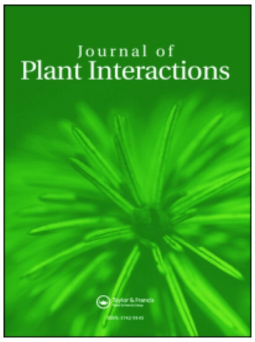

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Plant-Environment Interactions

The interactions among herbaceous diversity, edaphic factors, and topography under typical afforestation in the transition zone between the qinghai–Tibet Plateau and Loess Plateau

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ABSTRACT

The herbaceous layer plays a crucial role in afforestation and could provide important information in the process of restoration. Thus, we investigated herbaceous communities (composition and diversity), related factors (soil properties and topography), and their interactions in the afforestation of the 'Grain-for-Green' program in the transition zone between the Qinghai–Tibet Plateau and Loess Plateau. We found 52 herb species belonging to 41 genera of 18 families, among which perennial herbs dominated. Our results revealed two different restoration mechanisms for Qinghai spruce (*Picea crassifolia*) and Prince Rupprecht's larch (*Larix principis-rupprechtii*). The community in the Qinghai spruce forest was more competitive and mainly comprised xeric herbs, while the Prince Rupprecht's larch forest provided shadier conditions with higher herb diversity. Soil available nitrogen (AN), available potassium (AK), available phosphorus (AP), slope position, and elevation were significant factors affecting herbaceous diversity. The upper slope position should be the primary consideration since topography exacerbated nutrient loss. Soil water remains the underlying factor of succession, and Prince Rupprecht's larch on hillslopes might be at risk of water stress in the future. Understanding the significance of the herbaceous layer and environmental factors will provide a comprehensive picture of sustainable management on the alpine Loess Plateau.

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Herb diversity; soil properties; afforestation management; alpine Loess Plateau

1. Introduction

The herbaceous layer is a crucial stratum in forest ecosystems. It represents up to 90% of plant biodiversity and facilitates the flux of energy and nutrition (Gilliam 2007; Thrippleton et al. 2016). The characteristics of herbaceous layer could provide indicators of site quality and afforestation status due to its quick response to environmental changes (Gracia et al. 2007; Von Oheimb & Härdtle 2009; Durak 2012). Ecological drivers of herbaceous species composition are crucial to understand forest succession (Burrascano et al. 2011; Andra 2016), since the herbaceous layer could affect other layers through competition for water, nutrition, and light utilization (Simonson et al. 2014; De Long et al. 2016). In the initial restoration stage, herbs colonize rapidly due to high light availability, abundant soil nutrients, and adequate forest floor space (Hart & Chen 2006). Large herb communities will restrict the growth of saplings (Gafta & Peet 2020), replace some pioneer species, and stop the process of natural regeneration (Pickup et al. 2013). The overstory may change the conditions to establish new plant communities (Bartels & Chen 2010; Reich et al. 2012). In artificial forests, the features of species composition and structure are affected by the afforestation strategy (Wang et al. 2014), which most directly results in edaphic conditions such as the soil water content, pH, soil texture, and nutrient availability (Bartels & Chen 2013). Improving biodiversity plays a crucial role in sustainable management in alpine regions (Zhou et al. 2019).

Historically, the transition zone between the Loess Plateau and the Qinghai–Tibet Plateau has been regarded as the most vulnerable region in the world due to intense climate change and long-term interactions between agriculture and grazing (Wu et al. 2017). The erosion of soil and water has induced ecological problems, including plantation degeneration, water scarcity, and dust storms in Northwest China, which has restricted the agricultural and economic development of many provinces (Z. Wang et al. 2015; Liu et al. 2016; Liu et al. 2017). In 1999, the 'Grain-for-Green' project in the Datong region of Qinghai Province was started by converting sloping croplands into forestlands or grasslands. Although these methods achieved some results in the initial stages, some afforestation sites started to show signs of weak growth and low biodiversity. Water and nutrient conditions were not sufficient to support the existing forest density, resulting in an unreasonably simple structure for the forest (Xiao & Xiao 2019). The primary goal of such programs is to mitigate ecological problems caused by the substantial loss of forests and degraded landscapes (Ali et al. 2019), so the significance biodiversity conservation has been partly ignored in long-term forest management (Brockerhoff et al. 2008). There is an urgent need to assess how herbaceous species diversity affect current afforestation based on a comprehensive databank and to provide management suggestions for long-term restoration strategies.

