy Land, China. We conducted a vegetation survey at different topographic positions on sand dunes at four different types of restoration sites (i.e., grazing-exclusion, shrub-planting, pine-planting, and poplar-planting sites) with restoration periods of ≤35 years and two control sites (i.e., shifting sand dunes and fixed sand dunes). We found a restoration trajectory, starting from shifting sand dunes and aligning all the sites in chronological order. Five restoration phases were identified by distinct species composition in the trajectory. The planting of trees progressed vegetation restoration faster than livestock exclusion and the planting of shrubs. The planting of trees restored shifting sand dunes to the same level of fixed sand dunes after 25 years. Thirty-five years may restore shifting sand dunes to a near-stable state characterized by *Cleistogenes squarrosa*. We found sequential turnover in species composition along the upward topographic gradient throughout the restoration trajectory, indicating that vegetation restoration on sand dunes is promoted by a process where diaspores establish and spread upward from interdune lowland. Our study provides ecological foundations and suggestions for developing and implementing practical restoration programs in the sand dune area.

1. Introduction

Restoring degraded land is a crucial task for people living in drylands because their livelihoods have a very close relationship to biological productivity. Drylands cover more than 40% of the earth's land area, and desertification directly affects over 250 million people (MA, 2005). Although many restoration projects have been carried out globally, some have failed partly from a lack of good ecological perspectives (Choi, 2004). Since desertification is a localized phenomenon as well as a global problem (Dodd, 1994), simple application of a generally accepted method to an untested site has often failed (Clewell and Rieger, 1997). A long-term comparative perspective supporting the appropriate selection of site-specific restoration measures is significant for improving the success rate of restoration projects. Local ecological contexts need to be understood and simultaneously incorporated in that perspective. Such ecological foundations have proved to be essential in efficiently and successfully restoring degraded land, but the empirical development of that baseline is still under way.

In China, desertification has affected over 25% of the country (Liu and Diamond, 2005). The prevention of desertification and the restoration of degraded land have included such methods as livestock exclusion, and the planting of trees and grasses (Fan and Zhou, 2001). In the Horqin Sandy Land, one of the most seriously degraded areas in China (Zuo et al., 2008b, 2008a), prevention and restoration methods previously mentioned have been implemented since the mid-1970s (Li et al., 2003). With regard to vegetation restoration, many studies have demonstrated the effectiveness of grazing exclusion (Katoh et al., 1998; Su et al., 2003,

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2005a; Zhang et al., 2005; Zuo et al., 2008a, 2008b, 2010) and the planting of shrubs (Su and Zhao, 2003; Su et al., 2005b; Zhang et al., 2006; Zhao et al., 2007) and trees (Li et al., 2003); most of these studies examined the long-term effects of these measures. However, few studies have compared the effectiveness of different restoration techniques (Li et al., 2009), which reflects a general trend in relevant research. While many research projects in other areas have assessed the long-term effectiveness of restoration measures (e.g., Daryanto and Eldridge, 2010; Daryanto et al., 2012; Hejcmanová et al., 2010; Lawley et al., 2013; Mekuria, 2013; Mekuria et al., 2007; Read et al., 2011; Seymour et al., 2010; Verdoodt et al., 2010, 2009; Witt et al., 2011; Yang et al., 2011; Yayneshet et al., 2009), few researchers have included a comparison of various restoration techniques (e.g., Daryanto and Eldridge, 2010; Daryanto et al., 2012; Verdoodt et al., 2009, 2010). Further research is needed to clarify the variations in the long-term effectiveness of different restoration methods to guide the appropriate selection of various techniques.

