Soil moisture and temperature dynamics in typical alpine ecosystems: a continuous multi-depth measurements-based analysis from the Qinghai-Tibet Plateau, China

Si-Yi Zhang and Xiao-Yan Li

ABSTRACT

Soil temperature and moisture are the key variables that control the overall effect of climate and topography on soil and vegetation in alpine regions. However, there has been little investigation of the potential soil temperature and moisture feedbacks on climate changes in different alpine ecosystems and their impact on vegetation change. Soil temperature and moisture at five depths were measured continuously at 10-min intervals in three typical ecosystems (Kobresia meadow (KMd), Achnatherum splendens steppe (ASSt), and Potentilla fruticosa shrub (PFSh)) of the Qinghai Lake watershed on the northeast Qinghai-Tibet Plateau, China. The findings of this study revealed that the KMd and PFSh sites had relatively low soil temperature and high soil moisture, whereas the ASSt site had relatively warm soil temperature and low soil moisture. The soil and vegetation characteristics had important effects on the infiltration process and soil moisture regime; about 47%, 87%, and 34% of the rainfall (minus interception) permeated to the soil in the KMd, PFSh, and ASSt sites, respectively. In the context of the warming climate, changes to soil moisture and temperature are likely to be the key reasons of the alpine meadow deterioration and the alpine shrub expansion in the alpine regions.

Key words | alpine ecosystems, Qinghai-Tibet Plateau, soil moisture, soil temperature

INTRODUCTION

Global surface temperature increased 0.85 °C between 1880 and 2012, and is projected to increase 1.1–2.6 °C by 2100. On the Qinghai-Tibet Plateau, China, the surface temperature is projected to increase by 0.9–4.9 °C, and the precipitation is projected to change by −1% to 32% by 2100 in a medium emissions scenario (IPCC 2014). Climate change has caused extensive vegetation changes across the world but especially in alpine regions (Kelly & Goulden 2008; Wilson & Nilsson 2009). The Qinghai-Tibet Plateau is considered to be one of the regions most sensitive to global climate change (Yao & Zhu 2006). As a result of climate warming, alpine meadows and steppes are projected to deteriorate on the Qinghai-Tibet Plateau, while shrubs are projected to expand (Zhao et al. 2011). Plant cover, height, and biomass are expected to be affected by climate change (Alatalo et al. 2016). The responses of vegetation to climate change rely on complicated interactions between productivity, disturbances, plant functional composition, and richness (Virtanen et al. 2010). According to Zhao et al. (2011), the area of alpine meadows is projected to decline by 29% from that in the baseline term (1961–1990) by 2050 and the shrubs are mostly expected to expand and replace the meadows. By 2080, the original vegetation in the northern Qinghai-Tibet Plateau is projected to be replaced by the shrubs entirely (Zhao et al. 2011). The changes of vegetation pattern are expected to have considerable impacts on the cycling of water, carbon and nitrogen in alpine soils, which are susceptible to soil moisture, temperature, and vegetation types (Doerfer et al. 2013; de Graaff et al. 2014; Goulden & Bales 2014).
Soil moisture and temperature are the key variables involved in integrating the influence of climate, soil, vegetation (Breshears et al. 1998; Wen et al. 2006), and topography (Legates et al. 2011) in alpine regions. Nutrient availability and water uptake by roots (Binkley et al. 1994; Lv et al. 2012), soil organic matter decomposition and mineralization rates (Sierra et al. 2015; Zhang et al. 2015), and plant growth processes (Domisch et al. 2002; Aphalo et al. 2006) are all affected by soil moisture and temperature. Soil moisture and temperature also control plant distribution and community composition at high altitudes (Körner 1999; Wieser & Tausz 2007). Therefore, quantification of soil moisture and temperature is important to understand the complex ecosystem dynamics under a changing climate (Aalto et al. 2013). However, a full understanding of the variation of soil moisture and temperature in various ecosystems on the Qinghai-Tibet Plateau is crucial to predict accurately the influence of climate change on alpine ecosystems.

