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Dune-scale distribution pattern of herbaceous plants and their relationship with environmental factors in a saline–alkali desert in Central Asia

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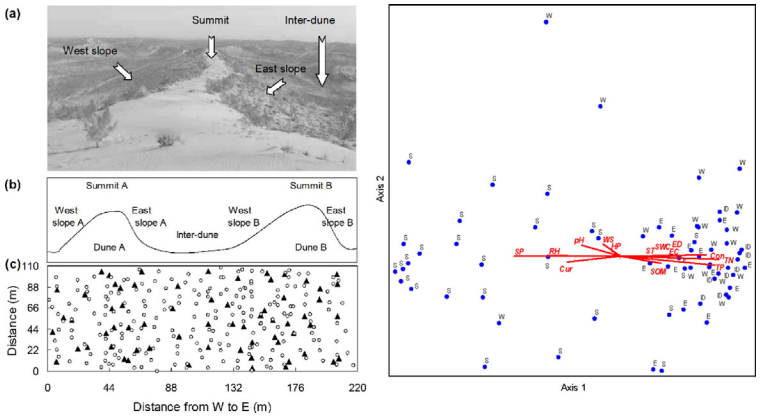
HIGHLIGHTS

- The herb distribution and relationship with environments were evaluated on dunes.
- Univariate, ordination and geostatistical techniques were used.
- A moderate spatial dependence and strong zonal distribution of herbs were observed.
- The dune topography, soil nutrients and shrubbery controlled the herb distribution.
- Dune fixation and vegetation recovery contributed to the stability of the desert.

GRAPHICAL ABSTRACT



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ABSTRACT

Sand dunes are the main landforms in modern deserts worldwide. As an important type of desert vegetation, herbaceous plants have long been acknowledged for their important ecological functions. We focus on the dune-scale distribution pattern of herbaceous plants and their relationship with the environment. During the early summer of 2010, the herbaceous plant density, coverage, aboveground biomass and eighteen environmental factors were surveyed from 214 plots (5 m × 5 m) across two linear sand dunes (220 m × 110 m) located in the Gurbantunggut Desert, China, a typical saline–alkali desert in Central Asia. Data were analyzed using univariate, ordination, and geostatistical techniques. Three vegetation variables represent a significant clumped distribution ($P < 0.01$) across the entire study site. Obvious differences were observed among different slope positions/transects, with the lowest values observed at the summit. Geostatistics indicated that all of the variables showed a moderate spatial dependence and obvious zonal distribution along the sand dunes. The ranges (lag distance) of density (32.2 m) and coverage (33.5 m) were close to the average width (31.4 m) of the transects. The biomass range (74.1 m) was almost equal to the average width (75 m) of the sand dunes. Pearson's correlation analysis and nonmetric multidimensional scaling analysis consistently demonstrated that the distributions of herbs on sand dunes were dominantly influenced by sand dune topography (slope position, convexity, and relative height), soil nutrients (total nitrogen and phosphorus) and deep-rooted shrubbery (*Ephedra distachya*). Compared to large, mobile and steep sand dunes, low, fixed and gentle sand dunes contribute to herbaceous plant abundance and distribution as well as the stability maintenance of the whole desert ecosystem.

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1. Introduction

Desert ecosystems occupy approximately 20% of the earth's land surface (Whitford, 2002; Zhang and Wang, 2008), but they are the least understood terrain type (El-Baz, 1988). Deserts characteristically lack biodiversity and stability; thus, they have lower carrying capacities and productivities and are slow to recover from disturbance (Whitford, 2002; Ward, 2009). Deserts in varying types of climates are generally covered by various sand dunes. Linear dunes are the most common dune form in modern deserts (Wasson et al., 1988). Sand dunes are generally classified as free of vegetation (active), partly vegetated (semi-active or semi-fixed), or fully vegetated (fixed). All fixed dunes have been previously active and became stable when vegetation increased. In other words, sand dunes can be mobile or fixed, depending on the vegetation (Tsoar, 2005). Thus, vegetation is a critical biotic factor that influences the sand fixation and stability of desert ecosystems (McNaughton, 1977; Whitford, 2002; Tsoar, 2005). Herbaceous plants play a key role in diversity (Roberts, 2004; Whigham, 2004; Gilliam, 2007), net primary productivity (NPP), carbon dynamics, energy flow (Gilliam, 2007) and nutrient cycling (Muller and Bormann, 1976; Muller, 2003; Gilliam, 2007) of various terrestrial ecosystems. Desert herbaceous plants account for a very small proportion of the biomass, but the herbaceous layer provides the richest and most diverse contribution to the biomass (Tao and Zhang, 2011). Hence, herbaceous plants are closely related to the stability of desert ecosystems.

Spatial distribution is an important topic in plant ecology, and it is the key to understanding the structure and dynamics of populations and communities (Condit et al., 2000). The plant spatial distribution, which is scale dependent, is influenced by various factors (Friedman et al., 2001; Lan et al., 2012). For example, at a large scale, the climate (precipitation and temperature), soil, and vegetation types differ largely; thus, the factors that influence the vegetation distribution may be classified as macroenvironments. The macroenvironmental factors include the average precipitation over the past 30 years, elevation, latitude, and longitude; these are the primary environmental factors that affect the spatial variations in plant diversity in the Gurbantunggut Desert, China, with average precipitation as the most important and soil factors as relatively less significant (Zhao et al., 2009). The herbaceous species diversity in deserts is also affected by soil physical and chemical properties, such as nutrients, salt, water content, and pH (Qian et al., 2004). Additionally, grazing increases soil instability and reduces vegetation coverage, thereby changing the vegetation distribution, especially for herbaceous plants (Wang et al., 2007).

