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Association of Vegetation Patterns and Environmental Factors on the Arid Western Slopes of the Helan Mountains, China

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We studied the distribution and composition of plant communities along an altitudinal gradient on the arid western slopes of the Helan Mountains in northwestern China by means of multivariate analyses. Two data sets that originated from fieldwork in 2005–2006 were subjected to principal component analysis (PCA), resulting in 3 major vegetation categories: desert shrubland, desert grassland, and prairie shrubland. Ordination based on canonical correspondence analysis (CCA) divided the desert shrubland category into a Caragana tibetica *community, a* Salsola passerina–Oxytropis aciphylla *community, and a* Reaumuria soongarica–S. passerina *community; the desert grassland category into a* Stipa grandis *community and a* Stipa breviflora *community; and the prairie shrubland category into an* Ulmus glaucescens–Prunus mongolica *community, a* P. mongolica–Potentilla fruticosa *community, and a* P. mongolica *community. In the desert shrubland category, the* C. tibetica, S. passerina–O. aciphylla, *and* R. soongarica–S. passerina *communities appear consecutively along the soil alkalization gradient, and the* C. tibetica, R. soongarica–S. passerina, *and* S. passerina–O. aciphylla *communities appear consecutively along the soil texture gradient. In the desert grassland category, the* S. breviflora *and* S. grandis *communities appear consecutively along the soil water gradient. In the prairie shrubland category, the* U. glaucescens–P. mongolica, P. mongolica–P. fruticosa, *and* P. mongolica *communities appear consecutively along the soil organic matter and total nitrogen gradient, while the* P. mongolica, P. mongolica–P. fruticosa, *and* U. glaucescens–P. mongolica *communities appear consecutively along the soil pH gradient. Better understanding of these and similar relationships can enable better management of arid and semiarid ecosystems, which may be more vulnerable to such environmental factors than their counterparts in more humid regions.*

Keywords: *Vegetation communities; soil water; soil properties; cluster analysis; Helan Mountains; China.*

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Introduction

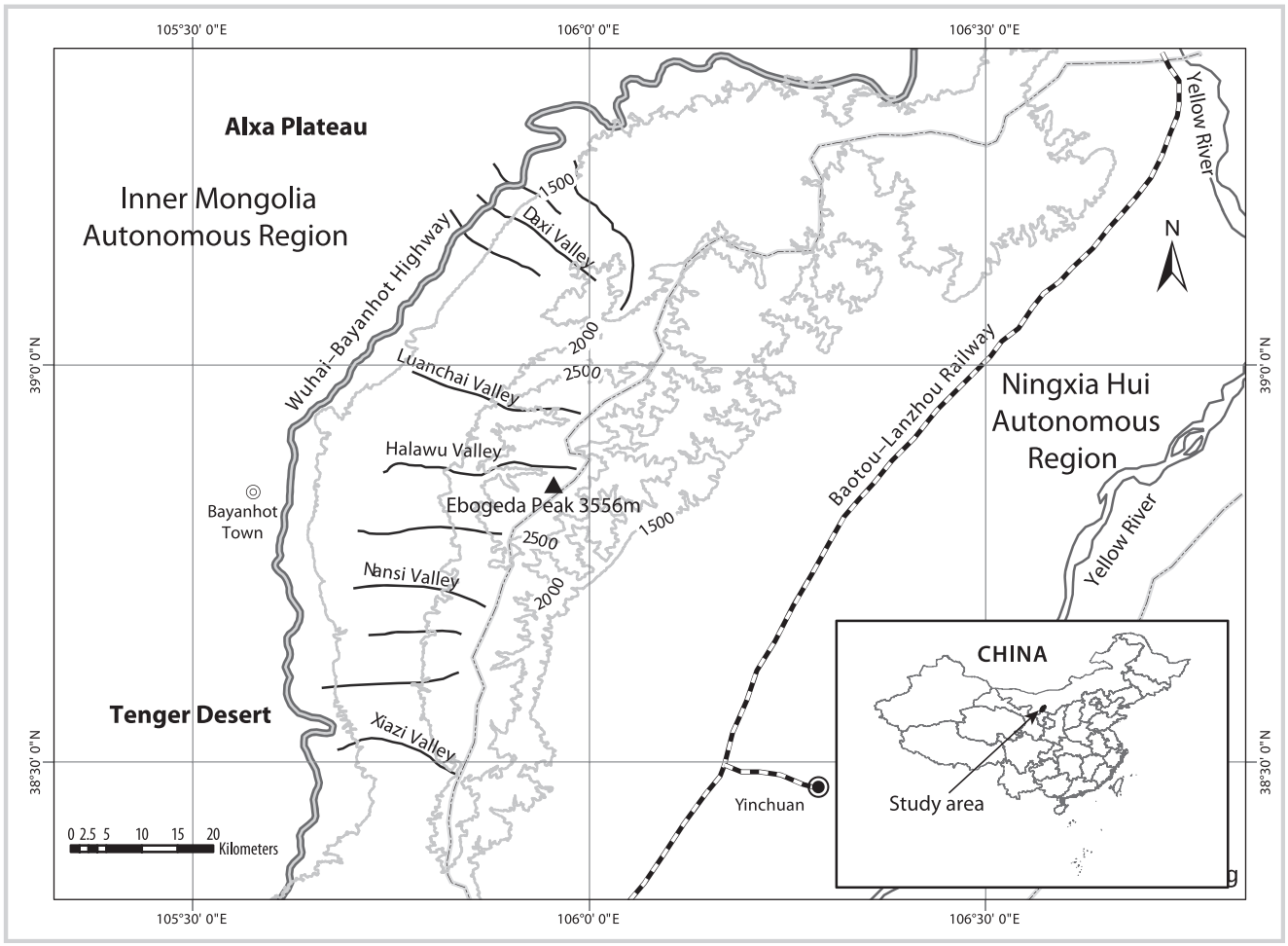
The species–environment relationship has always been a central issue in ecology (Guisan and Zimmermann 2000), especially when the purpose of ecology is to inform rangeland management (Zhang et al 2013). For over a century, ecologists have attempted to determine the factors that control plant species distribution and variation (Motzkin et al 2002). In combination with other environmental factors, climate has been used to explain vegetation patterns around the world (Walker 1985; Ellenberg 1988; Comstock and Ehleringer 1992; Cook and Irwin 1992). Arid and semiarid regions are characterized by minimal precipitation and frequent droughts; thus, water availability is one of the primary factors controlling the distribution of species (Noy-Meir 1973; Yair and Danin 1980; Li et al 1998). Rooting depth, soil potential for water absorption, and distribution of nutrients are influenced by the amount and availability of soil moisture (Jafari et al 2004).