Understanding relationships between vegetation restoration and the surrounding environment is practically important for restoration projects (Keitt et al., 2002). The Horqin Sandy Land landscape is characterized by sand dunes alternating with interdune lowland. Sand dune ecosystems are dynamic environments determined by wind erosion, sand accumulation, and dune encroachment, where plant distributions are influenced by their position on the sand dunes (Katoh et al., 1998; Liu et al., 2007; Yan et al., 2005; Zuo et al., 2008a, 2008b, 2010). For example, interdune lowlands are "vegetation islands" because various plants such as psammophytes, steppe species, and limnocryptophyte-meadow species occur in this environment (Liu et al., 2007). Topographic features are crucial in determining the distribution of existing plant species and presumably also affect the progress of vegetation restoration. However, the role of sand dune topography in vegetation restoration remains poorly understood (Zuo et al., 2008a). Clarification of sand dune topography could provide some ecological foundation for future restoration projects.

We hypothesized that restoration effectiveness changes among different restoration methods, but that sand dune topography consistently regulates vegetation restoration despite these methods. To test our hypotheses, we examined plant communities at different positions on sand dunes under different restoration methods, for short-and long-term periods in the Horqin Sandy Land. The objectives of the study were to elucidate: (1) the short- and long-term effectiveness of different methods on vegetation restoration; and (2) the consistent role of sand dune topography in vegetation restoration.

2. Methods

2.1. Study area

The study area was located in the central part of Naiman County, an agropastoral region of Inner Mongolia, China (42°55′N, 120°42′E). The elevation of the site was approximately 360 m above mean sea level. The region is in a temperate zone with a continental semi-arid monsoon climate, with the highest rainfall occurring in the summer months and in springtime dry/windy conditions prevail. The mean annual precipitation is ~360 mm, mainly falling between June and August. The mean annual temperature is 6.4 °C, with the coldest and warmest monthly mean air temperatures in January (−13.1 °C) and July (23.7 °C), respectively. The soils are characterized by coarse texture and loose structure, susceptible to wind erosion. The Aeolian sand, on which these soils have formed, originated from alluvial and lacustrine deposits formed in the Middle and Late Pleistocene periods, with the fixed sand dunes formed in association with soil development during the Holocene Optimum (Yang et al., 2004, 2008, 2010). In spring and winter, the threshold wind velocity for sand movement is exceeded on ~200 days (Li et al., 2009).

2.2. Site selection

We selected the following nine restoration sites to collect data by interviewing local residents and staff at the Naiman Desertification Research Station, Chinese Academy of Sciences. The sites were grazing-exclusion sites maintained for 5 years (GR-5), 25 years (GR-25), and 35 years (GR-35); shrub-planting sites (*Caragana microphylla* and *Salix gordejevii*) maintained for 5 years (SH-5) and 25 years (SH-25); pine-planting sites (*Pinus sylvestris*) maintained for 25 years (PI-25) and 35 years (PI-35); and poplar-planting sites (*Populus simonii*) maintained for 5 years (PO-5) and 25 years (PO-25). All sites were classified as shifting sand dunes (SS) when restoration commenced. Grazing was prohibited at the three plantation sites and the grazing-exclusion sites. However, the low economic situation of local farmers meant that the grazing exclusion was generally unreliable, resulting in light grazing occurring in these areas (Katoh et al., 1998). The density and distribution of the initially planted shrubs and trees were not accurately measurable because some natural dispersal had occurred and some individuals may have been lost since the initial planting. We assumed that those initial conditions did not differ significantly among the planting sites because the current shrubs and trees were well distributed across the variety of topographical positions available at every site, and their densities were adequate for this analysis.

In addition to the restoration sites, we selected two types of grassland as control sites: SS and fixed sand dunes (FS). The SS were considered as the initial state of each restoration site and the FS were regarded as a target state of restoration, because one goal of desertification control is to convert SS to FS (Li et al., 2009). Some pioneer psammophytes, such as an annual forb *Agriophyllum squarrosum* and a shrub *Artemisia halodendron*, typically appear in SS. The major species in FS include annual grasses (e.g., *Chloris virgata*, *Digitaria ciliaris*, and *Setaria viridis*) and forbs (e.g., *Artemisia scoparia*, *Euphorbia humifusa*, and *Chenopodium acuminatum*), and perennial grasses (e.g., *Cleistogenes squarrosa*, *Pennisetum centrasiaticum*, and *Phragmites australis*) and forbs (e.g., *Cynanchum thesioides*, *Ferula bungeana*, and *Melissitus ruthenicus*).