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Edaphic factors are usually regarded as the most important factors for the herbaceous layer (Ikauniece et al. 2013; Hossain et al. 2016; Khan et al. 2017). The variation of soil properties leads to changes in the composition and traits of herbs, which in turn affect soil characteristics (Laughlin et al. 2007). Compared with the tree and shrub layers, the herb layer is more sensitive to soil nutrient change and more competitive in nutrient cycling (Rieger et al. 2019). According to previous research on the alpine region and Loess Plateau, the soil nitrogen, phosphorus, potassium, and soil organic carbon (SOC) have significant interactions with herbaceous composition and diversity (Zhang et al. 2018; Zhou et al. 2019). Soil phosphorus has a synchronous variation with herbaceous diversity in environmental changes (Ali et al. 2019), which could be regarded as a driver for the establishment of the community composition (Zemunik et al. 2016). Long-term afforestation can greatly improve self-regulating capacity by advancing the content of soil organic carbon and nitrogen (Fu et al. 2010; Ren et al. 2016; Gonzalez-Ollauri & Mickovski 2017), and mitigate the adverse effects of droughts on the water and nutrient supply (Prietzel & Bachmann 2012). Understanding the relationship between vegetation communities and soil nutrition is critical to understanding the restoration of fragile ecosystems (Zhang et al. 2018). On the other hand, water plays an essential role in large-scale forestation programs in semi-arid regions in China (Song et al. 2012). Other soil physical properties, including bulk density (BD) and soil texture, can strongly effect plant community diversity through water and nutrient retention and root traits (Gould et al. 2016). Many studies have explored changes in nutrient cycling, soil function, vegetation in large scale during the 'Grain-for-Green' project. However, in the transition zone, given the alpine ecosystem characteristics of the Loess Plateau, little is known of how the unreasonable forest structure formed – especially the potential drivers and limiting factors, which could be discovered through analysis of the herbaceous and edaphic characteristics.

The high topographic variability, e.g. in the altitude, slope position, and slope exposure in the transition zone between the Loess Plateau and the Qinghai–Tibet Plateau is responsible for the heterogeneity of the microenvironment due to changing the light and water conditions, and affecting the soil texture, nutrient, vegetation diversity, and distribution (Xu et al. 2020). Forests might be more prone to nutrition loss from hilltops (Zou et al. 2014). The results of previous studies have suggested using strategies according to different topographic conditions of the Loess Plateau to maximize the benefits of afforestation, such as mitigating soil degradation and improving biodiversity (Taye et al. 2013; X. Zhang et al. 2020). The idea of using different restoration strategies according to the topography still requires further understanding of the ecological role of topography in established forests (Tang et al. 2010).

However, after about 20 years, afforestation usually faces the challenge of species diversity reduction (Paillet et al. 2010), which might deteriorate problem of simple forest structure. Thus, this study selected general sites to represent the typical afforestation of the 'Grain-for-Green' program in the transition zone, aiming to interpret the feature of interactions among the herbaceous layer and environmental factors to find potential drivers and limiting factors in order to provide suggestions for the forest transformation strategy. The specific objectives of this study were to (1) investigate the current situation and analyze relationship between herbaceous diversity and related factors in typical afforestation modes and (2) explore potential limiting factors by interpreting features of interactions and provide suggestions for management to optimize afforestation.

2. Materials and methods

2.1. Study area and site description

This study was conducted in the Anmentan watershed (101° 40′17″–101°41′12″ E, 36°54′57″–36°55′51″ N), a typical region in the transition zone between the northern Qinghai–Tibet Plateau and the Loess Plateau, which is characterized by a plateau continental climate, with 450 mm average annual precipitation, a mean annual temperature of 3.9 °C, and an average annual frost-free period of 102 days. The Anmentan watershed has an area of 1.16 km^2, providing water for agricultural and economic activities in Datong County in Qinghai Province. This watershed has had 20 years of 'Grain-for-Green' project history, during which time farmland was converted into tree plantations with species such as *Picea crassifolia*, *Larix principis-rupprechtii*, *Betula platyphylla*, and *Populus cathayana*. Additionally, the precipitation in the Anmentan watershed has seasonal characteristics; the rainy season is from May to September. According to the recorded data from the Datong weather station, the average precipitation from 2016 to 2018 was higher than the average level.