Arid and semiarid vegetation patterns are affected by environmental factors more intensively than those in humid areas (Boer and Sargeant 1998). Much of the research on species–environment relationships has been carried out in arid or semiarid regions of North America, Australia, and other desert regions such as Egypt, India, and Iran (Parker 1991; Cook and Irwin 1992; Monier and Wafaa 2003; He et al 2007). Knowledge about interactions of vegetation patterns and environmental factors in arid regions of China is rather poor (Hilbig 1995; Li et al 2004). Determining which factors control the presence and relative abundance of plant species remains a central goal of research in arid and semiarid desert ecosystems.

The Helan Mountains, located in the northwestern part of China, are a transitional zone from steppe to desert. This zone is also an important link between the flora of the Qinghai-Tibet and Mongolia Plateaus and the North China plain (Liang et al 2004). This area has been subjected to grazing, lumber felling, harvesting of

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FIGURE 1 Location of the study area. (Map by Tian LS)



medicinal plants, and firewood cutting for the past 50 years (Jiang et al 2007). Therefore, our research focused on the interpretation of vegetation patterns associated with major environmental factors and variations in plant community composition. Classification and ordination are 2 important approaches to generating hypotheses with respect to vegetation and environment. Using multivariate analyses to generate classification and ordination, this article presents a quantitative description of vegetation in relation to the major environmental variables on the western slope of the Helan Mountains.

Material and methods

Study area

The Helan Mountains are located at the border of Inner Mongolia and Ningxia in China; their western slopes lie in Inner Mongolia (Figure 1). North and south of the main summit (Ebogeda, 3556 m), the ridge elevation decreases stepwise (Jiang et al 2000). As an important ecological shelter in northwestern China, the Helan Mountains block the eastward motion of the Tengger Desert. They also intercept the sandstorms originating on the Alxa Plateau and effectively protect the Ningxia Plain (Zheng et al 2009). Frequent grazing and other human disturbances over the past 50 years have resulted in the expansion of shrub patches of *Salsola passerina* in *Stipa breviflora* grassland on the western slopes of the Helan Mountains (Ma and Luo 2000; Zheng et al 2008). Research sites on these western slopes (38°24′–39°08′N; 105°43′–105°56′E; 1500–2050 m above sea level [masl]) were selected for this study. The average annual temperature is 8.2–8.6°C, and the average annual rainfall is 202.8 mm (of which 60–70% is received in July, August, and September). The average potential evaporation reaches 1600–1800 mm (Zheng et al 2008). On the western slope of the Helan Mountains, the vertically distributed ecosystems include a montane desert zone (1500–1600 masl), a montane steppe zone (1600–1900 masl), a montane coniferous forest zone (1900–3100 masl), and an alpine bush and meadow zone (above 3100 masl) (Tian 1996).

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TABLE 1 Vegetation types in 5 valleys on the west slope of the Helan Mountains.