Soil moisture and temperature are controlled by a variety of factors, such as meteorological factors (e.g., radiation, rainfall, air temperature and humidity, wind and snow cover), topography (e.g., altitude, slope, and aspect), soil physical properties (e.g., texture structure and porosity), and vegetation cover (Balisky & Burton 1995; Famiglietti et al. 1998; Kang et al. 2000; Qiu et al. 2001; Redding et al. 2003; Bond-Lamberty et al. 2005; Williams et al. 2009; Zhong et al. 2014). Soil moisture and temperature could vary with microporographic site conditions (Yang et al. 2007; Wundram et al. 2010). Topography leads to orographic precipitation and runoff redistribution, and affects the soil moisture (Henninger et al. 1976; Anquetin et al. 2006). Soil temperature decreases or increases with altitude because of vertical attemperation or cloud immersion (Shanks 1956; Richardson 2004). Soil texture, clay content, and porosity are thought to be the key factors controlling the spatial variation of soil moisture (Henninger et al. 1976; Crave & Gascuel-Odoux 1997; Famiglietti et al. 1998). Soil moisture variations in different ecosystems could be related to the differences in interception, infiltration, and evapotranspiration between ecosystems (Vivoni et al. 2007, 2008).

This study took place in the Qinghai Lake watershed, northeastern Qinghai-Tibet Plateau, China; high-resolution and multi-depth soil moisture and temperature were continuously measured on three alpine ecosystems. The main objectives of this paper were: (1) to ascertain the range of temperature and moisture levels and variability in alpine ecosystems with different vegetation types and soils in the context of weather changes in the Qinghai Lake watershed; and (2) to discuss the interaction between the thermal moisture regime of soils and vegetation in alpine regions.

MATERIALS AND METHODS

Study area

Three experimental sites, including Kobresia meadow (KMd), Achnatherum splendens steppe (ASSt), and Potentilla fruticosa shrub (PFSh) ecosystems were selected in the Qinghai Lake watershed (Figure 1). The KMd, ASSt, and PFSh ecosystems represent alpine meadow, alpine steppe, and alpine shrublands, respectively, which are the three main ecosystems of the Qinghai Lake watershed, and which occupy 55.9%, 15.6%, and 5.0% of the total land area, respectively (Figure 1) (Zhang et al. 2016). For logistical reasons (convenient access), the three experimental sites were all selected in the second largest subwatershed, the Shaliu River watershed (Figure 1). The three selected locations are typically representative of alpine meadow, alpine steppe, and alpine shrub, respectively, with uniform vegetation cover and without serious disturbance. The KMd and PFSh sites were selected in the middle reaches, and the ASSt site was located in the lower reaches. The underground water level in the KMd and PFSh site is about 8 m, and it is about 2.5 m in the ASSt site. A National Weather Station was located about 30, 10, and 27 km away from the KMd, ASSt, and PFSh sites, respectively (Figure 1). The mean annual temperature recorded at the National Weather Station is 0.1 °C and the temperature in January is −14.3 to −9.8 °C and in July is 10.9 to 15.6 °C. The mean annual precipitation is 389.4 mm, and 85% of the precipitation happens from May to September. The main growing season is from May to September (Zhang et al. 2016).

The location and vegetation composition information at experimental sites are included in Table 1 (Zhang et al. 2016). Plant height at the KMd site was lower than that at PFSh and ASSt sites. Coverage, leaf area index (LAI), and

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aboveground biomass in the ASS1 site are lower than those in the KMd and PFSh sites.

Belowground biomass was much higher than the aboveground biomass in all three ecosystems (Table 1 and Figure 2). The belowground biomass of annual herbs in the KMd and PFSh sites was about 50 times their aboveground biomass, the belowground biomass of perennial herb *A. splendens* patch was about 100 times its aboveground biomass, and the belowground biomass of perennial *P. fruticosa* shrub patch was about two times its aboveground biomass (Table 1). Belowground biomass was mainly concentrated in the surface layer (Figure 2). The biomass at the soil depth of 0–10 cm occupied about 77% of the whole belowground biomass in the KMd site. Under the *P. fruticosa* shrub patches, the belowground biomass was mainly distributed at 0–50 cm. Because few roots were present at soil depths greater than 40 cm, the soil organic matter content was low in both the PFSh and KMd sites. The roots of *A. splendens* could reach as deep as 80 cm, and the biomass at the soil depth of 80 cm was about 0.25 kg m$^{-2}$. Correspondingly, soil organic matter at soil depth of more than 40 cm in the ASS1 site was the highest of the three ecosystems (Table 2). The distribution of belowground biomass had an important effect on the soil organic matter.