In our study watershed, the 'Grain-for-Green' project primarily focused on the shady and half-shady slopes due to the higher survival rate under infertile soil (Wang et al. 2014); thus, we selected two shady slopes as our research plots. Additionally, some broad-leaved tree species (e.g. *Populus cathayama*) had shown poor growth after the initial stage of afforestation in this area and are being transformed, so we chose plots that are mainly composed of coniferous trees (*Picea crassifolia* and *Larix principis-rupprechtii*), which represent the typical afforestation of the 'Grain-for-Green' project on the alpine Loess Plateau (Table 1). The soil type in our study watershed is loess castanozem, while there is a small part of mountain brown cinnamon in this county. Shrub species in the reforested area are rarely found, with the exception of *Hippophae rhamnoides* Linn.; *Artemisia L*, *Saussurea japonica* (Thunb.) DC., *Geranium sibiricum* L., *Poa annua* L., and *Cirsium setosum* (Willd.) MB. are dominant herb species.

2.2. Investigation and sampling

The field work was conducted from 15 May to 25 July in 2018. We investigated plots according to slope position and tree species as they were main considerations of afforestation strategy in 1999. Sample plots were set along the slope, including in upper, middle, and lower slope positions, we took the average of each slope position. For each position on the slope, three 20 m × 20 m plots were established as pseudo-replications for field investigation and sampling. In each sampling plot, we measured the height and diameter at breast height (1.3 m) of all the trees. Basic information of the site included the slope aspect, elevation, stand density, and canopy cover. Nine herb quadrats (1 m × 1 m) were established uniformly to investigate the species and number of herbs. Additionally, the average height and cover degree of each species were recorded.

In soil sampling, we randomly selected three 50 cm × 50 cm areas in each 20 m × 20 m sampling plot. In each

Table 1. Summary of sampling plots in the Anmentan watershed.

No.	Dominant Species	Slope Position	Slope Gradient	Aspect	Elevation	Woody Plant Density	Average Status of Growth	Canopy Cover
P1	*Picea crassifolia*	Upper	12°	NE10	2550 m	1350/ha	H:2.63 m, DBH:4.34 cm	39.80%
P2	*Picea crassifolia*	Middle	10°	NE10	2529 m	1700/ha	H:2.69 m, DBH:5.36 cm	62.10%
P3	*Picea crassifolia*	Lower	9°	NE10	2509 m	1700/ha	H:3.45 m, DBH:5.65 cm	60.50%
P4	*Larix principis-rupprechtii*	Upper	14°	NW16	2539 m	1000/ha	H:6.62 m, DBH:10.37 cm	89.50%
P5	*Larix principis-rupprechtii*	Middle	11°	NW20	2525 m	1800/ha	H:7.99 m, DBH:8.82 cm	91.80%
P6	*Larix principis-rupprechtii*	Lower	9°	NW10	2501 m	1800/ha	H:8.07 m, DBH:9.08 cm	94.70%

Note: H represents height, DBH represents diameter at breast height (1.3 m).

location, six soil samples were collected by a ring-knife with a diameter of 7 cm. Because surface soil layer was easily affected and quickly responded to rainfall (Jin et al. 2018), we sampled at two soil depths: 0–20 cm (layer 1) and 20–40 cm (layer 2). Three replicates were sampled at each depth. Samples of the two layers were then well mixed at a ratio of 1:1 to obtain a representative bulk sample for each sample plot (Tang et al. 2010). A total of 162 soil samples were collected from 54 soil profiles, located in 18 sample plots. All samples were air-dried at room temperature, sieved through a 2 mm screen to remove coarse fragments, and stored in sealed aluminum. until further laboratory measurement.

2.3. Soil sample analysis

2.3.1. Analysis of physical properties

Soil BD samples were collected using the soil core method and were oven-dried at 104 °C for 48 h (Ren et al. 2016). The soil texture was analyzed using a laser particle size analyzer (Mastersizer 2000, Marlven, Ltd. UK). A soil moisture neutron probe device (CNC503DR) was used to determine the soil water content. The saturated water-holding capacity of the soil (SWHC) was measured using the ring knife method (Liu et al. 2013).

