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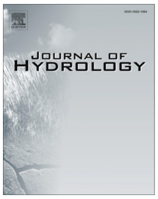

Interactions of soil water content heterogeneity and species diversity patterns in semi-arid steppes on the Loess Plateau of China

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SUMMARY

Soil water is a major driving force for plant community succession in semi-arid area. Many studies have focused on the relationships of species diversity–productivity, but few studies have paid attentions to the effects of soil water content heterogeneity on the plant species diversity in the semi-arid loess regions. To determine relationship of soil water content heterogeneity and plant community structure properties a semi-arid steppe on the Loess Plateau, we conducted a gradient analysis of soil water content variation and above- and below-ground properties of plant communities. Results showed that community coverage, above- and below-ground biomass were significantly and positively related to the surface soil water contents (0–5 cm). Plant diversity (Shannon index and Richness index) were closely correlated to soil water content at the soil depth of 0–10 cm. But plant height, litter biomass and root/shoot ratio were not related to soil water content. These results showed that there is an positive interaction effects for plant diversity and soil water content in the semi-arid grassland communities. Our observations indicate that change of plant species diversity is also an important community responses to soil water content heterogeneity in the semi-arid grassland ecosystem.

1. Introduction

Water is fundamental to the biophysical processes that sustain ecosystem functions, particularly in the arid and semi-arid regions where tight coupling exists between ecosystem productivity, surface energy balance, and water source availability (Potts et al., 2006; Heisler-White et al., 2008; Wang et al., 2012; Yang et al., 2012, 2014). The moisture stored in different soil layers is recognized as an important driver of the productivity and sustainability of semi-arid terrestrial ecosystems (Legates et al., 2011). Because vegetation strongly affects the water cycle and soil erosion and runoff, the interactions between vegetation and soil moisture are fundamental for ecological processes in semiarid regions.

Vegetation types and structures can have significant influence on oil water content (Wang et al., 2012). This issue is particularly crucial in ecohydrology, and has recently been investigated in many studies. For example, plant species diversity significantly impacted on soil moisture by their different live biomass and litter quantity and quality in growing season (Eviner, 2004). Chen et al. (2007) reported that vegetation type have a significant influence on soil moisture dynamics. Vivoni et al. (2008) revealed that vegetation can mediate the soil moisture response to precipitation and change the spatial distribution of soil moisture, and Yang et al. (2012) found that plant growth conditions can change the spatial pattern of shallow and deep soil moisture in semi-arid regions. Different land use and vegetation types played an important role in reducing water erosion on the Loess Plateau (Wei et al., 2010). Meanwhile, vegetation coverage and grass stem density are also important factors in controlling soil loss and runoff by influencing microchannel and runoff characteristics (Flenniken et al., 2001; Zhou et al., 2006). Research shows that different plant species can lead to different rainfall–runoff responses, and thus lead to temporal variation in soil moisture (Jost et al., 2012; Yang et al., 2012, 2014). Better community condition also improved the soil physical properties and soil–water capability in steppe grassland of the Loess Plateau (Wu et al., 2014). The effects of vegetation on the dynamics of soil moisture were not only limited to shallow soil layers, but also to deep layers (Yang et al., 2012). Shallow soil moisture was always low and more prone to be affected by vegetation transpiration and soil evaporation on the Loess Plateau, soil moisture at this depth was often intensively affected by aboveground plant cover and root systems (Yang et al., 2012). Plant spe-

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cies diversity in community can significantly influence soil moisture and its spatiotemporal patterns (Niklaus et al., 2007).

