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Above- and below-ground response to soil moisture change on an alpine wetland ecosystem in the Qinghai-Tibetan Plateau, China

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Abstract

Climate change is expected to affect plant communities worldwide. However, less is known about the consequences of global warming-induced decrease of soil moisture on alpine wetland ecosystem in the Qinghai-Tibetan Plateau. To determine response of natural alpine wetland community to decrease of soil moisture, we did a gradient analysis of soil moisture by sequence space-series variation. We used sequence space-series variation of soil moisture to reflect potential time-series variation of soil moisture in alpine wetland community, by examining the effects of spatial heterogeneity of soil moisture on wetland community, as well as by determining how shifts in above- and below-ground properties of alpine wetland community. We found that vegetation aboveground biomass, cover and height all significantly increased with increase of soil moisture, but species richness was decreased. Soil organic carbon, total nitrogen, available nitrogen, total phosphorus and available phosphorus all significantly increased with increase of soil moisture, but soil pH value, total potassium and available potassium were significantly decreased. Meanwhile, species richness showed significantly positive correlations to aboveground biomass, covers and height. Aboveground biomass, vegetation covers and height were all significant positively related to soil organic carbon, total N, P, and available N, P, but negatively related to total K. But, species richness were significant negatively related to soil organic carbon, total N, P, and available N, P, but positively related to total K. Our observation indicates that decreasing of soil moisture may potentially negatively impact on the above- and below-ground properties in alpine wetland community.

1 Introduction

Information on responses of ecosystems to climate warming can improve our understanding on its function and potential succession direction to the global climate change. Global average temperature has increased by 0.74° approximately in recent decades and is expected to continue increasing (IPCC, 2007) and the latest report by the Intergovernmental Panel on Climate Change (IPCC) predicts a 1.4–5.8° average increase in the global surface temperature over the period 1990 to 2100 (Houghton et al., 2001). Global climate change is expected to have a major impact on ecosystems worldwide (Rosenzweig et al., 2008), affecting both above-ground properties, e.g. biodiversity, productivity. Some study had reported that climate change play an important impact on changes in species composition at the regional level (biogeographic regions or political entities) or local scale (e.g. site or ecosystem diversity), which mainly were conducted in Europe and North America for various-type ecosystems (Rosset et al., 2010) and focused on the description and prediction of changes affecting species distribution, phenology and functional groups composition (Walther et al., 2002; Parmesan and Yohe, 2003; Hickling et al., 2006; Parmesan, 2006; Lenoir et al., 2008; Morin et al., 2009). Study had reported that warming tends to significantly increase ecosystem species richness in terrestrial environments (Pauli et al., 2007; Vittoz et al., 2009; Rosset et al., 2010). And other studies had reported that climatic warming has already led to dramatic shifts in plant functional groups (e.g. C_3 litter with high quality and C_4 litter with low quality), and they suggest that this may cause appreciable changes in soil chemical properties by altering the quantity and quality of plant material entering into the soil (Day et al., 2008; Fissore et al., 2008).

But few studies were conducted to explore the effect of climate warming on soil chemical traits based on decrease of soil moisture (Brinkman and Sombroek, 1996; Díaz et al., 1997; Wang et al., 2004). Water is the most important factor potentially affecting wetland ecosystems and plant communities. Even if precipitation may increase at some places, the aridity tendency is still obvious because of the increasing of evaporation along with the temperature rising from global climate warming. This has a far-reaching influence to the regional environment and local ecosystem. It is therefore important to conduct investigations across a range of soil moisture gradient to ascertain the impact of climate change on wetland ecosystem. Understanding the effects of climate change at the local scale is currently one of the main challenges of ecological

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study (Rosset et al., 2010). The Qinghai-Tibetan Plateau may be more strongly impacted than the average of the global scale, because Nogues-Bravo et al. (2007) had reported that temperature increases will be particularly high in mountain regions. Alpine wetland ecosystem studies are scarcer than those covering the terrestrial environment and existing work tends to describe species composition of assemblages rather than local species richness.

Climate change is likely to affect above- and below-ground properties of alpine wetland community by altering key habitat factor – soil moisture (Engel et al., 2009). Ecological science deals with the complex interactions between ecosystem and their environment, particularly interconnections that allow ecosystem to change their properties to adapt variational environment. These interconnections involve "potential response" when a change in environmental conditions affects ecosystems in ways that ecosystem can make potential changes to environmental change. An important role of ecological research is to provide accurate information on the probability that global change will have impacts on ecosystems. Warming-induced changes in the soil moisture and soil chemical traits may regulate the availability of soil C, N and P to vegetation growth and ultimately influence the net primary productivity and community structure of grassland ecosystems. Hence, it is imperative for us to understand how global warming will affect soil chemical dynamics.

In this study, we used sequence space-series variation of soil moisture to reflect potential time-series variation of soil moisture in alpine wetland community, by examining the effects of spatial heterogeneity of soil moisture on wetland community, as well as by determining how shifts in above- and below-ground properties of alpine wetland community. We hypothesized that decrease of soil moisture can significant negatively impact on above- and below-ground properties of alpine wetland ecosystem. To test this hypothesis, we studied the relationships of soil moisture gradient and community above- and below-ground properties. The specific objectives of this study were to: (1) evaluate the impact of decrease of soil moisture on the aboveground vegetation biomass, cover, height and richness of natural alpine wetland community; (2) evaluate

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the impact of decrease of soil moisture on soil organic carbon, pH value, total nitrogen, available nitrogen, total phosphorus, available phosphorus, total potassium and available potassium of natural alpine wetland community; and (3) predict potential variation trend of above- and below-ground properties in natural alpine wetland ecosystem in the Qinghai-Tibetan Plateau.