2.3.2. Analysis of chemical properties

The determination of soil chemical properties was completed by the Analytical and Testing Center of Qinghai Province Academy of Agricultural and Forestry Sciences. Soil samples were sifted at 1 mm to test soil available nutrients and sieved through a 0.149 mm mesh to determine the content of SOC, TP and TN.. SOC was measured by the Walkley–Black method, reacting 1 g soil with 2 N $K_2Cr_2O_7$ and 20 mL of H_2SO_4 at 185 °C for 20 min, followed by titration with standardized $FeSO_4$. The content of total nitrogen (TN) and total phosphorus (TP) were determined by the Kjeldahl method and colorimetric method, respectively (GS, Liu et al. 1996). Available phosphorus (AP) was determined by the Olsen method (Naelson & Sommers 1996). Available nitrogen (AN) was extracted using 4 M KCl after seven days of incubation at 40 °C and was then measured with a Kjeltec Auto-sampler System 1035 Analyzer. Available potassium (AK) was analyzed by the Mehilich No. 1 method (GS, Liu et al. 1996). Soil pH was measured using a pH meter after shaking a soil water (1:5 *w*/*v*) suspension for 30 min (Zhang et al. 2018).

2.4. Data calculation and Statistical Analysis

2.4.1. Species importance value index

The species importance value index (IV) in this study was calculated as follows:

$$\mathrm{IV} = (\text{Relative abundance} + \text{Relative frequency} + \text{Relative dominance})/3 \quad (1)$$

where relative dominance was calculated by the average height of the species and relative abundance was the coverage of a herb in the investigated quadrat.

2.4.2. Species diversity index

Shannon–Weiner diversity index (H'):

$$H' = -\sum P_i \ln P_i. \quad (2)$$

Margalef abundance index (R):

$$R = (S - 1)/\ln N. \quad (3)$$

Simpson dominance index (D):

$$D = 1 - \sum P_i^2 \quad (4)$$

where S is the total number of species, N is the total number of individuals observed, and P_i is the proportion of individuals of the i-th species ($i = 1, 2, 3, \ldots, S$).

In the calculation of the species diversity indexes above, we combined the herbage data for the same tree species and slope position to achieve precise processing.

2.4.3. Statistical Analysis

We classified the sample plots by indexes of slope position and tree species as they were afforestation strategy basis in 1999. Differences in soil properties and species diversity indexes were compared using least-significant difference (LSD) test ($p < 0.05$), following ANOVA procedures. To determine the relationships between the herbaceous diversity and environmental variables, as well as inter-correlation between environmental variables, redundancy analysis (RDA) was employed through the 'vegan' package of R (version 3.6.2). Variation partitioning was performed using the 'varpart' function in vegan and was represented schematically using Venn diagrams. In this study, the Shannon–Weiner diversity index, Margalef index, and Simpson dominance index were set as diversity variables, represented in an RDA ordination diagram by red arrows; whereas the edaphic and topographic factors were set as the environmental variables, represented by blue arrows. Prior to the above analysis, the upper, middle, and lower slope positions were converted to numerical values (3, 2, and 1, respectively). The scaling of the ordination focused on inter-species correlations, and a Monte Carlo test ($n = 999$) on permutations was conducted to test the significance of the eigenvalues of the canonical axis. The species data and environmental variables were log-transformed to reduce the effects of extreme values. Then, stepwise regression analysis was applied to determine the significance of each variable. The coefficient of determination (R^2) is the unbiased form of the coefficient that takes into account the number of input variables in the model and was calculated by the 'RsquareAdj' function in the vegan package. The descriptive statistical parameters and significance tests were calculated using the 'agricolae' package in R (version 3.6.2).

3. Results

Our field survey found a total of 52 herb species belonging to 41 genera of 18 families in 18 sampling plots. Therophytes accounted for 13.5% of the herbs, while perennial herbs (86.5%) were the dominant type in the study area. The dominant herbaceous families were *Compositae* (10 species), *Leguminosae* (9 species), and *Gramineae* (5 species). A total of 25 herb species were recorded in the *Picea crassifolia* forest, while 38 species were recorded in the *Larix principis-rupprechtii* forest; the dominant species were *Poa pratensis*, *Geranium wilfordii*, *Achnatherum inebrians*, *Thalictrum aquilegifolium*, *Adenophora stricta*, and *Potentilla chinensis* (Table 2). The herb species composition was quite similar between the lower slope position and middle slope position in all plots. Drought-tolerant plants were more prevalent in the upper slope position. The biomass and herbaceous cover degree were abnormally low in P6.

In Figure 1, the three diversity indexes show a similar pattern. According to the results of the LSD test, P4, P5, and P6 had significantly higher species diversity than P1, P2, and P3 among all diversity indices. The highest Margalef richness index was observed in P6; herb diversity declined with increasing slope position. The Simpson index and Shannon–Wiener index had small difference in different slope positions.