Soil water is the primary constraint to plant community in many terrestrial ecosystems (Heisler-White et al., 2008), and influence plant uptake and community succession processes. Soil water variation can also directly and indirectly influence the grassland plant communities and soil properties (Wu et al., 2013). Some researchers had reported that the effects of soil water on plant productivity (Heisler-White et al., 2008; Wu et al., 2013), the distribution of fine root, species diversity (Fehmi and Kong, 2012), soil nutrients (Wu et al., 2013), soil microbial structure (Schjønning et al., 2011; Tian et al., 2013) and soil C cycling and storage (Xue et al., 2013). The decline of soil moisture in the 0–1 m layers was found during the process of ecological restoration in the Loess Plateau, and the soil moisture replenishment by rainfall during the rainy season was not sufficient to recharge the soil moisture storage (Chen et al., 2010). The soil moisture stored in different depths is critical for plant growth and serves as a key water source for sustaining ecosystems in this region (Yang et al., 2014). The temporal variations of soil moisture at different depths may have varying responses to vegetation and play different roles in sustaining plant growth and community stability. High species density may be the key reason for the severity of the temporally stable soil moisture deficit (Yang et al., 2014).

In the semi-arid loess hilly regions, introduced vegetation with high planting density not only drastically decreased deep soil water content, but also changed the dynamic rules of soil water content in shallow and deep layers (Yang et al., 2012). These processes were more significant in the fragile arid environments with sparse vegetation covers (Wang et al., 2005). Soil water is one of the most important factors of limiting plant growth and community structure in this region. Meanwhile, vegetation patterns response are important in the regulation of earth surface hydrological processes in arid and semi-arid areas (Zhang et al., 2014).

Therefore, understanding the relationships of soil water content heterogeneity and plant community structure in a semi-arid steppe has several important implications for both scientific communities and decision makers. Thus, the objectives of the present study are to determine: (i) effects of soil water content heterogeneity on plant aboveground community structure, (ii) relationships between above- and belowground plant community structure properties and soil water content in the semi-arid steppe on the Loess Plateau.

2. Material and methods

2.1. Study area

The study was located at Gansu Province, People's Republic of China. The region is characterized by a semi-arid climate. Longitude from 103°24′ to 104°54′E, latitude from 35°15′ to 37°22′ N, and an altitude within 2085–2483 m. This area stands in the southwest part of the Loess Plateau, which dominated by warm-humid summers and cold-dry winters. The mean annual precipitation (from 1960 to 2005) is 255 mm, of which the majority (more than 80%) falls from July to September. The evaporation is relative high (Yang et al., 2014), and average annual air temperature (from 1960 to 2005) is 8.8 °C. This area of nature grassland account for 77.2% of the total area. The vegetation is temperate grassland with the primary plant species being herbaceous plants (i.e., *Thymus mongolicus*, *Stipa bungeana*, *Stipa grandis*, *Agropyron cristatum*, *Heteropappus altaicus*, *Artemisia gmelinii*, *Artemisia ordosica*, *Artemisia frigida*, *Peganum multisectum*, etc.). The soils developed from loess, which ranges in depth from 40 to 60 m. Groundwater is not available for vegetation growth due to the deep loess. Rainfall is thus the only water resource. The soil water contents ranged from 3.8% to 17.9% in the 0–30 cm soil layer in this area. Dominant soil in the region is a calcic Cambisol. According to the FAO classification with a clay content of 33–42%, organic matter of 4–13 g/kg. Soil pH ranged from 7.7 to 9.1 and soil bulk density from 1.00 to 1.53 g cm^{-3} within 1 m depth, respectively.

2.2. Plant community survey

Twenty grassland sampling sites were conducted across Gansu during the summers (July to August) of 2011 (Fig. 1). At each site surveyed ten plots (1 × 1 m). Five plots of them were undivided (UP) and chosen to investigate as a whole community for canopy coverage, height, above- and below-ground biomass, litter biomass and soil water, and the other five plots were divided (DP) and collected individual species composition, height, density (number of individuals per square meter) and species richness (number of species per square meter).

In the UP plots, the aboveground parts of all green plants and litter from the entire plot were cut, collected, and put into envelops and tagged. To measure the belowground biomass, 9 cm diameter root augur was used to take three soil samples for each depth of 0–5, 5–10, 10–20, 20–30 cm. Samples taken at the same layer were then mixed to create a single sample. The 2 mm sieve was used to isolate the majority of plant roots from each sample was used to isolate the majority of plant roots from each sample. The remaining fine roots taken from the soil samples were isolated by spreading the samples in shallow trays, overfilling the trays with water and allowing the outflow from the trays to pass through a 0.5 mm mesh sieve. All the roots thus isolated were oven-dried at 65 °C and weighed. Due to the large size of the aboveground biomass samples, each was weighed fresh and then a portion of each sample was dried and weighed. The total above-ground biomass of the samples was calculated by multiplying the ratio of the dry weight/fresh weight ratio within the subsample by the entire fresh weight. For the DP plots, all green, aboveground plant parts for each individual species, as well as all litter were sampled in the same way.