2 Materials and methods

2.1 Study description

This study was conducted in alpine wetland ecosystem with average 3500 m a.s.l. at the Maqu Wetland Protection Area, which was 98.03×10^4 ha. We selected typical zone extending from 33°66′ N to 33°95′ N, 101°67′ E to 102°16′ E, in Gansu Province, PR China which located at the eastern Qinghai-Tibetan Plateau (Wu et al., 2010a, b). The mean daily air temperature is 1.2 °C, ranging from −10 °C in January to 11.7 °C in July. Mean annual precipitation is 620 mm, mainly falling during the short, cool summer. The monthly mean temperature, monthly mean precipitation, annual accumulated temperature of ≥0 °C and average precipitation from 1969 to 2005 in this protection area were showed in Wu et al. (2009),which predicted that annual accumulated temperature is increasing and the regional climate become warmer along the global climate change for decades. The annual cloud-free solar radiation is about 2580 h. The potential natural vegetation of the majority of the study area is alpine wetland and is dominated by clonal *Kobresia tibetica* Maxim., *Kobresia humilis* (C. A. Mey. ex Trautv.) Sergiev, *Blysmus sinocompressus* Tang et Wang, *Deschampsia caespitosa* (Linn.) Beauv. and *Carex atrofusca* Schkuhr.

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2.2 Experiment design and sampling

Fifteen sampling sites, where had the same Humic alpine soil (felty soil) and similar historical wetland vegetation, were selected for this study in September in alpine area of the Qinghai-Tibetan Plateau. The selected sites and aboveground vegetation characteristics of studied meadows were showed in Table 1. All the sites that we selected for studying were completely excluded livestock grazing during the plant growth-seasons from April to October and slight grazing was done only during the hay-stage in winter, because of "Return Livestock Production to Grassland Ecology Project" of China from 2001. Grazing from a medium density of Tibetan sheep and yaks (the approximate proportion of sheep vs. yaks was about 1.6:1) during the winter of each year. In this study, we selected three plots (each plot was about 0.5 ha) in each selected site and three diagonal sampling quadrats (1 m × 1 m) per plot. Night quadrats were were investigated and sampled in each studied site. All vegetation samples were taken in early September of 2009, when biomass had reached its highest, from nine sampling quadrats (1 m × 1 m) from each studied sites. We determined the aboveground dry biomass of each quadrat by weighing the plants after drying at 80 °C for 48 h to constant weight. Vegetation covers, mean height, productivity based on aboveground biomass, richness of plant community were measured. Richness index (*R*) was determined by the total species numbers of each community.

The top-soil (0–10 and 10–20 cm) moisture of weight ratio in studied sites were determined by ordinary gravimetric measurement. Meanwhile, we collected five soil samples from each soil depths (0–10 and 10–20 cm) by bucket auger from each quadrats in a simple random pattern, then fixed them. Soil samples at the same depths in each sampling quadrat were mixed. 15 mixed soil samples in each soil depth in each quadrat were used to analyze soil properties. All soil samples were air-dried and then passed through a 0.14 mm sieve. Soil pH was determined using a soil-water ratio of 1:5; soil organic carbon content in the soil samples was measured using the $K_2Cr_2O_7$ method (Nelson and Sommers, 1982). Soil total nitrogen, available nitrogen, total phosphorus,

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available phosphorus total potassium and available potassium content were measured by the methods of Miller and Keeney (1982) in laboratory. The content of each nutrient trait calculated by the proportions of soil organic matter, total nitrogen, available nitrogen, total phosphorus, available phosphorus, total potassium and available potassium account for per soil dry weight.

2.3 Data analysis

All vegetation and soil properties data were expressed as mean ±1 standard error in Tables 1 and 2. The soil samples data for the 0–10-cm and 10–20-cm soil layer were used to analyze the soil chemical properties of studied sites. Tests of between-subjects effects were conducted with Two-way ANOVA of General Linear Model (GLM) for soil properties among studied sites and two soil depths to assess the effect of sites differences and two soil depths and their interaction on soil properties. One-way ANOVA analyses were conducted for vegetation community characteristics among different study sites to assess the effect of sites differences on aboveground properties. Significant differences for all statistical tests were evaluated at the level of $P \leq 0.05$. Correlations between soil moisture and soil chemical- and community-properties were calculated using the data from all sample quadrats by a linear mixed-effects model, after values were log-transformed. All statistical analyses were performed using the software program SPSS, ver. 13.0 (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Aboveground vegetation changes to soil moisture gradient

ANOVA result showed that there are significant difference for vegetation cover ($F = 33.64$, $P < 0.001$), height ($F = 20.27$, $P < 0.001$), aboveground biomass ($F = 20.07$, $P < 0.001$) and species richness ($F = 16.28$, $P < 0.001$) among sampling sites with

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different soil moisture. Vegetation covers were ranged from 44.0 to 95.0 %, aboveground productivity were ranged from 114.6 to 344.5 $g\,m^{-2}$, vegetation height were ranged from 3.0 to 20.3 cm, and species richness were from 9.4 to 20.0 for different sampling sites with different dominant species (Table 1). Some sites with higher soil moisture were dominated by typical constructive species in local alpine wetland community such as *Kobresia tibetica* Maxim., *Blysmus sinocompressus* Tang et Wang, *Deschampsia caespitosa (Linn.) Beauv.*, *Carex atrofusca Schkuhr*, *Halerpestes sarmentosa* (Adams) Kom and *Batrachium bungei* (Steud.) L. Liou, and some companion species were dominant species such as *Kobresia macrantha* Bocklr., *Kobresia humilis* (C. A. Mey. ex Trautv.) Sergiev, *Ranunculus tanguticus (Maxim.) Ovcz*, *Deschampsia caespitosa (Linn.) Beauv. (Linn.) Beauv.* and *Potentilla anserine* Linn. in sampling sites with moderate soil water contents, this is a transitive wetland community. And, community were dominted by some drought-resistant species, such as *Stipa aliena* Keng, *Pedicularis kansuensis* Maxim., *Elymus nutans* Griseb., *Kobresia pygmaea* (C. B. Clarke) C. B. Clarke, *Stipa aliena* Keng, *Leontopodium alpinum*, *Anemone rivularis* Buch.-Ham., *Scirpus pumilus* Vahl and *Ligularia virgaurea Maxim.* in sampling sites with lower soil moisture (Table 1).