2.3. Data collection

A vegetation survey was conducted at the 11 sites in August 2008 and 2009. At each site, we established a sampling line on three different sand dune slopes. Three quadrats (1 × 1 m) were placed at each of the following four topographic positions per line: interdune lowland (IL); the lower part of the sand dune (LS); the middle part of the sand dune (MS); and the upper part of the sand dune (US). We recorded the percentage cover of all plant species in each quadrat ($n = 36$ per site).

2.4. Statistical analysis

Vegetation data for each topographic position on each line (using pooled data from the three quadrats) were subjected to detrended correspondence analysis (DCA; Hill and Gauch, 1980) to identify a restoration trajectory. We performed a regression tree analysis (Breiman et al., 1984) using the DCA scores representing a restoration trajectory as the response variable. The predictor variables were the sites (i.e., the combination of restoration methods and periods) and the topographic positions. The best regression tree model was selected through 10-fold cross-validation and the

1-SE method (Breiman et al., 1984). Cross-validation was performed 10 times and the average error value was used to select the best model. This regression tree analysis aimed to identify some distinct phases in the restoration trajectory, considering topographic effects. In each restoration phase derived from the regression tree analysis, we performed an indicator species analysis (Dufrêne and Legendre, 1997) and also calculated the Shannon's diversity index (H') to interpret species-composition change through the restoration trajectory. H' is defined as:

$$H' = -\sum_{i=1}^{n}(p_i \log p_i) \quad (1)$$

where p_i is the relative abundance of species i on the basis of its cover and n is the number of species recorded on each line at the sites. The average H' for each phase was then computed. To test the result of the indicator species analysis we used the Monte Carlo test with 10,000 permutations. All statistical analyses were performed using the R software version 2.8.1 (R Development Core Team, 2008).

3. Results

3.1. Effects of different restoration methods and sand dune topography on vegetation restoration

The DCA indicated that the restoration sites aligned chronologically from SS to PI-35 along the first axis (Fig. 1), showing that the first axis reflected a restoration trajectory. The best regression tree model using the scores from the first axis as the response variable (Fig. 2) showed there were five restoration phases and non-linear effects of topography in the trajectory. Phase 0 included only SS; phase 1 included SH-5 and GR-5; phase 2 included PO-5, SH-25, and GR-25; phase 3 included PI-25, FS, and PO-25; and phase 4 included GR-35 and PI-35. Vegetation restoration progressed more at lower dune positions in all phases except for phase 0, i.e., IL in phase 2 and IL and LS in phases 1, 3, and 4.

3.2. Species-composition change through the restoration trajectory

All indicator species in each restoration phase, derived from the indicator species analysis (Table 1), were grouped and called

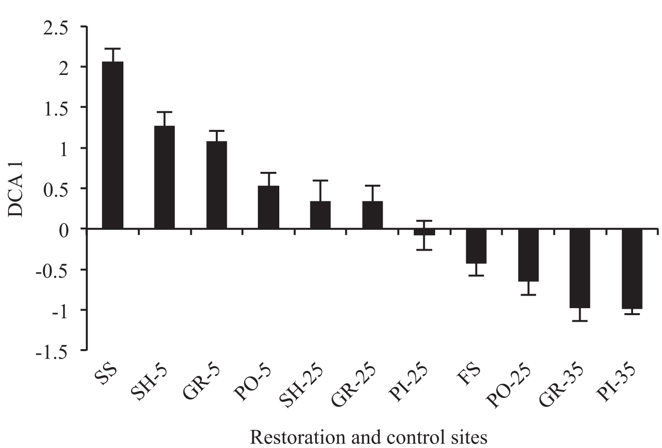

Fig. 1. Restoration and control sites arranged in the order of the score of the DCA axis 1. GR-5, GR-25, and GR-35, grazing-exclusion sites maintained for 5, 25, and 35 years; SH-5 and SH-25, shrub-planting sites maintained for 5 and 25 years; PI-25 and PI-35, pine-planting sites maintained for 25 and 35 years; PO-5 and PO-25, popular-planting sites maintained for 5 and 25 years; SS, shifting sand dunes; and FS, fixed sand dunes. Vertical bars represent standard errors.

indicator species groups (ISGs). Fig. 3 shows that an ISG was sequentially replaced by the ISG of the next restoration phase along the topographic upward gradient throughout the restoration trajectory. H' constantly increased from phase 0 but decreased after peaking in phases 2 and 3 (Fig. 4).