Site	Shrub	Herb
Xiazi Valley	*Oxytropis aciphylla* *Reaumuria soongarica* *Ephedra lepidosperma* *Ammopiptanthus mongolicus*	*Peganum multisectum* *Cleistogenes squarrosa* *Heteropappus altaicus* *Achnatherum inebrians*
Nansi Valley	*Caragana tibetica* *Salsola passerina* *Salsola laricifolia* *Convolvulus tragacanthoides*	*Stipa breviflora* *Heteropappus altaicus* *Cleistogenes squarrosa* *Plantago lessingii*
Halawu Valley	*Convolvulus tragacanthoides* *Salsola passerina* *Reaumuria soongarica* *Caragana roborovskyi*	*Stipa breviflora* *Artemisia frigida* *Allium eduardii* *Poa angustifolia*
Luanchai Valley	*Sabina procumbens* *Berberis thunbergii* *Potentilla fruticosa* *Cotoneaster acutifolius*	*Agropyron cristatum* *Artemisia hedinii* *Heteropappus altaicus* *Cyperus fuscus*
Daxi Valley	*Leptodermis ordosica* *Prunus mongolica* *Lonicera microphylla* *Clematis fruticosa*	*Artemisia xerophytica* *Artemisia dubia* *Urtica angustifolia* *Taraxacum mongolicum*

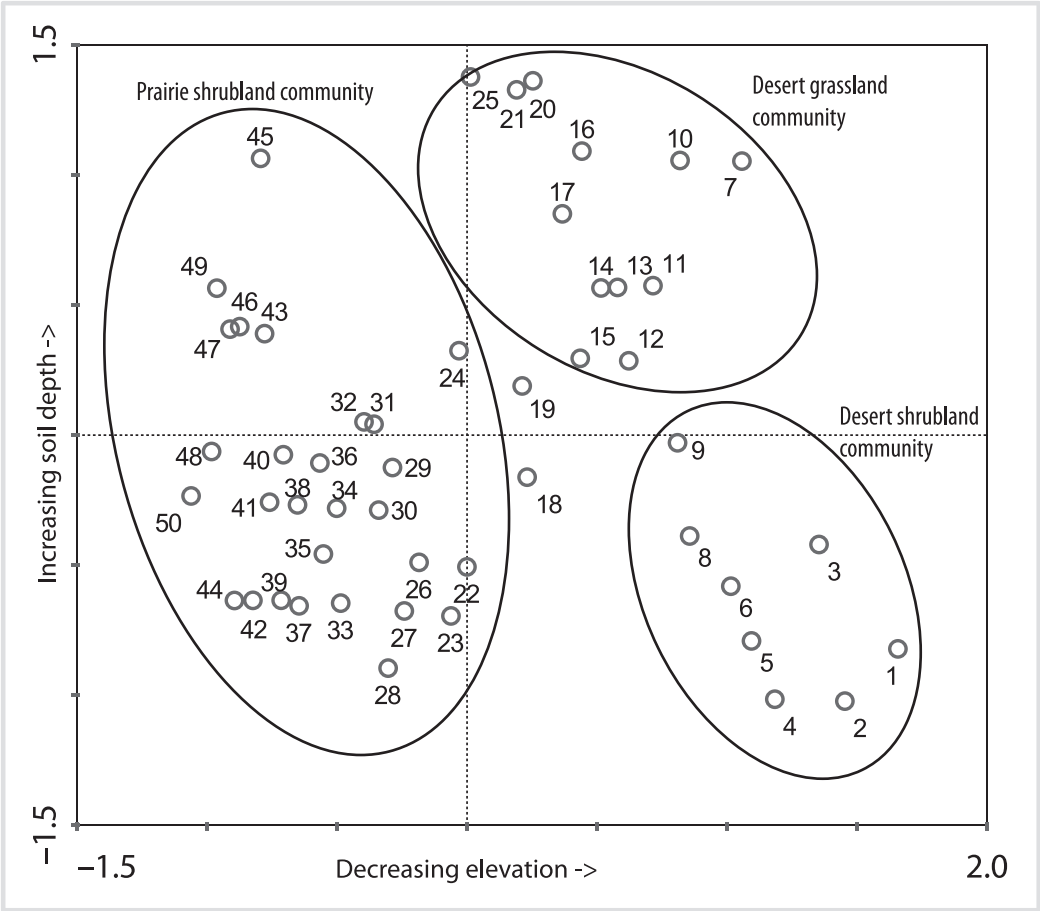
This article focuses on vegetation between 1500 masl and 2050 masl, and vegetation categorization is introduced to perform vegetation classification. The predominant vegetation forming the montane desert zone at the base of the Helan Mountains is an *S. passerina* community. Dominant species include *S. passerina*, *Reaumuria soongarica*, *Caragana brachypoda*, *Asterothamnus centraliasiaticus*, *S. breviflora*, and *Cleistogenes squarrosa*

TABLE 2 Explanatory environmental variables.