Correlation analysis showed that vegetation aboveground biomass, cover and height all significantly increased with increase of soil moisture with different slope for two soil depths. But, species richness was significantly decreased with soil moisture for two soil depths in natural wetland community of studied sites (Fig. 1).

3.2 Belowground soil chemical changes to soil moisture gradient

ANOVA tests of between-subjects effects showed that sampling sites ($F = 56.57$, $P < 0.001$) and soil depth ($F = 11.97$, $P < 0.01$) both significantly affected the soil moisture, and there is a significant interaction effect on ($F = 14.02$, $P < 0.001$). Soil moisture were ranged from 17.6 to 103.3 % in the upper layer (depth of 0–10 cm) and from 113.1 to 16.5 % in the lower layer (depth of 10–20 cm) for fifteen sampling sites. And the upper layer showed higher soil moisture than the lower layer except site 1 (Table 2). Sampling

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sites also significantly affected the soil pH value ($F = 20.38$, $P < 0.001$), soil organic carbon ($F = 8.45$, $P < 0.001$), total nitrogen ($F = 6.88$, $P < 0.001$), available nitrogen ($F = 4.38$, $P < 0.01$), total phosphorus ($F = 5.79$, $P < 0.01$), available phosphorus ($F = 5.64$, $P < 0.01$), total potassium ($F = 11.54$, $P < 0.001$) and available potassium ($F = 12.83$, $P < 0.001$). Soil pH value ranged from 5.18 to 7.97 in the upper layer and from 5.56 to 8.25 in the lower layer for fifteen sampling sites. Soil organic carbon ranged from 1.89 to 25.53 % in the upper layer and from 0.96 to 19.43 % in the lower layer; total nitrogen ranged from 0.15 to 1.99 % in the upper layer and from 0.07 to1.43 % in the lower layer; available nitrogen ranged from 63.86 to 473.55 mg kg^{-1} in the upper layer and from 40.18 to 366.64 mg kg^{-1} in the lower layer; total phosphorus ranged from 0.06 to 0.26 % in the upper layer and from 0.06 to 0.31 % in the lower layer; available phosphorus ranged from 5.39 to 25.46 mg kg^{-1} in the upper layer and from 4.49 to 17.42 mg kg^{-1} in the lower layer; total potassium ranged from 1.02 to 3.22 % in the upper layer and from 1.33 to 2.88 % in the lower layer; available potassium ranged from 41.44 to 313.42 mg kg^{-1} in the upper layer and from 34.21 to 329.24 mg kg^{-1} in the lower layer (Table 2). Additionally, soil depth significantly affected soil total nitrogen ($F = 5.43$, $P < 0.05$), available nitrogen ($F = 7.80$, $P < 0.05$), available phosphorus ($F = 10.18$, $P < 0.01$), available potassium ($F = 20.37$, $P < 0.001$).

Correlation analysis found that soil organic carbon, total nitrogen, available nitrogen, total phosphorus and available phosphorus all significantly increased with soil moisture for two soil depths with different slope (Fig. 2). But, soil pH value, total potassium and available potassium were significantly decreased with soil moisture for two soil depths with different slope in natural wetland community of studied sites (Fig. 2).

3.3 Relationships among above- and below-ground properties

Results showed that aboveground biomass were significant positively related to soil organic carbon ($R = 0.757$, $P < 0.01$), total N ($R = 0.716$, $P < 0.01$), P ($R = 0.623$, $P < 0.01$), and available N ($R = 0.692$, $P < 0.01$), P ($R = 0.439$, $P < 0.01$), but negatively related to total K ($R = -0.492$, $P < 0.01$). Vegetation covers and height were

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also significant positively related to soil organic carbon (cover, $R = 0.723$, $P < 0.01$; height, $R = 0.705$, $P < 0.01$), total N (cover, $R = 0.684$, $P < 0.01$; height, $R = 0.667$, $P < 0.01$), P (cover, $R = 0.665$, $P < 0.01$; height, $R = 0.640$, $P < 0.01$) and available N (cover, $R = 0.680$, $P < 0.01$; height, $R = 0.617$, $P < 0.01$), P (cover, $R = 0.482$, $P < 0.01$; height, $R = 0.399$, $P < 0.01$), and available K (cover, $R = 0.201$, $P < 0.05$), but negatively related to total K (cover, $R = -0.519$, $P < 0.01$; height, $R = -0.692$, $P < 0.01$). But, species richness were significant negatively related to soil organic carbon ($R = -0.381$, $P < 0.01$), total N ($R = -0.375$, $P < 0.01$), P ($R = -0.331$, $P < 0.01$), and available N ($R = -0.340$, $P < 0.01$), P ($R = -0.271$, $P < 0.01$), but positively related to total K ($R = 0.221$, $P < 0.01$). Meanwhile, species richness showed significantly positive correlations to aboveground biomass ($R = -0.470$, $P < 0.01$), covers ($R = -0.421$, $P < 0.01$) and height ($R = -0.572$, $P < 0.01$). Additionally, there are some other positive or negative correlations among aboveground properties or below-ground properties in natural wetland community of studied sites (Table 3).