Table 3 suggests that most soil chemical properties changed significantly in different study plots, but soil texture was the only soil physical property where the change was significant. The contents of AN, TN, and SOC were high in the lower slope plots. AP, AK, and TP were recorded to be relatively higher in P2 and P3 than in other plots. Most of the edaphic variables were significantly lower in the upper slope positions, while no significant differences were recorded among the lower and middle slope positions.

The first two axes of RDA-ordination (Figure 2) explained 99.15% of the cumulative variance of the species–environment relationship. The eigenvalues of the first and second axes were 0.69 and 0.24, respectively. Axis 1 was more related to soil nutrition, while Axis 2 was more related to topography. From the results of stepwise selection, AP was the most significant factor for species diversity in the RDA. AN, AK, elevation, and slope position were also found to be significant ($p < 0.05$). The simplified RDA model with the aforementioned five variables ($p = 0.001$, $R^2 = 0.85$) explained 90.44% of species diversity differences; only 8.3%

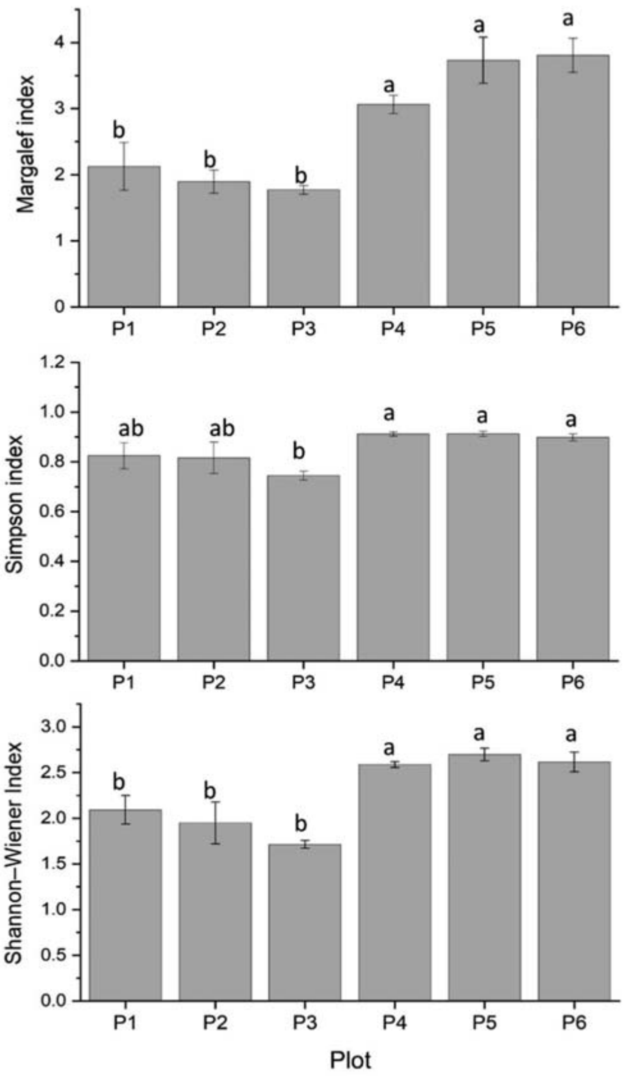

Figure 1. Margalef index, Simpson index and Shannon–Wiener index for different sampling plots. Various alphabetical characters depict significant differences at the $p < 0.05$ level. The error bar represents standard deviation between three replicate samples.

Table 2. Characteristics of the herbaceous layer of the Anmentan watershed.

No.	Family	Genus	Cover Degree	Biomass	Dominant Species	
					Species	IV
P1	5	14	88.33	40.87	*Achnatherum inebrians*	20.51
					Poa pratensis	14.48
					Cirsium setosum	12.17
P2	5	12	82.25	51.05	*Poa pratensis*	23.51
					Geranium wilfordii	19.59
					Elymus dahuricus	17.99
P3	5	11	77.22	52.7	*Poa pratensis*	30.63
					Geranium wilfordii	19.56
					Elymus dahuricus	12.33
P4	11	19	61.13	11.17	*Potentilla chinensis*	12.57
					Geum aleppicum	9.92
					Clematis florida	9.43
P5	11	23	53.21	16.58	*Thalictrum aquilegifolium*	19.67
					Artemisia sacrorum	15.3
					Puccinellia tenuiflora	11.82
P6	14	22	9.88	6.15	*Thalictrum aquilegifolium*	20.4
					Adenophora stricta	14.48
					Elymus dahuricus	7.11

Table 3. Statistical summaries of soil properties in different sampling plots, shown by the means ± standard deviations.