2.3. Data analyses

Species richness was based on the number of species in each plot (Stirling and Wilsey, 2001). The richness index (R) and Shannon–Winner diversity index (H) were calculated as:

Richness index (R): $R = S$.
Shannon–Wiener diversity index (H): $H = -\sum_{i=1}^{s}(Pi \ln Pi)$.
Evenness index (E): $E = \frac{H}{\ln S}$.

where S is the total species numbers of grassland community, H is the Shannon–Wiener diversity index and Pi is the density proportion of i species.

The average biomass of UP plots was calculated to represent the value of sampling site. Accordingly, we calculated the coverage, height, plant productivity (above-ground biomass, below-ground biomass, litter biomass, total biomass), root/shoot ratio and plant diversity (Shannon–Winner index, Evenness index, Richness index) of different site. All analysis of variance (ANOVA) were analyzed using SPSS Version 16.0 (SPSS, Chicago, IL, USA). Linear models were used to identify correlations between soil water content and plant diversity (Shannon–Winner index, Evenness index, Richness index). All statistical significances was p¼0.05 unless otherwise noted.

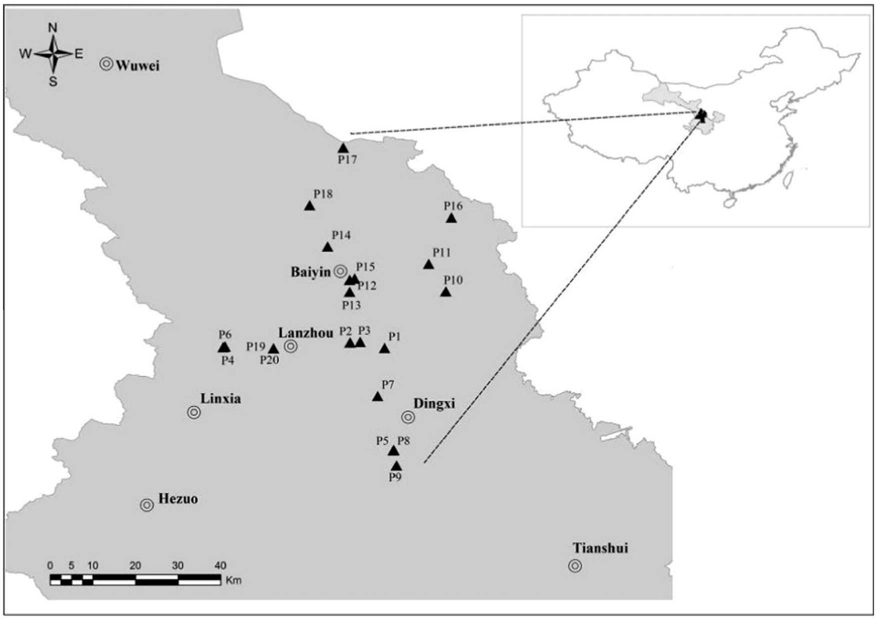

Fig. 1. Location of sampling sites used in this study.

3. Results

3.1. Plant communities with different soil water contents

ANOVA results showed that there are significant differences for coverage ($F = 69.6$, $P < 0.01$) and height ($F = 5.9$, $P < 0.01$) among sampling sites with different soil water contents (Table 1). Coverage ranged from 5.6% to 97.2% and height ranged from 10.4 to 25.0 cm for different sampling sites. Plant above-ground biomass, litter biomass, below-ground biomass and total biomass were significantly different among sampling sites ($P < 0.01$), with the mean value and scope numbers as shown in Table 1. Plant diversity (Shannon–Wiener diversity index, Evenness and Richness index) was also greatly differences in the twenty sites with different soil water contents.