The soil depths of the three ecosystems were no more than 1.1 m above the parent material layer (Figure 3, Figure 1).
Table 3). Horizon A was 18–30 cm, varying in different ecosystems. There were apparent cambic horizons between horizons A and B, B and C in the PFSh site (Figure 3). Soil texture was similar in the KMd and PFSh site, and in the ASSt site there was less sand and more silt and clay. In the A horizon, $W_s$ was highest in the PFSh site and lowest in the KMd site, and $W_f$ was highest in the PFSh site and lowest in the ASSt site. In the B horizon, $W_s$ was highest in the ASSt site and lowest in the PFSh site, and $W_f$ was highest in the ASSt site and lowest in the PFSh site (Table 3).

Bulk density, total soil porosity, and soil organic matter in the three ecosystems is shown in Table 2. At 10 cm soil depth, bulk density was lowest in the PFSh site and highest in the ASSt site; while at soil depths of more than 40 cm, bulk density was highest in the PFSh site and lowest in the ASSt site. The total soil porosity in the three ecosystems was inversely related to the bulk density. In the KMd and PFSh sites, the bulk density increased and the total soil porosity decreased with increasing depth, while in the ASSt site, the bulk density at 10 cm soil depth was higher than at 20 cm soil depth. Soil organic matter decreased with increasing depth in all three ecosystems (Table 2). In the upper layers (0–20 cm), soil organic matter was much higher in the PFSh site than in the other two sites; whereas, in the deeper layers (60–100 cm), soil organic matter was higher in the ASSt site than in the KMd and PFSh sites.

Soil water content and temperature measurements

ECH2O 5TE sensors (Devices, USA) were installed in the soil profile to measure soil moisture ($\text{cm}^3 \text{cm}^{-3}$) and...
temperature (°C). The 5TE sensor uses the dielectric method to measure soil moisture and a thermistor to take temperature readings, an electromagnetic field to measure the dielectric permittivity of the surrounding medium (Decagon Devices Inc. 2010). The 5TE sensors can measure soil moisture and temperature accurately and continuously (Czarnomski et al. 2005), and have been used in many similar studies (D’Odorico et al. 2007; Li et al. 2013). The accuracy of the sensors is ±0.02 m³ m⁻³ for moisture measurement and ±0.3 °C for temperature measurement. Moreover, the variability among different sensors was less than 2%. The resolution of soil moisture measurement was 0.0008 m³ m⁻³.

To install the sensors, a profile was dug in each site, and then the sensors were inserted into the profile vertically. At each site, five 5TE sensors were inserted into the profile at the soil depths of 10, 20, 40, 60, and 100 cm (except the PFSh site with a sensor at 80 cm instead of 100 cm because the thickness of soil was only 80 cm). At each site, soil moisture and temperature were logged into an Em50 data logger (Decagon Devices, Pullman, Washington, USA) at 10-min intervals. The measurements of soil water content and temperature were carried out between July 2012 and June 2013.

### Meteorological observations

An auxiliary meteorological station with a 3-m-high pillar was installed at each experimental site. Three stations were installed in total, each with the same instruments. Air temperature and relative humidity were measured using a 225-HMP50YA probe (NOVALYNX, USA) at a height 2.0 m above ground level. Rainfall was recorded using a rain gauge (ARG100, Campbell, USA). A net radiometer (240–100, NOVALYNX, USA) was used to measure net radiation. Soil heat flux was measured using a heat flux plate (HFP01, Dynamax Inc., USA). Wind speed and direction were measured by an anemometer (05103-5, RM-YOUNG, USA) positioned at 2 m above the ground. The data were recorded by a DT 500 data logger (Datataker, Australia) every 10 min. The meteorological observations were carried out simultaneously with the soil water content and temperature measurements.
Statistical analyses

Differences in soil moisture between different soil layers or between different ecosystems were analyzed using one-way analysis of variance (ANOVA) and Fisher’s protected least significant difference test. The ANOVA analysis was completed using SPSS 17.0 software (SPSS Inc., Chicago, USA, 2008) and at the $p = 0.05$ level of confidence. To analyze the effects of weather factors on the soil moisture and soil temperatures, the redundancy analysis (RDA), a multivariate