4. Discussion

4.1. Short- and long-term effects of different restoration methods on vegetation restoration

We showed that vegetation restoration, through livestock exclusion and planting shrubs and trees, was described in a single trajectory (Fig. 1). Although studies have examined the effects of single restoration measures, we found that restoration after 5 and 25 years progressed better at the tree-planting sites compared with the grazing-exclusion and shrub-planting sites (Fig. 2). According to Liu (1985) and Li et al. (1997), the four phases of vegetation restoration from SS to FS are generally classified into: 1) a *A. squarrosum* phase (phase of SS); 2) a *A. halodendron* phase; 3) a *S. viridis* phase; and 4) a *A. scoparia* and *C. squarrosa* phase (phase of FS). In addition, Li et al. (2009) reported that the state of vegetation at the 8-year-old grazing-exclusion and shrub-planting sites were both at the *A. halodendron* phase. The indicator species of each phase (Table 1) almost corresponds to the key species in the course of restoration (see above description). Furthermore, the findings by Li et al. (2009) agreed with the first restoration phase (Fig. 2 and Table 1). Thus, earlier research supports the restoration trajectory and restoration phases found in our study. Our results suggest that planting trees promotes vegetation restoration faster than other restoration measures.

The restoration effect of trees and shrubs has been described as a nursery effect in numerous studies. According to Stachowicz (2001), nurse plants reduce soil erosion, buffer harsh winds, and reduce temperature and evaporation, facilitating the persistence of other species. These effects seem common in arid and semi-arid environments. However, the scale and degree of the effects would differ among nurse plants from differences in individual plant sizes. For example, Li et al. (2003) reported that the protective effect of poplar forest against the wind reaches a distance of approximately 12-fold tree height from the forest fringe on the leeward side. In contrast, the effect of shrubs appears limited to the area under the canopy and in close proximity. The amount of shade and litter from trees would also be more compared with shrubs. Consequently, restoration at the tree-planting sites progressed faster than at other sites. In this study, we only examined the restoration effects at the site scale, including the nursery effect of shrubs. Thus, the quality of the restored vegetation from shrub planting and livestock exclusion was not differentiated and would only be detected at a finer scale of investigation (e.g., Zhao et al., 2007).

Earlier studies have examined whether restoration methods improve vegetation conditions for a certain period. However, the rate of change from a degraded to a more desirable community is one of the most important considerations in ecological restoration (Bradshaw, 1992). We showed that after 25 years the effect of planting trees resulted in SS reaching the same ecological level of FS (Fig. 2). Zhang et al. (2005) stated that *C. squarrosa*, a phase 4 indicator species, is a dominant species of the zonal vegetation type in this region and can maintain a stable population. They predicted that species diversity would decrease, including the dominance of *C. squarrosa*. Since species diversity decreased after peaking at phases 2 and 3 (Fig. 4), phase 4 characterized by *C. squarrosa* seems close to a stable state. Therefore, the current restoration measures restore SS to the same level of FS in 25 years and to a near-stable state in 35 years. GR-35 reached phase 4, as