3.2. Above-ground community structure properties and soil water content heterogeneity

Correlation analyses showed that plant coverage was significantly positive correlated with soil water content at the soil depth of 0–5 cm ($R = 0.45$, $P < 0.05$), but there was no significant correlation at the soil depth of 5–30 cm ($P > 0.05$, Table 2). Plant height had no significant correlation with soil water content at the full soil depth ($P > 0.05$, Table 2).

Plant above-ground biomass showed a positive relationship with soil water content at the soil depths of 0–5, 5–10, 20–30 cm, respectively (Table 2). Similarly, total biomass showed a positive correlation with soil water content at the soil depths of 5–10 and 10–20 cm ($R = 0.52, 0.45$, $P < 0.05$; Table 2), except that litter biomass and root/shoot ratio had no significant correlation with soil water content (Table 2).

Shannon–Winner diversity index showed a positive linear correlation with soil water content at the soil depth of 0–10 cm (Fig. 2a and b). There were no significant correlation between Evenness index and soil water content at all soil depth (Fig. 2e–h). Plant richness index showed a positive correlation with soil water at the all soil profile (Fig. 2i–l). Moreover, species richness showed strongly correlation with soil water content at the soil depth of 0–5 cm ($R = 0.83$, Fig. 2i).

3.3. Below-ground biomass and soil water content heterogeneity

Below-ground biomass was 965.58 ± 157.29 (mean ± SE) g/m^2 for the full soil profile of 30 cm soil depth in the twenty sites. Below-ground biomass was decreased with increasing of soil depth. In contrast, soil water was increased with increasing along soil depth (Fig. 3). Correlation analysis showed that belowground biomass and soil water content showed a positive significant correlation at the soil depth of 0–5 cm ($R = 0.65$, $P < 0.01$).

4. Discussions

Firstly, our results showed that plant community coverage, above- and below-ground biomass were significantly and

Table 1
Characteristics of plant communities with different soil water content in the semi-arid grassland of the Loess Plateau.

Community characteristics	Mean	SE	Minimum	Maximum	$F_{d.f.}$	P-value
Coverage (%)	46.0	6.8	5.6	97.2	69.6_{19}	<0.0001
Height (cm)	14.6	0.9	10.4	25.0	5.9_{19}	<0.0001
Above-ground biomass (g m^{-2})	68.7	11.2	19.8	194.7	13.3_{19}	<0.0001
Litter biomass (g m^{-2})	33.5	9.3	2.9	133.5	17.6_{19}	<0.0001
Below-ground biomass (g m^{-2})	965.6	157.3	180.1	3102.1	24.9_{19}	<0.0001
Total biomass (g m^{-2})	1067.1	163.2	242.9	3194.9	24.9_{19}	<0.0001
Root/shoot ratio	16.6	3.0	3.0	47.8	4.7_{19}	<0.0001
Shannon–Wiener diversity index (H)	1.3	0.1	0.6	2.5	19.8_{19}	<0.0001
Evenness index (E)	0.7	0.0	0.4	0.8	5.8_{19}	<0.0001
Richness index (R)	7.4	1.0	3.4	20.0	4.3_{19}	<0.0001

Table 2
Correlation analysis the relationships between the characteristics of aboveground community and soil water content at different soil depth.

Aboveground community characteristics	Soil water content (%)			
	0–5 cm	5–10 cm	10–20 cm	20–30 m
Coverage (%)	0.45*	0.32	0.27	0.26
Height (cm)	0.21	0.14	0.13	0.14
Above-ground biomass (g m^{-2})	0.57**	0.46*	0.35	0.46*
Litter biomass (g m^{-2})	0.067	0.015	−0.035	−0.018
Total biomass (g m^{-2})	0.44	0.52*	0.45*	0.42
Root/shoot ratio	0	0.141	0.174	0.109

[*] Correlation is significant at the 0.05 level (2-tailed).
[**] Correlation is significant at the 0.01 level (2-tailed).