Table 3 | Some characteristics of soil in the three ecosystems

<table>
<thead>
<tr>
<th>Ecosystems</th>
<th>Kobresia meadow</th>
<th>Potentilla fruticosa shrub</th>
<th>Achnatherum splendens steppe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil parent material</td>
<td>Colluvium</td>
<td>Colluvium</td>
<td>Alluvium</td>
</tr>
<tr>
<td>Soil orders^</td>
<td>Cambisols</td>
<td>Cambisols</td>
<td>Isohumosols</td>
</tr>
<tr>
<td>Soil layers (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>110</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>A</td>
<td>0–20</td>
<td>0–18</td>
<td>0–30</td>
</tr>
<tr>
<td>B</td>
<td>20–110</td>
<td>24–55</td>
<td>30–110</td>
</tr>
<tr>
<td>$W_s$ ($m^3/m^3$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.47</td>
<td>0.63</td>
<td>0.51</td>
</tr>
<tr>
<td>B</td>
<td>0.40</td>
<td>0.32</td>
<td>0.54</td>
</tr>
<tr>
<td>$W_f$ ($m^3/m^3$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.35</td>
<td>0.42</td>
<td>0.30</td>
</tr>
<tr>
<td>B</td>
<td>0.14</td>
<td>0.25</td>
<td>0.33</td>
</tr>
<tr>
<td>Soil texture (USDA, %)^</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>67.9 ± 1.9</td>
<td>50.65 ± 22.05</td>
<td>29.5 ± 14.6</td>
</tr>
<tr>
<td>Silt</td>
<td>20.5 ± 4.7</td>
<td>35.06 ± 20.19</td>
<td>48.7 ± 4.7</td>
</tr>
<tr>
<td>Clay</td>
<td>11.6 ± 4.0</td>
<td>14.3 ± 3.5</td>
<td>21.5 ± 10.6</td>
</tr>
</tbody>
</table>

^Chinese Soil Taxonomy

^Average values for the different soil layers (mean ± SD).

$W_s$: saturated water content; $W_f$: field water capacity.
direct gradient analysis method, was performed using CANOCO 5.0 software (Centre for Biometry, Wageningen, The Netherlands, 2012). First, a detrended correspondence analysis was run, and the results showed that it was opportune to analyze the data in this study using the linear model of RDA according to Lepš & Amilauer (2005).

RESULTS

Variation of soil temperatures and its relation to air temperature in the three ecosystems

Soil temperature varied greatly between the three different ecosystems (Table 2). In both the annual period and the growing season, soil temperatures were highest in the ASSt site and lowest in the PFSh site. In the KMd site, annual mean soil temperatures were highest at 20 cm soil depth and decreased with increasing soil depth below 20 cm. In the PFSh and ASSt sites, soil temperatures were the highest at 10 cm soil depth and decreased with increasing soil depth. Soil temperature in the ASSt site varied the most within a year, indicated by the largest standard deviations. In the growing season, the mean soil temperature at the surface depth (10 cm) reached 9.9 °C, 6.8 °C, and 14.2 °C in the KMd, PFSh, and ASSt sites, respectively.

Temporal and spatial distributions of soil temperatures in the KMd, PFSh, and ASSt sites are shown in Figure 4. From July to October, the soil within the depth of 100 cm was thawed in the three ecosystems. In early November, the surface soil began to freeze, about a week earlier in the ASSt site than in the KMd and PFSh sites in 2012. The layer of frost reaching the bottom of soil layers was earliest in the PFSh site at the end of November 2012 and latest in the ASSt site in the middle of January 2013. Soil began to thaw the earliest in the ASSt site in the middle of March 2013 and the latest in the PFSh site in the middle of April. Soil had thawed to the bottom of the soil layer the earliest in the ASSt site in early April and the latest in the PFSh site in the middle of June. In the KMd site, the frozen period lasted 125–135 days, whereas in the PFSh site it could be as long as 196 days at the 80 cm soil depth. In the ASSt site, because of its high salinity, the freezing and thawing temperature was –2.8 to –1.3 °C (Zhang 2014), lower than 0 °C, and its frozen soil period was shorter than 100 days. These results indicate that the PFSh ecosystem had the longest period of frozen soil.

Average soil temperature variations within a single day are shown in Figure 5. It is clear that soil temperature fluctuated considerably at the depths of 10 and 20 cm, and soil temperature changed little beneath the depth of 40 cm. Soil temperature change amplitudes were higher in the warmer May and August than in the colder February and November. The highest soil temperatures at the depth of 10 cm appeared from 17:00 to 19:00, and the lowest soil temperatures at the depth of 10 cm appeared from 9:00 to 10:00. The deeper the soil layer, the later the soil temperature peak time. Soil temperatures at the depth of 100 cm increased continuously during the warming period of February or May, fluctuated weakly in August, and decreased continuously in the cooling period of November.