	Abbreviation	Measurement
Soil properties		
Sand content	Sand	%
Silt content	Silt	%
Clay content	Clay	%
Soil water	Water	%
Organic matter	OM	g/kg
Total nitrogen	TN	g/kg
pH	pH	numeric
Electrical conductivity	EC	µS/cm
Geographical parameters		
Latitude	Lat	°
Longitude	Long	°
Altitude	Alt	masl
Slope aspect	SA	numeric
Slope position	SP	numeric

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FIGURE 2 Principal component analysis of 50 sample plots on the west slope of the Helan Mountains. The horizontal axis represents a water gradient, with the highest precipitation on the left. The vertical axis represents a soil depth gradient, with higher points on the axis representing an increase in the depth of the soil layer.



(Zheng et al 2008). Soils are Aridisols derived from calcareous alluvium with textures ranging from loamy sand in the shallow A_1 horizon (0–10 cm) to coarse sand in subsoil horizons (Di 1986).

Vegetation sampling

A quantitative survey of the vegetation was carried out during 2005–2006. Five transects of 10 m width were investigated, with samples taken at 50 m intervals along the elevation gradient. This included 8 samples from Xiazi Valley in the south section, 6 from Nansi Valley and 12 from Halawu Valley in the middle section, and 12 from Luanchai Valley and 12 from Daxi Valley in the north section (Figure 1). In total, 50 sample plots were selected on the west slope of the Helan Mountains (*Supplemental data*, Table S1; http://dx.doi.org/10.1659/MRD-JOURNAL-D-12-00088.S1).

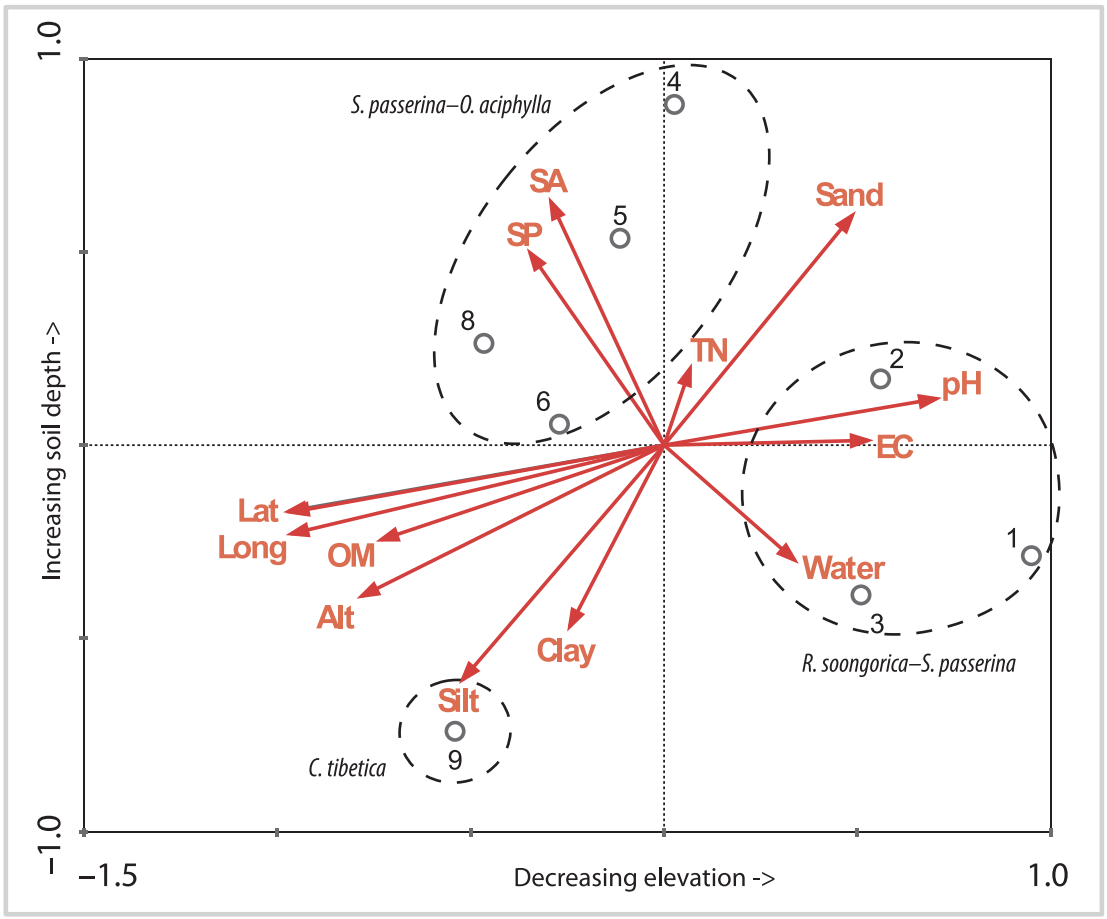
Vegetation types were identified based on field surveys. The survey quadrats for shrub species were 10 m × 10 m in size, whereas those for herbaceous species were 1 m × 1 m. The main plant species in each of the valleys are presented in Table 1. Frequency, density, and canopy cover percentage were recorded using the Braun-Blanquet (1932) method.