4 Discussion

4.1 Implications of decrease of soil moisture on aboveground vegetation related to climate change

Soil moisture is crucial to agriculture and is an important part of the agricultural drought outlook in many areas of the world. Climatic warming increases soil temperature and hence accelerate soil water transpiration by stimulating evapotranspiration (Rustad et al., 2001; Fontaine et al., 2004; Niu et al., 2008) and will accelerate the global hydrological cycle in general (Milly et al., 2002; Bosilovich et al., 2004). So, soil moisture variation is an important possible consequence of global warming.

Most concerns on the regional impacts of climatic change on ecosystem have been given to climate warming, due to the significance of increased temperature on many biological process. Many studies had reported that plant species and vegetation change

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resulting from small warming manipulations in terrestrial ecosystem (Hollister and Webber, 2000; Hollister et al., 2005; Oberbauer et al., 2007). Climate change has profound influences on community structure and composition, which was positively dependent upon soil moisture (Yang et al., 2010). Variation of annual average precipitation, interannual deviation of mean temperature and annual aridity index showed that the temperature changed along an increasing trend, rainfall changed along a decreasing trend and dryness changed along an increasing trend at this area (the Maqu Wetland Protection Area) in recent decades. And, local vegetation and soil moisture faced a situation with lower soil moisture gradually (Yao et al., 2007). It suggested that climatic warming-induced potentially decrease of soil moisture significantly decreased aboveground biomass, covers and height in alpine wetland ecosystem, which is consistent with many other reports (Klein et al., 2004; Keryn and Mark, 2009; Kardol et al., 2010; Yang et al., 2010).

Rapid losses of plant species under climate warming have widely been observed in the Tibetan Plateau (Klein et al., 2004), temperate steppe (Yang et al., 2010), salt marshes (Keryn and Mark, 2009) and Mediterranean shrubland (Prieto et al., 2009). But, our study found that species richness was significantly increased in warmed soils with lower soil moisture of alpine wetland ecosystem. Beacuse the change of soil water can alter growth and superiority of dominated species which distributed in higher-moisture habitats and decreased height and covers of these dominated species, which give opportunity for invasion and coexistence of other species. Climate change indirectly affects subdominant species via altering competitive interactions with the dominant species (Engel et al., 2009; Kardol et al., 2010). On the other hand, elevated temperature and decreased soil moisture can indirectly influence plant community via altering species interactions (Niu and Wan, 2008; Yang et al., 2010). Changes in interspecific relationships under warming (Klanderud and Totland, 2007; Niu and Wan, 2008) can also mediate the plant community composition, because of their intrinsic thermal sensitivity, plant species and functional groups can show different responses to warming, contributing to the shifts in the competitive ability and relative dominance

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of among species and functional groups (Walker et al., 2006; Post and Pedersen, 2008). In addition, our results suggested that dominant species within community were changed from typical constructive species with lower richness in local alpine communities – "wetland species" – to some drought-resistant species with higher richness along the climatic warming-induced decrease of soil moisture. Hence, soil moisture plays an important role in regulating the response of plant community structure and composition to climatic warming (Walker et al., 2006; Niu and Wan, 2008; Yang et al., 2010). All these revealed that climatic warming-induced decrease of soil moisture also play important roles in regulating plant community composition and species richness in response to climate change in the alpine wetland community.

4.2 Implications of decrease of soil moisture on soil chemical properties related to climate change

Our results showed climatic warming-induced potentially decrease of soil moisture significantly decreased SOC, total N, available N, total P, available P, but increased soil pH value and total K in studied alpine wetland ecosystem. Warming-induced changes of soil moisture may regulate the availability of soil C, N and P to vegetation growth and then regulate plant community composition and species richness. Warming could accelerate C and N turnover in the ecosystems (Wan et al., 2005). Xue et al. (2010) had reported that the losses of soil carbon and nitrogen were significantly correlated with climatic warming-induced decrease of soil moisture in tallgrass prairie. Hence, it is imperative for us to understand how global warming will affect soil chemical dynamics.

Our results showed that soil organic carbon, total nitrogen, available nitrogen, total phosphorus and available phosphorus all significantly decreased along decreasing soil water content. It may be interpreted by many aspects: first, in our and many other studies, warming leads to in soil C and N because of great decreases in biomass, covers and height in plant communities (Klein et al., 2004; Keryn and Mark, 2009; Kardol et al., 2010; Yang et al., 2010), which is consistent with our results that soil organic carbon, N and P all significant positively related to aboveground biomass covers and

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height in studied alpine wetland community. Second, climatic warming increases organic matter decomposition rates, and leads to loss of soil C and N (Rustad et al., 2001; Fontaine et al., 2004), because elevated temperatures have been shown to significantly affect net N mineralization across different biomes and the warming effects on soil N mineralization depending on soil moisture and vegetation type (Shaw and Harte, 2001). Additionally, human disturbances can also significantly affected above- and below-ground properties of alpine wetland ecosystem (Wu et al., 2009, 2001a, b). And, greater warming at night-time compared with daytime may accelerate litter mass loss (Klein et al., 2004), and grazing will enhance carbon loss to atmosphere in the region through a decrease of litter biomass and an increase of dung production with an increase of stocking rate in future warmer conditions (Luo et al., 2010). Climate change is also likely to combine with other human-induced stresses to further increase the vulnerability of ecosystems to above- and below-ground properties (Hollister and Flaherty, 2010). Climatic warming increases soil temperature and hence accelerate soil water tranpiration organic matter decomposition rates, and leading to loss of soil C and N (e.g. Rustad et al., 2001; Fontaine et al., 2004). Conversely, some studies have reported warming leads to increases in soil C and N because of great increases in biomass and litter inputs in tundra ecosystems (e.g. Welker et al., 2004; Day et al., 2008). Climatic warming potentially stimulates nutrient mineralization and lengthens growing seasons, which consequently increases plant growth and accelerate biospheric metabolism, because it lead to the greater release of heat-trapping gases to the atmosphere (Jenkinson et al., 1991) and increases carbon sequestration (Schimel et al., 1996). Meanwhile, some studies had reported that climatic warming can reduced ecosystem carbon uptake by increased carbon release through soil respiration (Wan et al., 2005) and warming treatment significantly stimulated soil CO_2 and CH_4 efflux in grassland ecosystem (Zhou et al., 2007; Wang et al., 2009), and CH_4 emission was increased linearly with decreases in soil moisture (Wang et al., 2009). Additionally, warming can improved the N and P retranslocation and allocation from stem to leaves (Sardans et al., 2008), which may be translated from soil subsystem in