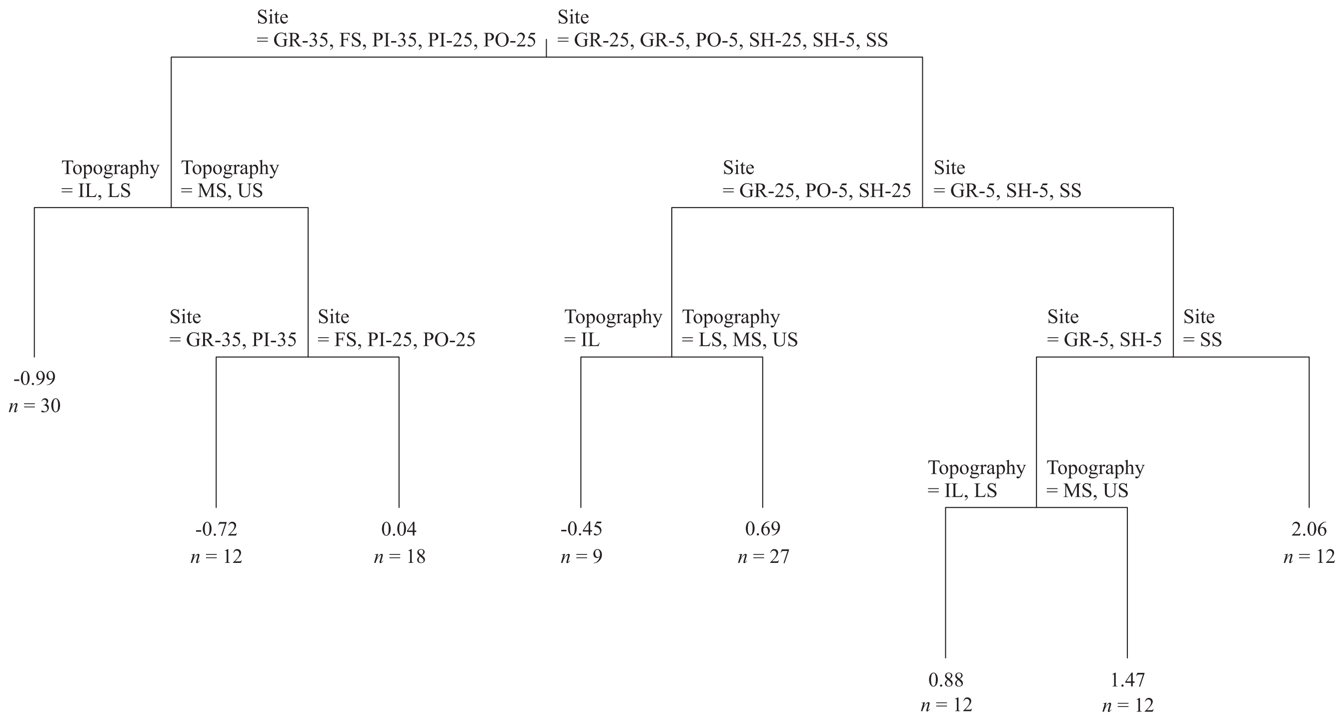

Fig. 2. Regression tree model for the score of the DCA axis 1. Topography represents topographic positions on sand dunes: IL, interdune lowland; LS, lower parts of sand dunes; MS, middle parts of sand dunes; and US, upper parts of sand dunes. Sites representing restoration and control sites: GR-5, GR-25, and GR-35, grazing-exclusion sites maintained for 5, 25, and 35 years; SH-5 and SH-25, shrub-planting sites maintained for 5 and 25 years; PI-25 and PI-35, pine-planting sites maintained for 25 and 35 years; PO-5 and PO-25, popular-planting sites maintained for 5 and 25 years; SS, shifting sand dunes; and FS, fixed sand dunes. Numbers at terminal nodes are average values of the response variable in each terminal node, and n is the number of data contributing to the value for each node.

well as PI-35 (Fig. 2), because of the constant rate of vegetation restoration under grazing exclusion. The DCA scores exhibited a linear decline pattern temporally in the grazing-exclusion sites, starting from SS, whereas the temporal pattern from SS in the tree-planting sites tended to decrease in a concave-up exponential pattern, both of which can be derived from the values in Fig. 1. This difference represents the constant pattern of vegetation restoration over 35 years by livestock exclusion; the restoration occurred more rapidly for the first 25 years and subsequently restoration occurred more slowly where trees had been planted. Although further research is needed to clarify the cause of this difference in the temporal patterns, 35 years may be sufficient to approach a stable state regardless of the types of restoration measures used.