The RDA result clearly showed that the percentage of variance for soil temperatures explained by the first axis was 89.8%, 89.9%, and 92.2% in the KMd, PFSh, and ASSt sites, respectively. As the air temperature (Ta) lines were the longest lines in the RDA biplot diagrams (Figure 6), air temperature had the best correlations with soil temperatures, and soil temperature variations were mostly explained by air temperatures 74.8%, 71.8%, and 85.0% in the KMd, PFSh, and ASSt sites, respectively. The daily soil temperature has a good correlation with daily air temperature; the correlation coefficients were 0.94, 0.94, and 0.97 in the KMd, PFSh, and ASSt sites, respectively. The angles between the air temperature (Ta) lines and the soil temperatures increased as the soil depth increased (Figure 6), indicating that the correlations between air and soil temperature decreased. There was a time lag for the air temperature change to be transported to soil layers at different depths. The best relationships between hourly soil temperature at 10 cm soil depth and air temperature were 0.85, 0.85, and 0.88 with the time lags of 5, 4, and 4 hours in the KMd, PFSh, and ASSt sites, respectively. The best relationships between hourly soil temperature at 20 cm soil depth and air temperature decreased to 0.75, 0.74, and 0.68 with the time lags increasing to 511, 659, and 153 hours in the KMd, PFSh, and ASSt sites, respectively. At the 80/100 cm soil depth, there was no clear hourly fluctuation of soil temperature (Figure 5). The best relationships...
between daily soil temperature at 80/100 cm soil depths and air temperature were 0.92, 0.90, and 0.90 with the time lags of 41, 51, and 31 days in the KMd, PFSh, and ASSt sites, respectively.

Variation of soil moisture and its influencing factors in the three ecosystems

Soil moisture varied spatially and temporally in the KMd, PFSh, and ASSt sites. Annual mean soil moisture was 0.22, 0.24, and 0.20 m$^3$m$^{-3}$ in the KMd, PFSh, and ASSt sites, respectively. During the long winter period from November to March, soil was frozen and liquid soil water content was low in all three ecosystems (Figure 7). Soil moisture increased from April and reached peak values mostly in August, after which it decreased until the end of the year (Figure 7).

In the growing season, mean soil moisture of the whole profile was 0.27, 0.29, and 0.25 m$^3$m$^{-3}$ in the KMd, PFSh, and ASSt sites, respectively. In the KMd site, the growing season soil moisture decreased with increasing soil depth except at 60 cm soil depth, and the growing season soil moisture at 10 and 20 cm soil depth was significantly higher than that in other deeper layers. However, the growing season soil moisture at 40, 60, and 100 cm soil depth had no significant differences (Figure 7(a)). In the PFSh site, the growing season soil moisture at 10 and 20 cm soil depth was significantly higher than that at 60 and 80 cm soil depth, and the highest soil moisture appeared at 20 cm soil depth (Figure 7(b)). In the ASSt site, the highest growing season soil moisture occurred at 20 cm soil depth, and the lowest growing season soil moisture occurred at 40 cm soil depth (Figure 7(c)).

Frequency distributions of 10-min soil water contents (Figure 8) indicated that soil moisture at 10 cm soil depth in the KMd site was significantly higher than in the PFSh and ASSt sites. Soil moisture at 10 cm soil depth was the lowest in the ASSt site. At 20 and 40 cm soil depth, soil
moisture in the PFSh site was significantly higher than that in the KMd and ASSt sites and soil moisture in the KMd site was the lowest. At 60 and 100 cm soil depth, soil moisture was highest in the ASSt site.

The RDA result clearly showed that the percentage of variance of daily soil moisture explained by the first axis was 53.3%, 32.6%, and 54.9% in the KMd, PFSh, and ASSt sites, respectively. The vapor pressure (e) lines were the longest lines in the RDA biplot diagrams (Figure 9), indicating that vapor pressure had the best correlations with soil moistures and daily soil moisture variations were explained by vapor pressure at 18.0%, 13.7%, and 35.0% in the KMd, PFSh, and ASSt sites, respectively. The explanation of the first axis and the best correlation factor for soil moistures was much lower than found for soil temperature, which revealed that the factors influencing soil moisture were much more complicated than those controlling soil temperature, and weather factors were only part of the explanation.

Figure 5  | Mean hourly variation within 1 day of soil temperature in February, May, August, and November in the KMd, ASSt, and PFSh sites. The local solar time is 1 h 20 min later than Beijing time.