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sampling site by livestock grazing, because aboveground biomass and litter removal can significantly reduce C inputs to soil (Wan and Luo, 2003). But our result showed that total K increased in lower moisture soil. From the above, climatic warming and warming-induced changes in soil moisture both significantly affect soil chemical traits.

Additionally, we found that species richness were significant negatively related to soil organic carbon, total N, P, and available N, P, but positively related to total K. Richness also can be regulated by spatially heterogeneous of soil resources (Grace et al., 2000; Fernandez-Lugo et al., 2009). Plant-soil feedbacks play an important role in determining and potentially affecting species coexistence by influencing plant community structure (Kardol et al., 2006). Plant species richness was significantly influenced by soil organic matter and nitrogen content, and there was a variety of direct and indirect processes whereby mineral soil properties could influence richness and diversity (Stohlgren et al., 1999; Bashkin et al., 2003). Soil properties can impose directly and indirectly on local species diversity in plant communities and it is crucial for understanding the consequences of above- and belowground trophic interactions for ecosystem functioning (Ettema and Wardle, 2002).

5 Conclusions

Our study predict the potential variation trend of above- and below-ground properties by using the sequence space-series soil water gradient analysis to reflect potential time-series variation of soil moisture related to climate change in an alpine wetland community. Soil moisture gradient will significant negatively impact on the above- and below-ground properties related to climate change, because climatic warming-induced decrease of soil moisture significantly decreased aboveground productivity, cover and height, and belowground chemical properties of studied alpine wetland community. These results of sequence space-series study were expected to reveal the response of alpine wetland community to warming-induced decrease of soil moisture in time-series in alpine wetland community. Further, long-term field experiment should be conducted to improve our understanding of ecosystem responses to climatic warming over time.

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Table 1. Selected sites and aboveground vegetation characteristics of studied meadows. Values (± SE) are means of 9 squares. AL altitude; PD productivity; Dominant species show species which covers over 10 % in the community.

Site	Geographic location	AL (m)	Covers (%)	PD ($g\,m^{-2}$)	Height (cm)	Richness	Dominant species
1	102°01′79 E 33°94′92 N	3524	95.0 ± 1.0	339.9 ± 13.8	21.0 ± 1.5	12.0 ± 0.3	*Kobresia tibetica* Maxim., *Blysmus sinocompressus.Tang et Wang*, *Deschampsia caespitosa (Linn.) Beauv.*, *Carex atrofusca Schkuhr*
2	102°01′82 E 33°95′08 N	3521	92.2 ± 1.7	263.5 ± 7.5	20.3 ± 1.4	11.6 ± 0.5	*Deschampsia caespitosa (Linn.) Beauv.*, *Carex limosa Linn.*, *Blysmus sinocompressus Tang et Wang*, *Caltha palustris* Linn.
3	101°67′35 E 33°78′41 N	3521	85.6 ± 1.6	281.8 ± 11.5	10.4 ± 0.6	9.4 ± 0.5	*Batrachium bungei (Steud.) L. Liou*, *Halerpestes sarmentosa* (Adams) Kom, *Potentill aanserina* Linn.
4	101°67′36 E 33°78′41 N	3507	90.4 ± 1.6	287.8 ± 6.4	13.0 ± 0.4	12.4 ± 0.4	*Kobresia tibetica* Maxim., *Kobresia macrantha Bocklr.*, *Blysmus sinocompressus Tang et Wang*, *Carex atrofusca Schkuhr*
5	101°67′33 E 33°78′43 N	3504	78.4 ± 1.4	298.9 ± 7.8	8.4 ± 0.5	12.4 ± 0.5	*Carex atrofusca Schkuhr*, *Kobresia macrantha Bocklr.*, *Kobresia tibetica* Maxim.
6	101°71′49 E 33°76′57 N	3502	91.6 ± 1.5	344.5 ± 8.8	9.4 ± 0.8	16.0 ± 0.3	*Kobresia tibetica* Maxim., *Potentill aanserina* Linn., *Ranunculus tanguticus (Maxim.) Ovcz*, *Cremanthodium lineare* Maxim.
7	101°71′49 E 33°76′60 N	3506	59.0 ± 2.9	249.9 ± 9.5	6.6 ± 0.5	9.6 ± 0.5	*Descuminia sophia* (L) webb. Ex Prantl, *Potentill aanserina* Linn., *Sedum ulricae* Froed.
8	101°71′44 E 33°76′71 N	3512	78.0 ± 2.5	260.5 ± 4.6	6.8 ± 0.4	10.0 ± 0.3	*Potentill aanserina* Linn., *Kobresia macrantha Bocklr.*, *Carex atrofusca Schkuhr*, *Deschampsia caespitosa* (Linn.) Beauv.
9	101°76′62 E 33°77′16 N	3510	62.0 ± 2.0	245.6 ± 12.3	5.7 ± 0.3	13.8 ± 0.6	*Potentill aanserina* Linn., *Halenia corniculata*(L.) Cornaz, *Gentiana leucomelaena* Maxim.
10	101°76′65 E 33°77′16 N	3434	67.6 ± 1.1	243.5 ± 13.3	4.8 ± 0.4	16.2 ± 0.5	*Kobresia tibetica* Maxim., *Elymus nutans Griseb.*, *Kobresia humilis* (C. A. Mey. ex Trautv.) Sergiev, *Pedicularis szetschuanica* Maxim.
11	101°76′74 E 33°77′34 N	3435	58.0 ± 2.5	144.5 ± 12.2	4.2 ± 0.4	15.4 ± 0.5	*Kobresia humilis* (C. A. Mey. ex Trautv.) Sergiev, *Polygonum viviparum* Linn., *Deschampsia caespitosa (Linn.) Beauv.*, *Taraxacum officinale* F. H. Wigg.
12	102°15′73 E 33°72′10 N	3433	80.2 ± 3.8	271.3 ± 3.9	4.0 ± 0.3	16.6 ± 0.5	*Ligularia virgaurea Maxim.*, *Kobresia macrantha Bocklr.*, *Elymus nutans Griseb.*
13	102°16′02 E 33°71′99 N	3438	44.0 ± 2.9	114.6 ± 7.6	3.9 ± 0.3	16.6 ± 0.9	*Kobresia macrantha Bocklr.*, *Pedicularis kansuensis Maxim.*, *Potentill aanserina* Linn.
14	102°16′21 E 33°71′69 N	3449	49.0 ± 1.9	126.5 ± 10.5	3.0 ± 0.3	20.0 ± 0.7	*Ligularia virgaurea Maxim.*, *Leontopodium alpinum*, *Stipa aliena Keng*, *Kobresia pygmaea (C. B. Clarke) C. B. Clarke*
15	102°08′06 E 33°66′98 N	3433	75.2 ± 2.7	138.4 ± 14.5	6.1 ± 0.3	15.2 ± 0.9	*Anemone rivularis Buch.-Ham.*, *Scirpus pumilus Vahl*, *Herba heteropappi* Altaici