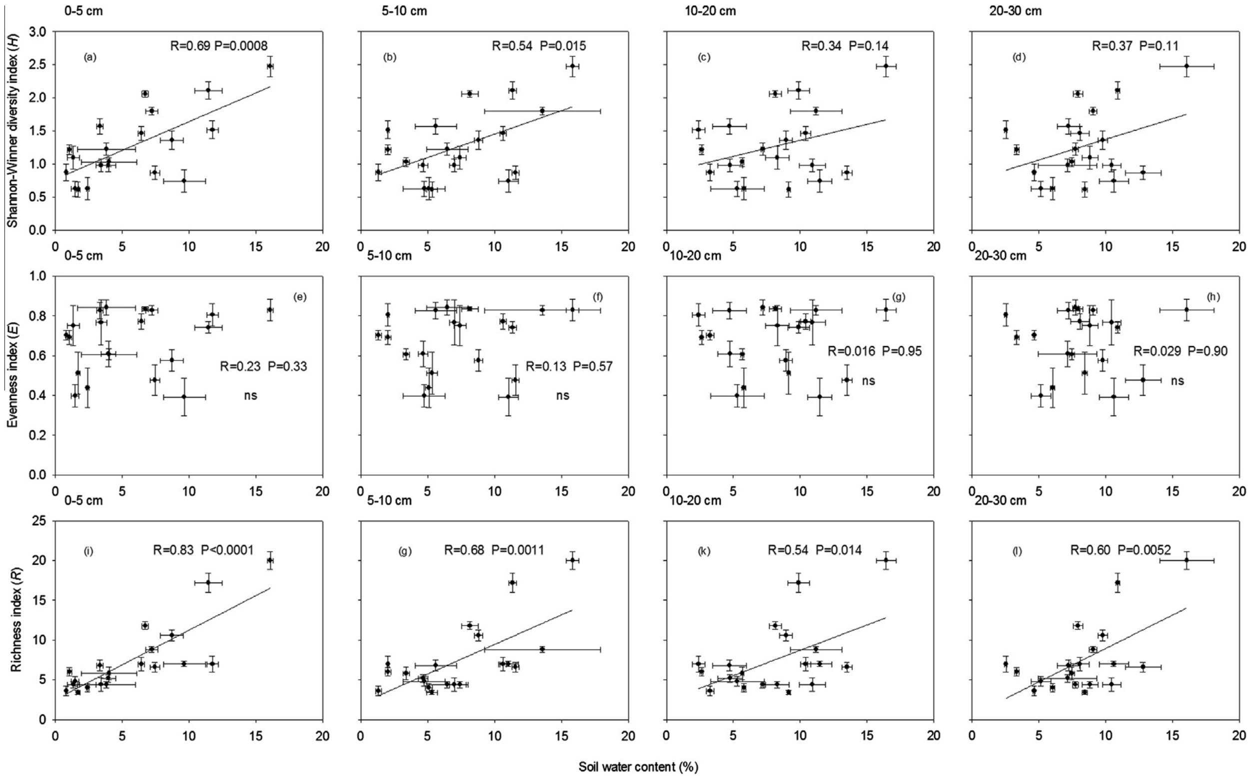

Fig. 2. The relationships between plant diversity (Shannon–Winner index, evenness index, richness index) and soil water at different soil depth in the semi-arid grassland. Lines show predicted values from the best significant regression model. *Note:* ns, no significant correlation.

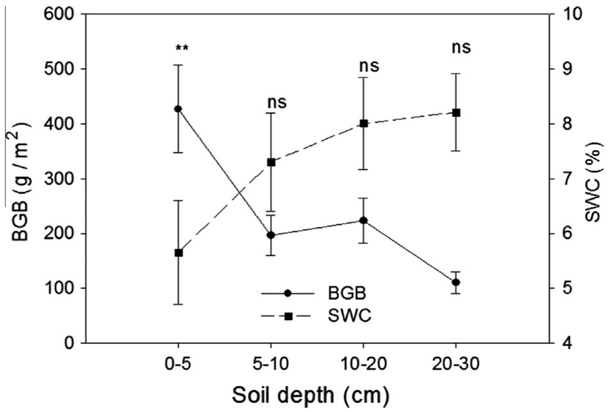

Fig. 3. The vertical distribution of BGB (below-ground biomass) and SWC (soil water content). The values are mean ± SE. significant correlation between BGB and SWC indicated by symbols, $^{**}P < 0.01$; ns, no significant correlation.