Figure 6  | Ordination axes 1 and 2 of the RDA for soil temperature at different depths (with solid arrowhead) and weather factors (with hollow arrowhead). ST##, soil temperature at the soil depths of ## cm; Rn, net radiation; G, soil heat flux; Ta, air temperature at 2 m; RH, relative air humidity at 2 m; e, vapor pressure; ed, vapor deficit; P, precipitation.
Rainfall is an important source of soil water, and is expected to be a key factor for soil moisture. Ten-minute soil moisture changes during different rain events are presented in Figure 10. It is clear that soil moisture only increased at 10 cm soil depth of the PFSh site when the rain was lower than 3.5 mm. When the rain was about 10 mm, soil moisture increased at 10 and 20 cm soil depth in the KMd and PFSh sites, but only increased at 10 cm soil depth in the ASSt site. When the rainfall was about 20 mm, rain could penetrate soil depth up to 100 cm and soil moisture increased in the entire soil layer of the KMd and PFSh site; however, soil moisture only increased at 10 cm soil depth at the ASSt site when the rainfall was 16.5 mm.

The responses of soil moisture to the rainfall pulses were also affected by the characteristics of the rainfall process and the antecedent soil moisture. When the rain intensity was gentle, there was a lag time for increasing soil moisture; otherwise, the soil moisture increased quickly. In the rain event during June 26–27, 2012, the rain intensity was 2.1 mm h$^{-1}$, and the soil moisture at 10 cm soil depth in the KMd site increased by 0.02 m$^3$ m$^{-3}$ (the accuracy of the sensors) within 50 min of commencement of the rain (Figure 10(a)). The total rain depth within the first 50 min was as high as 8.6 mm. In the rainfall event during July 3–4, 2013, the rainfall intensity was 1.5 mm h$^{-1}$, and the soil moisture at 10 cm depth of the KMd site increased by
0.02 m$^3$ m$^{-3}$ within 270 min of commencement of the rain (Figure 10(b)). The total rainfall depth within the first 270 min was 7.6 mm. The longest lag time for increasing soil moisture at 10 cm soil depth occurred in the ASSt site in the rainfall event of September 7, 2013. It took more than 12 hours before the soil moisture increased by 0.02 m$^3$ m$^{-3}$ after the rain began and the total rain depth was 10.2 mm. The responses of soil moisture at 20 cm soil depth lagged behind those at 10 cm soil depth (Figures 10(b) and 10(e)). However, if the antecedent soil moisture was approaching saturation and the rainfall intensity was high at the beginning of rain, soil moisture at 20 cm soil depth increased early simultaneously with that at 10 cm soil depth (Figure 10(a)).

Based on the monitoring soil moisture data at 10-min intervals in five depths, soil water storage of 0–100 cm soil profiles in each site was calculated by summed up soil water storage of the five soil layers. The changes of soil water storage of the soil profiles (0–100 cm) after rain in different ecosystems are presented in Figure 11. The changes of soil water storage in the KMd, PFSh, and ASSt sites could be estimated using the following equations,
Annual mean soil temperatures in the PFSh site were 1.9–
4.4°C lower than those in the KMd and ASSt sites. In the
growing season, the daily soil temperature difference
between different ecosystems could be as high as 8.4°C. The
observed variation of soil temperatures in different eco-
systems was a result of topography, soil property, and plant
characteristics (Balisky & Burton 1995; Kang et al. 2000;
of the PFSh site was about 300 m higher than that of the
ASSt site. As a consequence of the changes in altitudinal
air pressure and associated thermodynamic processes, the
air cools from about −0.98°C per 100 m for dry air to
about −0.4°C per 100 m for saturated air (Dodson &
Marks 1997); therefore, the annual air temperature in the
PFSh site was 1.2°C lower than in the ASSt site. In addition
to the elevation, the plant coverage and soil moisture var-
iance also led to the soil temperature differences in the
KMd, PFSh, and ASSt sites. The plant coverage and LAI
in the KMd and PFSh sites were significantly higher than
those in the ASSt site (Table 1). High coverage and LAI
accumulation in the KMd and PFSh sites could insulate
the soils, resulting in the air-soil temperature decoupling
during the growing season (Balisky & Burton 1995; Bond-
Lamberty et al. 2005; Bader et al. 2009), while the significant
decrease of plant coverage and LAI in the ASSt site could
enhance solar radiation reaching the ground surface (Red-
ding et al. 2003; Bond-Lamberty et al. 2005). The specific
heat of water was 4.2 J g⁻¹°C⁻¹, about five times that of min-
eral matter; therefore, the soil heat capacity was mainly
determined by the soil moisture (Wei 2011). In the growing
season, the soil moisture could be as high as 0.35 and
0.40 m³ m⁻³ at 10 cm soil depth in the KMd and PFSh
sites, much higher than that in the ASSt site (Figure 7).
This leads to higher soil heat capacity and lower soil warm-
ing in the KMd and PFSh sites than in the ASSt site.
Furthermore, the high aboveground biomass in the PFSh
site (Table 1) could result in thick and long-lasting snow
cover, although snow cover was not measured in this
research. Snow cover is thought to decouple soil tempera-
ture from air temperature and needs substantial energy to
melt, thus it generally delays soil warming in the spring
(Mellander et al. 2006; Liu & Luo 2011). In summary, high
elevation, substantial plant cover and LAI, and high soil
moisture result in low soil temperature and long soil-
frozen periods in the KMd site and especially the PFSh site.