Table 2. Soil properties of selected sites in this studied meadows. Values (± SE) are means of 9 squares ($n = 135$).

Site	Soil depth (cm)	Soil moisture	pH value	SOC	TN	AN	TP	AP	TK	AK
1	0–10	103.31 ± 7.48	5.18 ± 0.02	25.53 ± 1.24	1.99 ± 0.05	473.55 ± 57.40	0.16 ± 0.01	16.21 ± 0.06	1.02 ± 0.03	123.23 ± 11.29
	10–20	113.12 ± 6.75	5.57 ± 0.04	18.06 ± 0.17	1.43 ± 0.04	342.97 ± 30.14	0.12 ± 0.01	15.66 ± 0.44	1.33 ± 0.02	60.86 ± 1.56
2	0–10	93.96 ± 3.43	5.65 ± 0.05	19.91 ± 0.61	1.40 ± 0.11	390.51 ± 21.42	0.26 ± 0.03	23.04 ± 4.58	1.82 ± 0.04	182.02 ± 7.27
	10–20	81.45 ± 3.23	5.56 ± 0.05	17.12 ± 0.22	1.07 ± 0.11	266.91 ± 40.07	0.23 ± 0.02	12,12 ± 0.32	1.83 ± 0.05	73.06 ± 12.79
3	0–10	86.19 ± 2.75	5.61 ± 0.15	8.26 ± 0.38	0.68 ± 0.05	285.57 ± 33.81	0.14 ± 0.04	7.29 ± 1.51	2.11 ± 0.09	145.21 ± 23.28
	10–20	69.93 ± 4.29	5.65 ± 0.05	5.88 ± 0.32	0.48 ± 0.03	174.64 ± 4.13	0.10 ± 0.04	4.56 ± 0.50	2.26 ± 0.08	55.96 ± 4.58
4	0–10	83.63 ± 2.69	6.28 ± 0.10	19.87 ± 0.91	1.64 ± 0.05	471.04 ± 46.70	0.15 ± 0.02	20.82 ± 1.84	1.39 ± 0.04	142.94 ± 41.69
	10–20	80.28 ± 1.82	6.10 ± 0.23	17.97 ± 5.04	1.17 ± 0.07	351.14 ± 16.40	0.31 ± 0.19	14.32 ± 1.61	1.50 ± 0.13	52.62 ± 5.31
5	0–10	79.35 ± 2.10	5.93 ± 0.20	15.57 ± 2.32	1.05 ± 0.13	354.45 ± 37.99	0.17 ± 0.01	11.48 ± 0.59	1.65 ± 0.04	65.51 ± 17.79
	10–20	77.41 ± 3.13	5.97 ± 0.14	19.43 ± 0.32	1.16 ± 0.10	324.17 ± 25.48	0.16 ± 0.01	10.31 ± 0.85	1.61 ± 0.05	44.00 ± 8.86
6	0–10	77.93 ± 4.80	5.65 ± 0.04	17.38 ± 1.40	1.26 ± 0.05	437.68 ± 4.31	0.21 ± 0.04	19.14 ± 8.28	1.69 ± 0.07	150.27 ± 27.78
	10–20	61.58 ± 4.12	5.69 ± 0.13	9.05 ± 1.19	0.68 ± 0.12	260.45 ± 36.89	0.23 ± 0.05	10.72 ± 6.30	1.89 ± 0.05	45.28 ± 9.95
7	0–10	49.93 ± 7.87	7.90 ± 0.04	6.55 ± 0.10	0.64 ± 0.01	190.42 ± 4.17	0.09 ± 0.01	14.33 ± 2.16	2.61 ± 0.03	196.51 ± 13.97
	10–20	40.22 ± 0.88	8.04 ± 0.02	6.63 ± 0.18	0.59 ± 0.01	162.63 ± 4.84	0.08 ± 0.01	11.17 ± 0.81	2.54 ± 0.08	119.79 ± 4.77
8	0–10	46.87 ± 1.73	5.34 ± 0.05	13.53 ± 1.14	1.12 ± 0.10	418.30 ± 37.50	0.20 ± 0.01	25.46 ± 2.69	2.00 ± 0.10	210.88 ± 18.05
	10–20	34.04 ± 0.98	5.69 ± 0.04	6.34 ± 0.28	0.46 ± 0.04	175.07 ± 14.21	0.14 ± 0.01	16.72 ± 2.81	2.32 ± 0.06	106.75 ± 11.15
9	0–10	41.21 ± 3.55	6.44 ± 0.20	8.19 ± 1.48	0.74 ± 0.16	276.48 ± 56.03	0.08 ± 0.01	6.24 ± 1.59	1.97 ± 0.11	74.96 ± 26.23
	10–20	37.98 ± 1.33	6.54 ± 0.15	7.05 ± 0.85	0.61 ± 0.08	217.35 ± 41.73	0.08 ± 0.01	4.49 ± 1.23	2.01 ± 0.03	48.51 ± 13.07
10	0–10	58.43 ± 1.89	7.72 ± 0.05	5.56 ± 0.35	0.46 ± 0.03	153.11 ± 11.10	0.10 ± 0.01	11.63 ± 3.55	3.22 ± 0.06	112.56 ± 9.35