4.2. Effects of sand dune topography on vegetation restoration

The regression tree model showed differences in restoration effects among the topographic positions within each phase (Fig. 2).

Table 1
Indicator species of each restoration phase derived from an indicator species analysis with a Monte Carlo test (10,000 permutations).

Phase	Indicator species ($P < 0.01$)
0	*Agriophyllum squarrosum*
1	*Artemisia halodendron*, *Corispermum candelabrum*, *Hedysarum leave*
2	*Cynanchum thesioides*, *Melissitus ruthenicus*, *Euphorbia humifusa* *Salsola collina*, *Setaria viridis*
3	*Tribulus terrestris*
4	*Artemisia scoparia*, *Chloris virgata*, *Cleistogenes squarrosa* *Eragrostis pilosa*, *Ferula bungeana*, *Portulaca oleracea*

Additionally, we found a sequential turnover in species composition along the upward topographic gradient (Fig. 3). Vegetation restoration can be limited by seed dispersal, where diaspores are provided from soil seed banks and aboveground communities (Bakker and Berendse, 1999). In this region, Li et al. (2004) reported that seed banks were small in species number with more than half of the seeds recorded belonging to several species. Yan et al. (2005) reported that species composition showed poor similarity between seed banks and aboveground vegetation at different topographic positions on SS and FS. Therefore, the regeneration potential from soil seed banks in sand dunes is limited, with the sand dune restoration more dependent on seed dispersal from nearby plant communities (Yan et al., 2005). These transported diaspores are likely to initially germinate in the interdune lowland where water availability is higher (Katoh et al., 1998; Liu et al., 2007), in microsites with other advantages such as protection from harsh winds (Shirato et al., 2004) and the natural accumulation of soil nutrients (Zuo et al., 2008b, 2008a). The turnover in species composition along the topographic gradient will reflect a restoration process where species adapting to each restoration phase tend to disperse from elsewhere to the IL or the adjacent LS, into sites that are more supportive environments for diaspores to germinate than in the other topographic positions. Once species establish they then spread to the US, replacing the characteristic species of the previous phase.

The DCA scores of phases 3 and 4 did not significantly differ at the lower topographic positions (IL and LS, Fig. 2) and the scores of the lower and upper topographic positions in phase 4 were relatively close. This result implies that the invasion of new species slowed in phase 3 and that species composition gradually became stable in phase 4. This supports the previous description, that phase 4 seems close to a stable state.