No.	P1	P2	P3	P4	P5	P6
AN (mg kg^{-1})	58.00 (6.38) bc	80.67 (7.72) ab	76.33 (13.91) ab	38.67 (6.13) c	98.00 (11.43) a	101.67 (4.71) a
AP (mg kg^{-1})	7.87 (1.77) c	25.17 (2.40) a	18.87 (4.01) ab	3.53 (0.31) c	11.73 (4.26) bc	10.70 (1.76) bc
AK (mg kg^{-1})	65.00 (4.55) a	93.67 (13.27) a	85.00 (6.68) a	27.84 (4.52) b	90.33 (13.52) a	83.67 (9.88) a
TN (g kg^{-1})	1.05 (0.12) b	1.47 (0.07) a	1.72 (0.04) a	0.97 (0.07) b	1.64 (0.18) a	1.83 (0.05) a
TP (g kg^{-1})	0.60 (0.06) ab	0.83 (0.03) a	0.77 (0.01) ab	0.57 (0.08) b	0.75 (0.11) ab	0.72 (0.06) ab
SOC (g kg^{-1})	10.76 (0.50) cd	14.14 (1.99) bc	16.2 (0.55) ab	6.61 (1.35) d	18.50 (2.39) ab	19.92 (0.68) a
pH	8.79 (0.11) a	8.45 (0.02) b	8.46 (0.05) b	8.12 (0.03) c	8.38 (0.08) bc	8.51 (0.16) ab
Water (%)	22.24 (2.54)	22.02 (3.83)	19.32 (3.38)	17.19 (4.22)	21.68 (4.34)	21.68 (3.40)
BD (g/cm^3)	1.40 (0.14)	1.29 (0.13)	1.36 (0.19)	1.35 (0.19)	1.29 (0.10)	1.25 (0.09)
SWHC (%)	34.23 (6.73)	39.68 (4.90)	46.12 (9.35)	36.35 (2.80)	39.52 (10.45)	43.27 (3.31)
Silt (%)	24.68 (1.15) ab	22.40 (1.36) ab	22.00 (1.06) ab	19.49 (1.33) b	25.65 (2.90) a	20.36 (0.58) ab
Clay (%)	55.40 (3.40)	57.73 (1.63)	59.66 (1.35)	45.76 (8.16)	59.56 (3.87)	45.76 (3.24)
Sand (%)	19.92 (4.52) ab	20.57 (2.89) ab	18.90 (2.68) ab	34.75 (7.25) a	15.82 (4.52) b	20.40 (2.52) ab

One-way ANOVA and LSD test were applied to compare the data among different sampling plots. Different letters indicate significant differences at the $p < 0.05$ level.

lower than the model that contained all variables ($p = 0.018$, $R^2 = 0.92$).

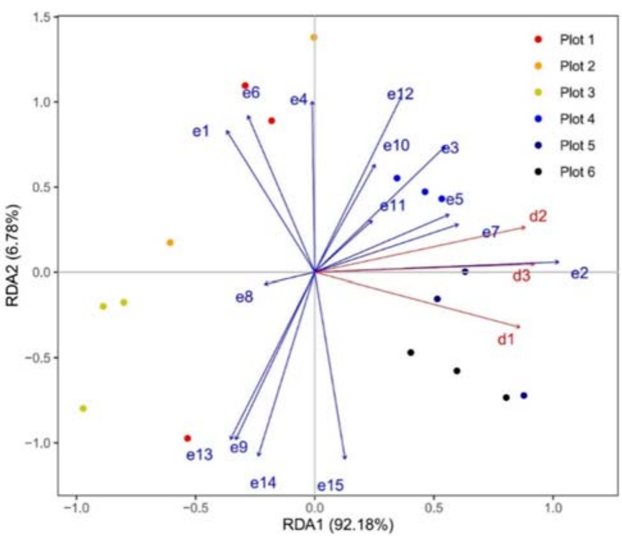

Figure 2. Ordination plot of redundancy analysis showing interactions between herbaceous diversity and environmental variables. e1 = available nitrogen, e2 = available phosphorus, e3 = available potassium, e4 = total nitrogen, e5 = total phosphorus, e6 = soil organic carbon, e7 = pH, e8 = soil water content, e9 = soil bulk density, e10 = saturated water-holding capacity, e11 = silt (%), e12 = clay (%), e13 = sand (%), e14 = slope position, e15 = elevation; d1 = Margalef diversity index, d2 = Simpson index, d3 = Shannon–Wiener index. The angle between the arrows shows their correlation. The vertical projection of sampling plots on the variable arrow represents the value in the sampling plot.