	10–20	39.03 ± 0.81	6.89 ± 0.09	14.79 ± 0.93	1.13 ± 0.10	366.64 ± 21.99	0.13 ± 0.01	17.42 ± 6.59	2.18 ± 0.11	89.46 ± 3.11
11	0–10	36.23 ± 1.96	7.35 ± 0.02	7.46 ± 0.56	0.70 ± 0.03	228.02 ± 21.13	0.11 ± 0.01	16.38 ± 3.90	2.88 ± 0.06	294.16 ± 20.08
	10–20	33.63 ± 1.53	7.88 ± 0.09	4.83 ± 0.42	0.44 ± 0.02	161.44 ± 7.42	0.09 ± 0.01	9.59 ± 3.93	2.92 ± 0.12	116.22 ± 11.91
12	0–10	30.95 ± 1.43	6.58 ± 0.13	7.40 ± 0.21	0.61 ± 0.01	207.43 ± 5.58	0.10 ± 0.01	17.35 ± 0.54	2.80 ± 0.03	607.89 ± 32.80
	10–20	24.06 ± 2.23	6.59 ± 0.01	4.73 ± 0.55	0.33 ± 0.03	115.01 ± 7.22	0.08 ± 0.01	12.37 ± 1.50	2.88 ± 0.14	372.95 ± 27.77
13	0–10	23.14 ± 0.27	7.97 ± 0.10	1.89 ± 0.36	0.15 ± 0.03	63.86 ± 12.41	0.06 ± 0.01	6.46 ± 0.36	2.70 ± 0.03	41.44 ± 5.70
	10–20	19.29 ± 0.06	8.25 ± 0.02	0.96 ± 0.15	0.07 ± 0.01	40.18 ± 6.73	0.06 ± 0.01	5.53 ± 0.16	2.64 ± 0.06	34.21 ± 8.95
14	0–10	18.80 ± 0.09	6.48 ± 0.15	5.29 ± 0.49	0.49 ± 0.03	189.85 ± 11.92	0.08 ± 0.01	5.39 ± 1.05	1.92 ± 0.10	102.61 ± 10.11
	10–20	16.53 ± 0.21	7.54 ± 0.13	3.13 ± 0.11	0.32 ± 0.01	125.42 ± 4.62	0.08 ± 0.01	4.78 ± 1.80	1.95 ± 0.04	58.01 ± 1.99
15	0–10	17.61 ± 0.33	6.21 ± 0.03	3.59 ± 0.18	0.33 ± 0.01	153.65 ± 8.34	0.07 ± 0.01	9.76 ± 0.89	2.52 ± 0.11	313.42 ± 51.74
	10–20	16.45 ± 0.22	6.11 ± 0.05	3.18 ± 0.24	0.31 ± 0.03	126.15 ± 7.01	0.06 ± 0.01	8.65 ± 0.73	2.47 ± 0.14	329.24 ± 57.22

Soil moisture (%); SOC soil organic carbon content (%); TN soil total nitrogen content (%); AN soil available nitrogen content (mg kg^{-1}); TP soil total phosphorus content (%); AP soil available phosphorus content (mg kg^{-1}); TK soil total potassium content (%); AK soil available potassium content (mg kg^{-1}).

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Table 3. Pearson's correlation coefficients (R) among soil moisture, soil chemical properties and vegetation properties of studied meadows ($n = 270$).

Pearson's correlation coefficients (R)	AN	TP	AP	TK	AK	Height	Richness	SOC	Cover	Aboveground biomass
SWC	0.772**	0.749**	0.421**	−0.656**	−0.131*	0.858**	−0.587**	0.856**	0.733**	0.769**
TN	0.974**	0.732**	0.563**	−0.692**	0.113ns	0.667**	−0.375**	0.982**	0.684**	0.716**
AN		0.746**	0.536**	−0.682**	0.124ns	0.617**	−0.340**	0.954**	0.680**	0.692**
TP			0.505**	−0.565**	−0.078ns	0.640**	−0.331**	0.782**	0.665**	0.623**
AP				−0.213**	0.455**	0.399**	−0.271**	0.566**	0.482**	0.439**
TK					0.322**	−0.692**	0.221**	−0.714**	−0.519**	−0.492**
AK						−0.127ns	0.004ns	0.048ns	0.201*	−0.016ns
Height							−0.572**	0.705**	0.763**	0.642**
Richness								−0.381**	−0.421**	−0.470**
SOC									0.723**	0.757**
Cover										0.740**