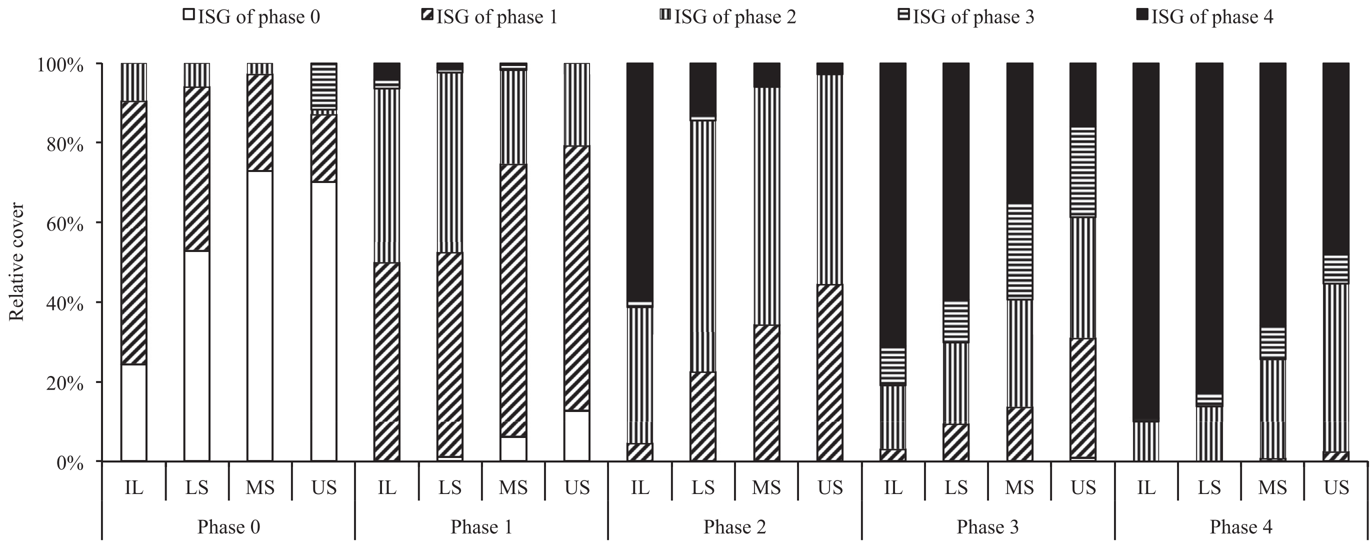

Fig. 3. Relative cover of indicator species groups (ISGs) at each topographic position in every restoration phase. IL, interdune lowland; LS, lower parts of sand dunes; MS, middle parts of sand dunes; and US, upper parts of sand dunes.

4.3. Implications for future land management

While this study only examined the vegetation, other natural and socioeconomic aspects should be also considered during practical management of land restoration. For example, large-scale afforestation may cause environmental problems including groundwater depletion, resulting in a waste of manpower and money (Wang et al., 2007). Therefore, we cannot make conclusive suggestions related to the selection of appropriate measures in all conditions. However, we believe that our study provides information that is critical to the promotion of vegetation restoration. The restoration phases, described in terms of specific vegetation states and elapsed time, will provide an informative guideline for field evaluation and goal formation in restoration projects. This finding could allow land managers to choose appropriate species and timing for restoration. Li et al. (2004) and Zhang et al. (2005) suggested that providing supplemental seeding will expedite restoration. Moreover, our findings that show interdune lowland is the starting point of vegetation restoration indicates that the reclamation of interdune lowland, preferentially practiced by local people, critically blocks surrounding vegetation restoration. The restriction of this type of reclamation is unlikely based on the economic hardship experienced by the local population; however, restricting this practice would prove beneficial to vegetation restoration.

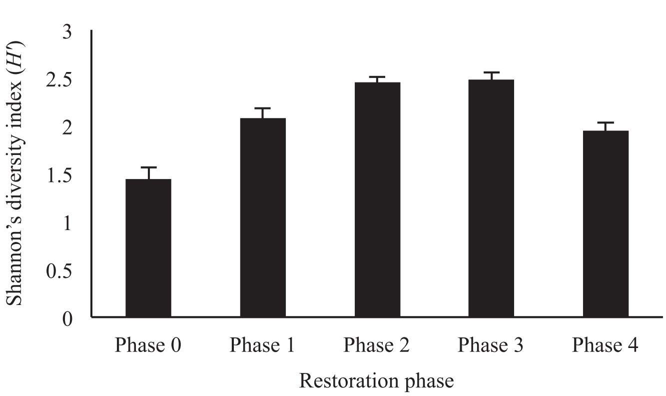

Fig. 4. Shannon's diversity index (*H'*) in each restoration phase. Vertical bars represent standard errors.

5. Conclusions

Our hypotheses were supported by our results demonstrating: (1) the short- and long-term effectiveness of different measures on vegetation restoration; and (2) the consistent role of sand dune topography in vegetation restoration. We showed a restoration trajectory, which started from SS and aligned all restoration sites in chronological order, with five restoration phases identified by a distinct species composition in the trajectory. The planting of trees progressed vegetation restoration faster than livestock exclusion and planting shrubs. For example, only planting trees restored SS to the same level of FS in 25 years. However, 35 years was sufficient time to restore SS to the near-stable state characterized by *C. squarrosa*, despite different kinds of restoration methods. We clarified that sand dune topography plays a consistent role in vegetation restoration in the sand dune area, which occurs when diaspores establish and spread upward from the interdune lowland. Our study provides ecological foundations and suggestions for developing and implementing practical restoration programs in the sand dune area.

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