positively related to the surface soil water contents in studied semi-arid steppe on the Loess Plateau, which is consistent with the previous study in other areas (Kardol et al., 2010; Yang et al., 2010; Wu et al., 2013). Other studies also found that vegetation with greater aerial coverage can better protect the soil against erosive forces of rainfall and increase soil water intake (Chen et al., 2007; Wang et al., 2012). These suggest that there is an positive interaction effects for plant community coverage and soil water content in the semi-arid grassland (Wei et al., 2010; Yang et al., 2012, 2014). Our study also found that soil water content influenced not only the quantity of plant biomass, but the distribution of below-ground biomass, which agree with the result of Zhou and Shangguan (2007) that soil water was a key control on fine root distribution in the Loess Plateau.

Secondly, in the present study we found that plant diversity (Shannon index and Richness index) were closely correlated to soil water content at the soil depth of 0–10 cm, which is opposite with the previous study results (Wu et al., 2013) that species richness significantly decreased with soil water content at the soil depth of 0–20 cm in alpine wetland ecosystem. The main reason is that the difference of soil water content. The soil water contents ranged from 3.8% to 17.9% in the 0–30 cm soil layer in this semi-arid steppe area on the Loess Plateau, but it ranged from 16.5% to 113.1% in the 0–20 cm soil layer in alpine wetland ecosystem on the Qinghai–Tibetan Plateau. Soil water altered the growth and relative superiority of dominating species (Wu et al., 2013). In the alpine wetland ecosystem, the effects of competition from high species density decreased the plant diversity. In the semi-arid grassland ecosystem, the effects of competition was relatively little due to the lower species density. So the plant diversity increased with increasing soil water content in the semi-arid grassland. These suggested that there is a positive correlation between species diversity and soil water content in arid or semi-arid areas with lower soil moisture, but a negative correlation in humid or semi-humid areas with higher soil moisture. Plant species diversity can enhance soil conservation because plant-soil feedback effects can alter plant community structure and soil properties (Bezemer et al., 2006). Higher plant species diversity can regulate and enhance soil conservation by increasing plant cover and density (Wang et al., 2012). Eviner (2004) had advanced that plant species did not influence soil moisture during the rainy part of the growing season because abundant precipitation kept soil saturated. Species composition effects on soil moisture were significant in dry soil condition (Eviner, 2004). Conversely, there were positive effects of plant species diversity on controlling of surface runoff, soil erosion, erosion of phosphorus and plant species diversity prevented from the degradation of soil environment (Wang, 2004). The positive interaction effects between surface soil water and plant community characteristics may be resulted from that plant cover regulated the runoff processes (Vásquez-Méndez et al., 2010), as well as canopy coverage altered the micro-environment in ways that promote plant growth and species coexistence (Bever, 2003). Hence, soil water content plays an important role in regulating plant community and species diversity coexistence in the semi-arid grassland ecosystem.

5. Conclusions

Relationship of soil water content heterogeneity and plant community structure properties were investigated and analyzed in the semi-arid steppe on the Loess Plateau. Results sd that grassland community coverage, above- and below-ground biomass were significantly and positively related to the surface soil water contents, especial at the soil depth of 0–5 cm. Plant diversity (Shannon index and Richness index) were closely correlated to soil water content at the soil depth of 0–10 cm. Based on these results, we suggest that there is an positive interaction effects for plant diversity and soil water content in the semi-arid grassland communities, which had lower soil water content. Soil water content heterogeneity plays an important role in regulating plant productivity and species diversity in the semi-arid grassland ecosystem. These results were expected to reveal that change of plant species diversity is also an important community responses to soil water content heterogeneity in the semi-arid grassland ecosystem.

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