Soil sampling and analysis

Five soil samples were collected from each plot, at 10 cm intervals, from the soil surface to 40 cm below. During data processing, we found that the differences between soil properties at different depths were small; therefore, we pooled samples to form 1 composite sample, which we air dried, mixed thoroughly, and hand-sieved through a 2 mm screen to remove roots and other debris. Soil water was determined for the soil profile using a portable Time Domain Reflectometer (Delta-T Devices Ltd, Cambridge, UK). Organic matter (OM) was measured by the potassium dichromate method (Liu 1996). Total nitrogen (TN) was measured with a Kjeltec System 1026 Distilling Unit (Tecator AB, Sweden). The pH of soil extracts (soil:water ratio = 1:5) was measured in accordance with the method described by the Nanjing Institute of Soil Research (1980). Electrical conductivity (EC) was measured with a handheld conductivity meter (Cole–Parmer Instruments Company, IL, USA). Soil particle size was determined by a Mastersizer 2000 particle size analyzer (Malvern Ltd, UK). Quadrat location (latitude, longitude, and altitude) was determined using a global positioning system device and recorded.

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FIGURE 3 Canonical correspondence analysis of the desert shrub category and environmental factors. Arrows represent environmental factors; arrow length indicates the contribution of the factor to the ordination axes; angle between arrows and axes indicates the correlation between the variable and the axes (Xu et al 2006)—in this case, the ordination axes for elevation and soil depth.



Data analysis

The computer program Canoco 4.5 was used for all ordinations, and plots were drawn using Canodraw 4.12. Rare species were downweighted to reduce distortion of the analysis. Preliminary analyses were made using principal component analysis (PCA) to check the magnitude of change in species composition along soil depth. A form of direct gradient analysis, canonical correspondence analysis (CCA), was used to examine the relationships between vegetation patterns and measured environmental factors. The significance of the species–environment correlation was tested by a distribution-free Monte Carlo test. In the Monte Carlo test, the distribution of the test statistics under the null hypothesis is generated by random permutations of cases in the environmental data. It has been suggested that PCA and CCA be used together to evaluate the extent to which the variation in species data is accounted for by the environmental data (ter Braak 1986).

All environmental variables for which data were collected are summarized in Table 2, which includes 8 soil physical and chemical parameters and 5 geographical parameters.

Results

Three vegetation categories were identified using PCA: prairie shrubland (samples 22–24 and 26–50), desert grassland (samples 7, 10–16, 20, 21, and 25), and desert shrubland (samples 1–9) (Figure 2). Each category differs from the others in its environmental attributes.

In the study areas, as elevation decreases, temperature increases and precipitation decreases (represented by the horizontal axis in Figure 2), and the prairie shrubland, desert grassland, and desert shrubland categories appear in turn. As the depth of the soil layer increases (represented by the vertical axis in Figure 2), the desert shrubland, prairie shrubland, and desert grassland categories appear in turn. The 3 vegetation categories contain different vegetation communities; their species components and geographical variables are summarized in Tables S1 and S2 (*Supplemental data*; http://dx.doi.org/10.1659/MRD-JOURNAL-D-12-00088.S1).

Desert shrubland plants and environmental factors

EC is significantly positively related to pH and soil water ($p < 0.05$) and significantly negatively related to latitude,

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TABLE 3 Vegetation communities and soil properties for 3 vegetation categories in the Helan Mountains.