The differences in soil moisture among the KMd, PFSh,
and ASSt sites are likely thought to be caused by the differ-
ent amount of rainfall and soil characteristics. There was
only 329 mm of rain in the ASSt site during the period
June 2012–July 2013, while there was 576 and 521 mm
rain in the KMd and PFSh sites, respectively. Less rainfall
input and the compacted soil of the 0–10 cm depth meant
a reduced water source and lower infiltration in the ASSt

\[
W_{KMd} = -0.01 + 0.46P, R^2 = 0.61, p < 0.001
\]

\[
W_{PFSh} = -2.07 + 0.87P, R^2 = 0.90, p < 0.001
\]

\[
W_{ASSt} = -0.31 + 0.34P, R^2 = 0.89, p < 0.001
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site. Higher air and soil temperature indicated a higher evapotranspiration demand (Liu & Zhang 2013), the ratio of evapotranspiration to rain in the ASSt site was larger than 1 (Zhang et al. 2016). However, the soil moisture at the 60–100 cm soil layer was highest in the ASSt site, which could be related to the groundwater. The groundwater level around the Qinghai Lake was about 3–6 m (Jin et al. 2010) and it is 2.5 m in the ASSt site, thus it is likely to have a major effect on the soil moisture at 60–100 cm (Zhu 2014). The soil characteristics had a significant influence on the soil moisture. The total soil porosity, soil organic matter, and $W_f$ of the A horizon in the PFSh site were the highest of all sites. The unsaturated hydraulic conductivity of soil in the PFSh site was significantly higher than in the KMd and ASSt sites (Hu et al. 2016), which may explain the higher infiltration in the PFSh site. Higher $W_f$ and infiltration meant that soil in the PFSh site could hold more water in the A horizon after rainfall. The compacted B horizon with high bulk density in the PFSh and KMd sites would reduce the seepage and maintain an udic moisture regime.

Surface runoff in the three experimental sites was quite low. The reported runoff coefficient in the alpine meadow, alpine shrub meadow, and alpine steppe site were 0.50%, 0.10%, and 1.34% (Chen et al. 2014; Jiang et al. 2017). There could be quite small differences in the surface runoff amount in the three sites. What played a more important role on the soil moisture could be the subsurface flow in the slopes (Chen et al. 2014). The $P. \text{fruticosa}$ shrub was mainly distributed in the middle or bottom of slopes, and the PFSh site could reach runoff and subsurface flow from the upper slopes, which brought higher soil water storage changes after rainfall in this site. At the ASSt site located in the flat lakeside plain with groundwater level of about 2.5 m, there could be little subsurface flow. High soil moisture in the PFSh site could have a positive feedback to the soil moisture. In the seasonal frozen and thawed soil, higher soil moisture would result in lower infiltration capacity due to lower hydraulic conductivity (Zheng & Fan 2000). Low infiltration capacity in the PFSh site could retard the vertical drain and retain the high soil moisture.