At the small scale/microscale, climate and soil texture are similar; thus, the factors that affect vegetation distribution are mostly microenvironmental, such as heterogeneity of soil properties, microrelief, and intra- and interspecific relationships. For example, at the sand dune scale, the aforementioned factors are significantly heterogeneous among different slope positions (Zhang and Wang, 2008). In most cases, soil water content (SWC) is regarded as the major environmental variable that limits plant survival and growth in deserts, especially the herbs in spring (El-Baz, 1988; Wang et al., 2004; Zhao et al., 2004; Li et al., 2010). Biological soil crusts (BSCs) are reportedly the key variable that determines plant distribution on sand dunes in the Negev Desert (Littmann and Veste, 2005; Veste et al., 2011). However, Xie and Liu (2010) found that the topography/terrain determines the distribution of two shrubs (*Ceratoides ewersmanniana* and *Haloxylon ammodendron*) in the south Gurbantunggut Desert. The topography/terrain of sand dunes is determined by the combination of various microscale environmental variables. In the early stage, wind plays a major role in sand movement and accumulation (Bagnold, 1941; Ahlbrandt, 1979). However, during sand fixation, vegetation, litter, BSCs, and soil mineral elements have also become involved (i.e., modern deserts are formed through the interaction of many environmental factors) (Tsoar, 2005). Therefore, the interaction would also form the distribution pattern of herbaceous plants on sand dunes. Unfortunately, the comprehensive impacts of those aforementioned factors on the spatial distribution patterns of herbaceous plants at the dune scale and their interactions remain unclear.

The Gurbantunggut Desert, the largest fixed/semi-fixed desert in China, is a typical saline–alkali desert in Central Asia. The desert is dominated by linear (longitudinal) dunes that vary in length from several hundreds of meters to several tens of kilometers. The strongest winds occur in this desert from April to July, but it has a lower sandstorm frequency and intensity than other deserts in China, mainly due to the abundant plant species (Wang et al., 2003). The desert has 208 species, and most of which are herbs (Zhang and Chen, 2002; Tao and Zhang, 2011). Among these species, ephemeral species constitute up to 47% of the total number of species. Ephemeral and ephemeroid plants account for approximately 60% of the NPP in shrub communities in late spring and occupy 40.2% of the total plant cover (Wang et al., 2003). Some studies have described the distribution patterns of dominant shrubs across sand dunes in the south Gurbantunggut Desert (Tao et al., 2008; Xie and Liu, 2010). However, knowledge on the distribution pattern of herbaceous plants at the dune scale and their influencing factors is still limited.

In the present study, we investigated herbaceous plant density, coverage and aboveground biomass in 214 sampling plots and gained 18 environmental factors in 65 plots across two continuous linear dunes in central Gurbantunggut Desert in early summer. This study aims to (1) explore the spatial distribution patterns of herbaceous plants on linear dunes and (2) comprehensively determine the relationship between the distribution of herbs and the environmental factors at the dune scale. This study would provide a better understanding of the mechanism underlying desert stabilization, which is essential for developing deserts for the benefit of humankind (El-Baz, 1988).

2. Methods

2.1. Study site

The Gurbantunggut Desert (4.88×10^4 km^2) is the second largest desert in China. The area is covered by massive, dense, semi-fixed sand dunes approximately 10 m to 50 m high and oriented south to north (Fig. 1a). The annual precipitation is approximately 70 mm to 150 mm, falling predominantly in spring and summer, with snow accumulating 10 cm to 30 cm in winter. The mean annual pan evaporation is >2000 mm, with the largest amounts occurring during April to September. The average annual temperature is 6 °C, with a maximum mean of approximately 30 °C and minimum mean of approximately −20 °C. Wind speeds are greatest during April to July and are predominantly from the northwest or the north (Wang et al., 2003). The study site is located at the central area (44° 95′ N, 87° 76′ E, average alt. 515 m) of the Gurbantunggut Desert. The dune slopes and interdune area in the study site are dominated by lichen and algal crusts, whereas the summits of sand dunes are bare sand (Zhang et al., 2010a).

2.2. Vegetation investigations

The investigation was conducted in early June (early summer) 2010. The sampling site was 220 m (from west to east) × 110 m (from south to north) across two linear dunes (Fig. 1a and b), which were approximately 5 m to 70 m and 130 m to 215 m from west to east, respectively (Fig. 1b and c). The two continuous sand dunes were divided into seven slope positions (i.e., seven transects): windward slopes A and B (west), summits A and B, leeward slopes A and B (east), and the interdune (Fig. 1a and b). A total of 214 plots (5 m × 5 m) were surveyed, and the numbers of plots at the slope positions/transects were 31, 32, 20, 40, 29, 30, and 32, respectively. The coordinate and altitude were recorded by GPS (with approximately 3 m accuracy) at the center of each plot.