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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