Vegetation category	Sand (%)	Silt (%)	Clay (%)	Water (%)	OM (g/kg)	TN (g/kg)	pH	EC (μS/cm)
Desert shrubland								
C. tibetica	38.95 ± 4.48	47.27 ± 4.09	13.78 ± 0.75	4.33 ± 1.19	1.76 ± 0.24	0.02 ± 0.00	8.66 ± 0.08	111.6 ± 25.81
S. passerina–R. soongorica	46.17 ± 6.25	42.32 ± 5.55	11.51 ± 1.20	6.17 ± 1.43	1.19 ± 0.14	0.03 ± 0.01	8.95 ± 0.04	308.26 ± 59.48
S. passerina–O. aciphylla	51.93 ± 8.81	38.74 ± 4.76	9.33 ± 1.86	5.24 ± 1.36	1.40 ± 0.51	0.05 ± 0.01	8.84 ± 0.06	249.43 ± 21.46
Desert grassland								
S. breviflora (lower)	15.00 ± 1.75	67.70 ± 4.93	17.30 ± 3.28	10.63 ± 1.66	2.73 ± 0.03	0.16 ± 0.04	8.30 ± 0.02	234.33 ± 25.51
S. breviflora (middle)	18.66 ± 2.43	65.40 ± 1.27	15.94 ± 2.32	11.27 ± 0.93	1.78 ± 0.02	0.11 ± 0.02	8.81 ± 0.04	320.67 ± 15.56
Stipa grandis	24.72 ± 3.02	61.02 ± 8.05	14.26 ± 5.21	12.40 ± 0.25	1.26 ± 0.07	0.07 ± 0.02	9.13 ± 0.04	724.33 ± 39.60
Prairie shrubland								
U. glaucescens–P. mongolica	21.97 ± 1.99	61.18 ± 5.52	16.85 ± 0.68	5.07 ± 0.35	2.66 ± 0.22	0.05 ± 0.01	8.74 ± 0.02	91.13 ± 9.42
P. mongolica–Potentilla fruticosa	36.83 ± 2.81	50.02 ± 6.43	13.15 ± 0.91	7.10 ± 0.30	3.09 ± 0.26	0.08 ± 0.01	8.68 ± 0.02	113.10 ± 21.28
P. mongolica	42.10 ± 3.67	46.44 ± 3.03	11.46 ± 0.47	8.65 ± 0.51	4.73 ± 0.11	0.12 ± 0.03	8.05 ± 0.04	157.46 ± 26.90

longitude, and OM ($p < 0.05$). Soil depth is significantly positively related to sand, TN, slope aspect (SA), and slope position (SP) and significantly negatively related to silt and clay content ($p < 0.05$) (Figure 3). Ordination based on CCA analysis divided the desert shrubland category into 3 groups: a *Caragana tibetica* community (sample 9) at the higher elevation, an *S. passerina–Oxytropis aciphylla* community (samples 4, 5, 6, and 8) at the middle elevation, and an *R. soongarica–S. passerina* community (samples 1–3) at the foot of the mountains.

As elevation decreases, the decrease in rainfall and increase in soil evaporation result in increasing soil alkalization. The *C. tibetica*, *S. passerina–O. aciphylla*, and *R. soongarica–S. passerina* communities appear in turn as alkalization increases. As soil depth increases, sand content increases, while silt and clay contents decrease, and the *C. tibetica*, *R. soongarica–S. passerina*, and *S. passerina–O. aciphylla* communities appear in turn (Table 3).

Desert grassland plants and environmental factors

Soil water is significantly negatively related to latitude ($p < 0.05$). Soil texture is significantly positively related to SA, altitude, and SP ($p < 0.05$) and significantly negatively related to OM, TN, and silt and clay content ($p < 0.05$) (Figure 4).

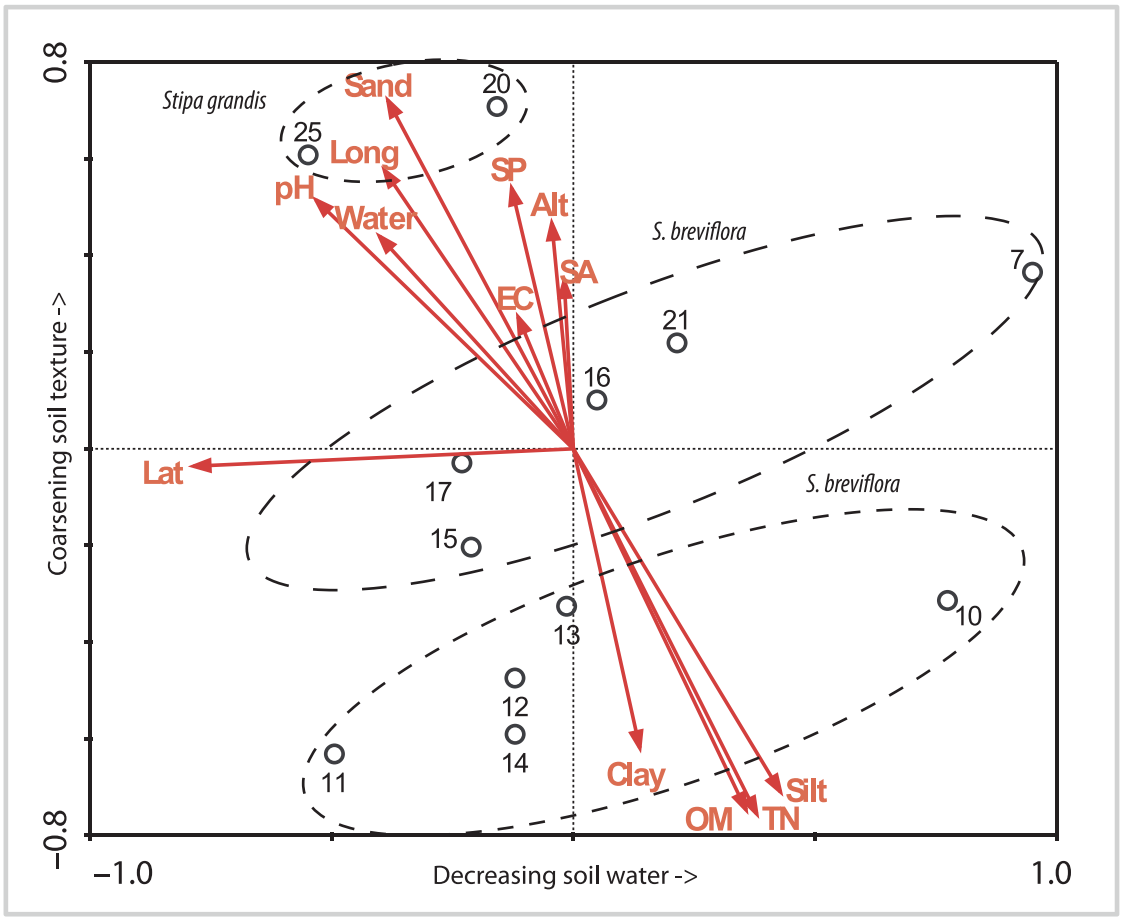
Ordination based on CCA clustered desert grassland plants into 3 groups: a *Stipa grandis* community (samples 20 and 25) at the higher altitude, and an *S. breviflora* community in the middle (samples 7, 15–17, and 21) and lower (samples 10–14) altitudes. The *S. breviflora* and *S. grandis* communities appear consecutively along the soil texture gradient (Table 3).