SWC soil water content; SOC soil organic carbon content (%); TN soil total nitrogen content (%); AN soil available nitrogen content (mg kg^{-1}); TP soil total phosphorus content (%); AP soil available phosphorus content (mg kg^{-1}); TK soil total potassium content (%); AK soil available potassium content (mg kg^{-1}).

ns not significant; *Correlation significant at the 0.05 level; **Correlation significant at the 0.01 level (2-tailed)

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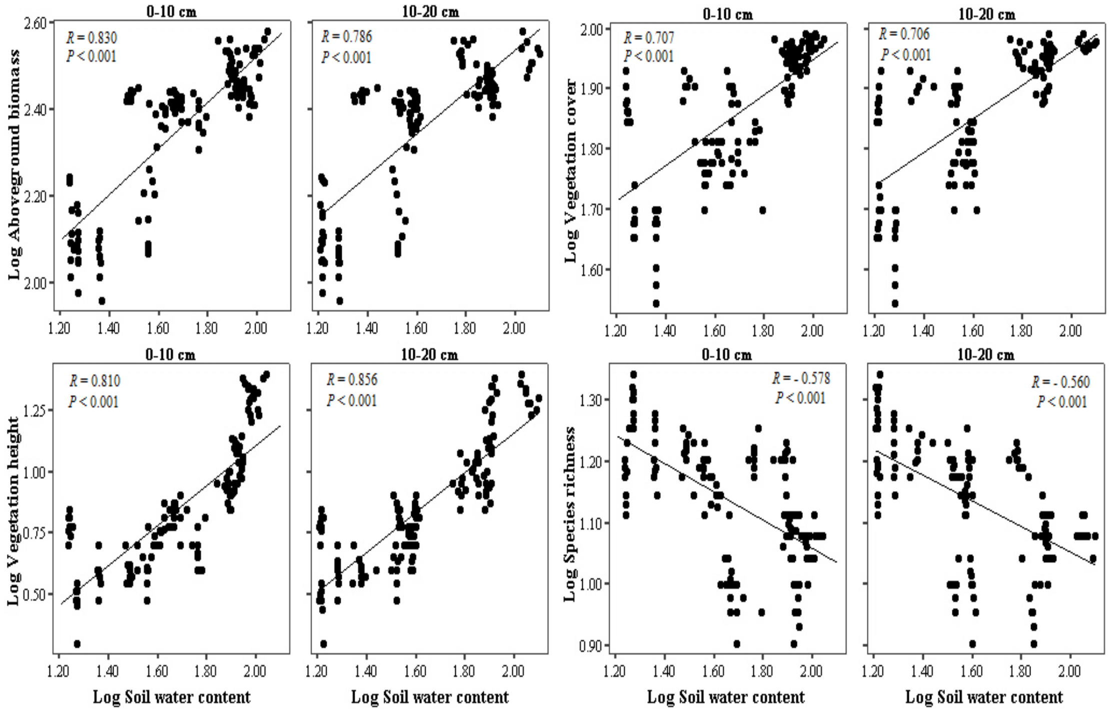

Fig. 1. Relationships of soil moisture with two soil depth (0–10 and 10–20 cm) and aboveground biomass, vegetation cover, vegetation height, and species richness in studied meadows.

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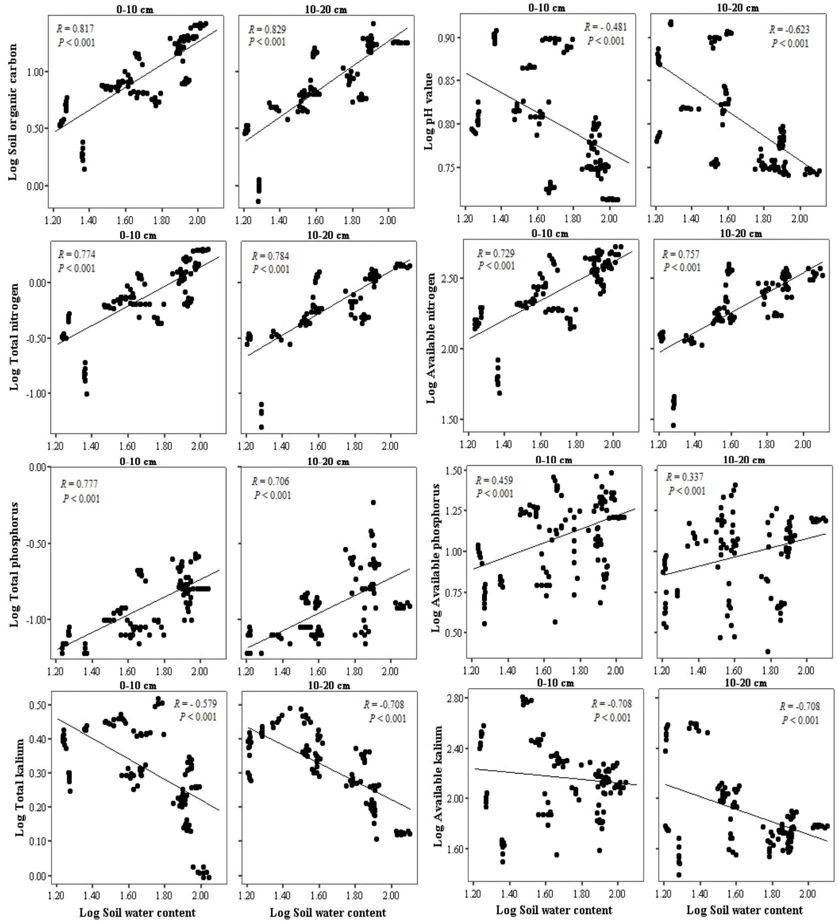

Fig. 2. Relationships of soil moisture and soil organic carbon, soil pH value, total nitrogen, available nitrogen, total phosphorus, available phosphorus, total potassium and available potassium with two soil depth (0–10 and 10–20 cm) in studied meadows.