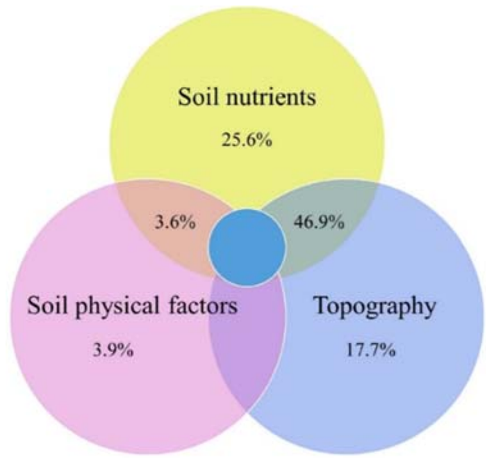

Figure 3. Venn diagram showing the absolute percentage variation explained by each component (values < 0 are not shown, residuals = 0.146).

Finally, we used variation partitioning to explore the contributions of edaphic factors and topography. The result (Figure 3) showed soil nutrients and topography explained most of the variations in herbaceous diversity, i.e. 25.6% and 17.7%, respectively, with a strong joint effect of 46.9%. Soil physical factors accounted for only 3.9% of the total contribution. The combined effect of the three factors was not significant.

4. Discussion

Our results suggest that herbaceous diversity differed significantly among different arbor species, Qinghai spruce had a significantly lower diversity despite being an important long-lived dominant evergreen species in this region (Zhao et al. 2006). Previous studies have shown the ecosystem service function of Qinghai spruce forests planted for the 'Grain-for-Green' project is decreasing due to irresponsible forest management, such as excessively high density and careless species selection (Bie et al. 2013; Fan et al. 2017). Our results confirmed this from the perspective of the herb composition. Drought-enduring and salt-tolerant species had a higher IV in the community due to their strong adaptability to the highly variable environment of the alpine Loess Plateau. Gramineous herbs represented the majority of herb species, but their simple community composition and high biomass may promote a competitive relationship with trees and affect seedling growth. By contrast, less competition was observed in the Prince Rupprecht's larch forest. Its higher herb diversity was mainly comprised of skiophytes. They represent different herbaceous community establish mechanisms in the initial afforestation stages – Qinghai spruce is a slow-growing tree species, so more resources are allocated to the herb layer (Yang et al. 2018), while Prince Rupprecht's larch absorbs most of the resources for rapid growth, providing a shadier environment for herbs.

Compared with previous research in the same region in 2006, we found the proportion of perennial herbs had doubled (Gao et al. 2007). The increase of perennial herbs indicates better resilience and resource storage ability (Jia et al. 2011). Especially in our research region, perennial herbs could relieve the impact from intense rainfall on the surface soil, as well as alleviate soil erosion and nutrient loss. Our findings on the herbaceous composition are more similar to those for the wetlands on the Qinghai–Tibet Plateau than on the Loess plateau or other alpine arid areas (Ma et al. 2011; Duchoslav et al. 2016), which might be evidence of afforestation, but it also may be the result of sufficient precipitation in previous years.

Different establish mechanisms have distinct features in herbaceous layer, which will inevitably interact with edaphic conditions during the process of restoration (Jiao et al. 2011; Ikauniece et al. 2013). In our study, AP, AN, and AK were significantly correlated with species diversity ($p < 0.05$). The RDA results suggested a significant positive correlation between soil AP and herbaceous diversity; some species with high P acquisition (e.g. *Poa pratensis*) showed higher IVs among all species. In the short term, AP is 'directly' associated with species diversity (Zhou et al. 2019); in the long term, the soil P stock could change the plantation use efficiency of P (Rieger et al. 2019). In our research, we believe soil P changed the community to one with a high P use efficiency, as P has been proven to be a key growth-limiting nutrient in strongly weathered soil (Laliberté et al. 2015). Additionally, AK was significantly positively related to herbaceous diversity, which is not common, but is consistent with some research conducted in the Gurbantunggut Desert in China (M. Wang et al. 2015). Several studies have shown that soil K nutrition can improve drought resistance (Egilla et al. 2001; Zahoor et al. 2017), because K plays a critical role in modifying xylem sap hydraulic conductance and water relation in plants (Oddo et al. 2011). We deduced that, despite our research area receiving sufficient precipitation in recent years, the vegetation community still retains the characteristics of drought tolerance, which implies short-term and seasonal rainfall cannot solve the problem of long-term soil erosion.