Prairie shrubland plants and environmental factors

Soil texture is positively related to silt and SP and significantly negatively related to OM and TN ($p < 0.05$). Soil pH is significantly positively related to altitude, water, and EC and significantly negatively related to SA ($p < 0.05$) (Figure 5).

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FIGURE 4 Canonical correspondence analysis of the desert grassland category and environmental factors; correlation to soil water and soil texture.



Ordination based on CCA clustered the prairie shrubland plants into 3 groups: a *Ulmus glaucescens–Prunus mongolica* community (samples 47–50), a *P. mongolica–Potentilla fruticosa* community (samples 34–46), and a *P. mongolica* community (samples 22–27 and 29–33). OM and TN increase gradually with a decline in silt content; *U. glaucescens–P. mongolica*, *P. mongolica–P. fruticosa*, and *P. mongolica* communities appear in turn as this occurs. As soil pH decreases, plant communities are found in the following sequence: *P. mongolica*, *P. mongolica–P. fruticosa*, and *U. glaucescens–P. mongolica* (Table 3).

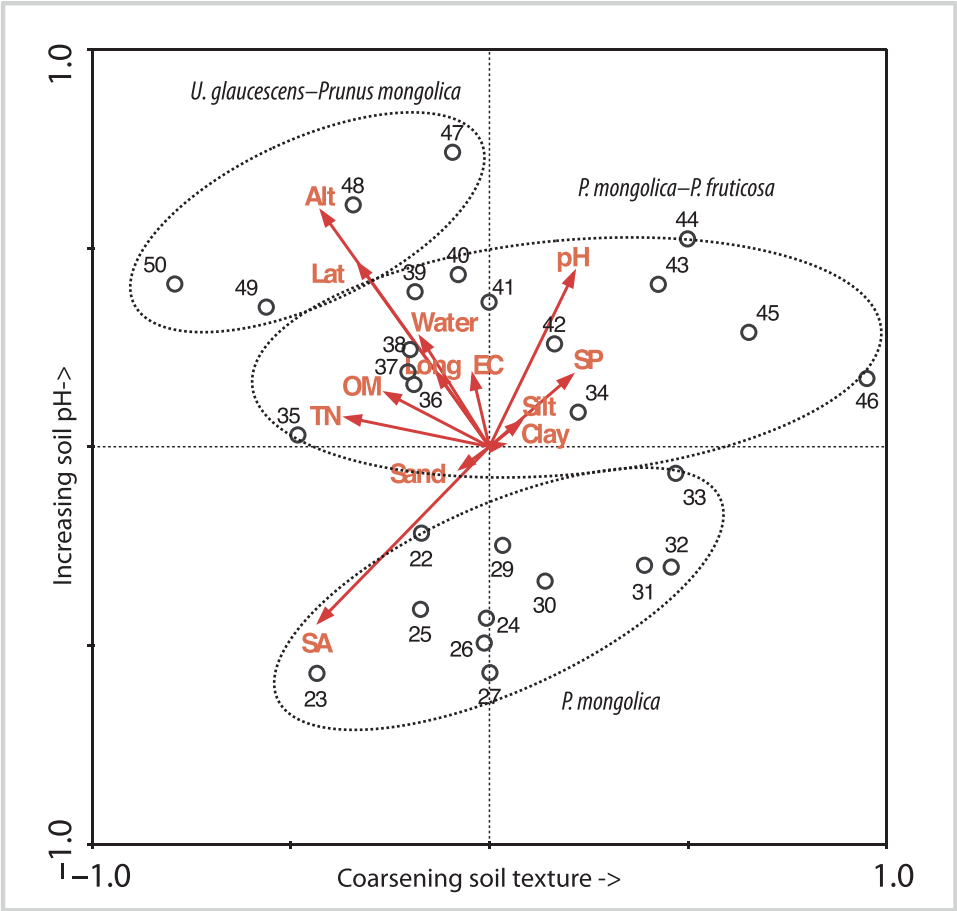
Discussion and conclusion

The conceptual model presented by Sala et al (1997) hypothesized that a dominance of shrubs and grasses is related to soil texture, since soil texture plays a significant role in regulating vegetation composition, structure, and functional groups. Burke et al (1990) found that soil clay content was positively correlated with total soil organic matter across large regions of the Great Plains of North America. The influence of soil texture changes on the composition of vegetation communities has been demonstrated by numerous other studies as well. Walker (1979) has put forward a simple model to explain a pattern of grassland woody plant distribution, in which herbaceous species with dense shallow-rooted systems utilize water resources close to the surface, while deep-rooted woody plants are able to access water from further down the soil profile. Furthermore, some studies have found that shrub species have a greater ability to adapt to coarse soil textures (Li et al 2004). Our results show that soil texture becomes coarser along the order of *C. tibetica*, *S. passerina–R. soongarica*, and *S. passerina–O. aciphylla* communities in the desert shrubland, and sand content increases by 12.98% from 38.95 ± 4.48% in the *C. tibetica* community to 51.93 ± 8.81% in the *S. passerina–O. aciphylla* community (Table 3).

The vegetation component of the above 3 communities was also obviously different. For instance, only 3 shrub species—*C. tibetica*, *Convolvulus tragacanthoides*, and *Caragana roborovskyi*—were found in the *C. tibetica* community. However, 7 shrub species—*O. aciphylla*, *S. passerina*, *R. soongarica*, *N. roborovskyi*, *C. tragacanthoides*, *Ammopiptanthus mongolicus*, and *Ceratoides arborescens*—were recorded in the *S. passerina–O. aciphylla* community.