The vegetation cover is another key factor affecting infiltration. $P. \text{fruticosa}$ is a chamaephyte functional group, and has much more aboveground biomass than $Kobresia$, especially in winter and spring when the aboveground biomass of herbs is consumed by domestic animals. The more aboveground biomass in the PFSh site could intercept more rainfall; however, it could have a more positive influence on soil moisture due to its improvement in the soil property. The dense stems of $P. \text{fruticosa}$ could protect the ground against animal treading, resulting in increased surface litter, higher soil organic matter, a lower bulk density and higher porosity at 10 cm soil depth than in the KMd site (Table 2). The mat-forming herbs in the KMd site have dense root systems and substantial belowground biomass (Table 1, Figure 2), which could impede rain infiltration (Wang et al. 2007). Conversely, the $P. \text{fruticosa}$ shrub patch has less dense roots (Table 1, Figure 2), and the living and dead shrub root architecture could result in a large number of macrospores (Hu et al. 2016) and preferential water flow into the deep soil layer (Zhang et al. 2012). As described above, the $Kobresia$ is adapted to a relatively cold and wet climate with low soil temperature, high soil moisture, and moderate infiltration. Similarly, the $P. \text{fruticosa}$ shrub is adapted to a relatively cold and wet climate with low soil temperature, high soil moisture, but with high infiltration. In contrast, the $A. \text{splendens}$ was adapted to a relatively warm and dry climate, with high soil temperature, low soil moisture, and low infiltration.

The surface temperature of the Qinghai-Tibet Plateau is projected to increase by as much as 4.9 °C in 2100 under the RCP 4.5 climatic scenario (IPCC 2014). Higher temperatures increase the moisture-holding capacity of the atmosphere and can lead to greater atmospheric demand for evapotranspiration (Weiss et al. 2009; Liu & Zhang 2013). Increases in precipitation or atmospheric humidity ameliorate this enhanced demand, whereas decreases exacerbate it. A future warming climate is likely to lead to degradation of the alpine meadows (Zhao et al. 2011), largely because warming climate increases soil temperature, and higher temperatures increase evapotranspiration demand. However, we found that rainfall infiltration was low in the KMd site; therefore, soil moisture would decrease and drought would often occur. Higher soil temperature and lower soil moisture changes the habitat of the alpine meadows and results in their decline. The degraded meadows
are expected to have a higher infiltration rate (Wang et al. 2007) and the soil moisture would reach a new balance with lower vegetation cover and decreased belowground biomass density. In the alpine shrubland (e.g., PFSh), the high plant coverage and soil moisture would slow down the response of the soil to climatic warming by insulating the soil against warm air and because of the greater water-holding capacity of its root zone (0–40 cm) (Wang et al. 2009, 2012). Furthermore, the high infiltration in these sites would provide soil moisture with sufficient water supplement even if the evapotranspiration increased. Thus, the alpine shrubland is likely to expand in the warming future, as reported by Zhao et al. (2011). The ASSt sites are mostly located along the Qinghai Lake within an area of 1.5 m depth groundwater depth (Zhang 2014), and the soil moisture at the depths of 60 and 100 cm were relatively high (Figure 8). Under a warming future, drought is likely to occur here more often; however, considering that the *A. splendens* could use water in deep soil layers with deep roots (Wu et al. 2015) and the capillary soil water flows from the local shallow groundwater table, the ASSt ecosystem would not deteriorate. It may even expand to the valley along the river with a shallow groundwater table; however, other herbs that are unable to access the groundwater resource are likely to degrade in the ASSt site.

**CONCLUSION**

The results of this study demonstrate the effect of topographies, soil properties, and biotic features on soil temperature and moisture. Topographic factors resulted in higher soil temperature and lower soil moisture in the ASSt site. In the ASSt site, high air and soil temperature increased evapotranspiration demand, which led to lower soil moisture and lower precipitation. This correspondingly resulted in reduced plant coverage and *LAI*, which redoubled the solar radiation and air temperature. Higher elevation, along with lower air temperature and increased precipitation resulted in lower soil temperature and higher soil moisture in the KMd and PFSh sites. Increased plant coverage and *LAI* in the KMd and PFSh sites would reflect more air temperature and solar radiation, and reduced soil warming in the growing season. The long-lasting frozen period in the KMd and PFSh sites reduced soil water consumption in winter, and maintained high soil moisture after the soil thawed. Higher infiltration beneath the shrubs than in the dense mat-forming meadow resulted in the highest soil moisture in the PFSh site. Under a future warming climate, soil temperature and evapotranspiration demand are likely to increase in all ecosystems. The KMd ecosystem might face water stress as a result of the limited rain infiltration and would thus deteriorate in the future. The PFSh ecosystem could withstand the climate impact because of its high plant coverage and soil water content, and thus may expand in the warming future. The ASSt ecosystem is likely to be affected by climate warming and the plants with shallow root systems in the ASSt site would face strong water stress and would degrade.

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