Unexpectedly, our results suggested that TN and SOC had insignificant effects on herbaceous diversity, while AN showed a significant positive effect. The significance of AN might due to the strong association between herbaceous root systems (especially legume herbs) and the soil surface nutrient concentration (O'Dea et al. 2015), which might be a major source of soil surface AN. The litter of coniferous forests has little regulation function in the early stage of afforestation, so it is difficult to significantly affect soil and herbs (Chang et al. 2016). Moreover, herbaceous composition features imply soil nitrogen might be a limiting factor in the process of succession; for example, the proportion of legumes in the herbaceous layer was relatively low, and the increased proportion of perennial herbs reduced the nitrogen fixation capacity of the soil (Hooper & Vitousek 1998). Meanwhile, the composition and diversity of herb community did not change significantly compared with previous study in the same watershed (Qiao et al. 2010). Additionally, the freeze–thaw process could exacerbate nitrogen loss in alpine ecosystems (Yang et al. 2016). Qinghai spruce is a shallow-rooted species that is prone to being restricted by nutrients in the surface soil (Wu 2015). Thus, we presume that the early stage of afforestation on the alpine Loess Plateau might be potentially limited by nitrogen. this deducion is consistent with the findings of multidisciplinary studies on the leaf stoichiometry and microbial community on the eastern Qinghai–Tibet Plateau (Xiong et al. 2016; Cai et al. 2019).

In addition to soil nutrients, we found slope position and elevation were significant factors driving herb diversity; the joint effect of topography and soil nutrients could explain 46.9% of the variation in herb diversity, which was the highest among all components (Figure 3). With a background of intense precipitation, we believe the topography exacerbated the loss of nutrients by accumulating runoff and sediment from the upper slope position to lower slope position (Tang et al. 2010; Zou et al. 2014), rather than by affecting herb diversity directly. On the other hand, we found the soil water content (0–40 cm) in our research was not significant and was only weakly correlated with soil nutrient and topography, even though water is usually considered to be the key limiting factor in semi-arid regions (Shao et al. 2018). This result is consistent with the results found by Li (Li et al. 2018); an increase in xerophytes and perennial herbs in the upper slope position might enhance the soil surface water-holding capacity, which might make the difference less obvious. The lowest soil water content was observed in the upper slope position, although this difference did not reach statistical significance; this might indicate a potential water limitation of Prince Rupprecht's larch due to its fast growth in the current stage.

Finally, we should caution the reader that this study was conducted at a watershed scale as a case study. We endeavored to select sampling plots to represent general forest structure in this region, but herbaceous layer in the transition zone between the two ecosystems is sensitive to slight environmental changes (Wang et al. 2013). Our presumption needs to be further confirmed by studies from multi-layer perspectives. Moreover, we could not accurately assess the impact of human activities; the lower slope position is prone to being affected by local residents. According to the practice history and related research, introducing native pioneer species to establish a stable herb community (Sun et al. 2017) and thinning the Prince Rupprecht's larch forest (P. Zhang et al. 2020) could alleviate competition and increase the soil nitrogen fixation capacity, as well as establish a stable plant community. Conservation managers need to monitor the change of herbaceous layer for more timely awareness of afforestation situation.

5. Conclusions

Our study demonstrated the interactions among herbaceous diversity, topography, and soil properties in typical afforestation in the transition zone between the Loess Plateau and Qinghai–Tibet Plateau. We found different restoration mechanisms for Qinghai spruce and Prince Rupprecht's larch forests. The Qinghai spruce forest had a more competitive community, while the Prince Rupprecht's larch forest showed higher diversity. Soil AN, AK, AP, slope position, and evaluation were significant factors affecting herbaceous diversity. In detail, soil AP might change the composition of the herbaceous community during succession, while soil AK might be considered a potential indicator for the amelioration of arid soil. Topographical factors strongly affected soil nutrients by accumulating runoff and sediment, as their joint effect was the main contributor to herb diversity variation. Our results showed the upper slope position should be the primary consideration in management strategies, due to relative severer nutrient loss. Soil water conditions might remain the underlying driving factor of the current afforestation; Prince Rupprecht's larch forests on hillslopes should be primary managed, because they may be at first risk of water stress in the future.

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