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FIGURE 5 Canonical correspondence analysis of the prairie shrubland category and environmental factors; correlation to soil texture and soil pH.



Similar results were found in the desert grassland and prairie shrubland categories. This is probably because soil texture regulates the formation and decomposition of soil OM and influences infiltration and moisture retention and the availability of water and nutrients (Sperry and Hacke 2002).

Topography influences local and regional microclimates by changing the pattern of precipitation and temperature (Dahlgren et al 1997; Tsui et al 2004), solar radiation, and relative humidity (Finney et al 1962). We also found a significant relationship between vegetation and slope positions, as is the case in other hill landscapes (Pinder et al 1997). For example, the *S. breviflora* community (sample 7) was located at the foot of the mountain in Nansi Valley, where the total coverage reached 80%, while some shrub species, such as *S. passerina*, *R. soongarica*, and *C. roborovskyi*, were distributed with no clear pattern, indicating a possible increase in soil heterogeneity, possibly due to human disturbances. Moreover, they were accompanied by some herbaceous species, *Heteropappus altaicus*, *A. centraliasiaticus*, and *C. squarrosa*; the protected location on the valley floor led to less soil erosion and a soil layer thicker than 40 cm. By contrast, the *C. tibetica* community (sample 8) was distributed on the middle slope of Nansi Valley (adjacent to sample 7), where the total coverage reached only 30% and was accompanied by some xerophytic dwarf shrub species, such as *Caragana ammannii*, *Ephedra lepidosperma*, *R. soongarica*, *S. passerina*, and *Salsola laricifolia*. Only a few perennial and annual herbaceous species were recorded there, and the soil depth was less than 20 cm, indicating greater exposure to erosion.

Vegetation and soil are the most conspicuous resources of arid grasslands. Grassland management must work with plant communities by taking into account all of the interrelated biotic and abiotic influences that affect production of animal feed and habitat. This study identified 3 vegetation categories—desert shrubland, desert grassland, and prairie shrubland—on the west slope of the Helan Mountains, and different soil properties and environmental factors that regulated the distribution of vegetation communities within those categories. Understanding the relationships between such environmental variables and vegetation distribution can help improve the management, reclamation, and development of arid and semiarid grassland ecosystems.

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Supplemental data

TABLE S1 Geographical variables of 50 samples in 3 vegetation categories.

TABLE S2 Species components of the 3 vegetation categories found on the western slopes of the Helan Mountains.

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