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Original Articles

Alpine shrub had a stronger soil water retention capacity than the alpine meadow on the northeastern Qinghai-Tibetan Plateau

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ABSTRACT

Soil water retention capacity is an essential component of the land surface processes and hydrological cycles. Although the effect of grassland degradation on soil water retention capacity have been well documented, few studies have focused on how soil hydrological properties vary between different vegetation types on the Qinghai-Tibet Plateau (QTP). This study selected three vegetation types: *Potentilla fruticosa* shrub (PFS), *Kobresia pygmaca* meadow (KPM), and *Kobresia humilis* meadow (KHM), and aimed to explore the variations and factors controlling soil water retention capacity across the three types. Results showed that the soil water retention capacity was higher in PFS than in KPM and KHM across 0–40 cm, whereas the 0–30 cm plant available water content was much lower in PFS than in KPM and KHM. Meanwhile, the soil properties within the different soil layers varied significantly between vegetation types. The 0–10 cm clay and silt contents were significantly higher in PFS than in the other two vegetation types, whereas the soil bulk density (BD) was lower in PFS than in KHM and KPM. Furthermore, the 0–50 cm soil capillary porosity (CP) was significantly higher in PFS than in KPM and KHM, except at 0–10 cm. Besides, the 0–10 cm soil organic matter (SOM) was significantly higher in KPM than in PFS and KHM, owing to its highest root biomass. Overall, the soil water retention capacity was most strongly influenced by CP, followed by BD, TP, SOM and root biomass, whereas the soil non-capillary porosity and soil particle size distribution exerted no significant impact on soil water retention capacity. Our results suggested that the alpine shrub had a stronger soil water retention capacity than the alpine meadow.

1. Introduction

Soil water retention capacity is an essential component of the land surface processes and hydrological cycles that are closely related to plant growth (Bens et al., 2007; Weng and Luo, 2008), through its influences on nutrient cycling, carbon allocation and the rate of photosynthesis (Minasny and Mcbratney, 2018). However, soil water retention capacity is strongly spatially and temporally heterogeneous (Ma et al., 2016), and is controlled by many factors, such as topography (Qiu et al., 2001; Yu et al., 2018; Sun et al., 2019), soil properties (Saxton and Rawls, 2006; Yang et al., 2014), and particularly the vegetation type (Deng et al., 2016; Mei et al., 2018). Furthermore, the growth of plant roots also plays a vital role in modifying soil hydraulic conductivity via altering soil pore space and hence modified soil hydraulic conductivity (Ni et al., 2019; Ng et al., 2019). Although the effect of vegetation type on soil water retention capacity have been widely reported (Peng et al., 2019; Wang et al., 2013), most previous studies were mainly conducted on arid and semi-arid region (Li et al., 2015; Pariente, 2002; Zhang et al., 2011), with little attention paid to comparing the soil water retention among different vegetation types of alpine ecosystems in Qinghai-Tibet Plateau (QTP).

The Qinghai Tibetan Plateau (QTP) as the highest plateau in the world, and covers an area of 2.5×10^6 km^2, almost 60% of which is covered by a grassland ecosystem (Dong et al., 2020). Meanwhile, the QTP is also the headwater region of many of Asia's largest rivers, which play an important role in water supply in China and Southeast Asia (Dai

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et al., 2020a; Yang et al., 2014). Compared to arid and semi-arid region, the alpine ecosystem was featured by low temperature, short growing season and high solar radiation, thus the soil water retention capacity in QTP displays a different pattern and controlling owing to its unique environment. Previous study had reported that the soil organic matter in alpine ecosystem was much abundance due to its lower decomposition rate, and soil organic matter is an important parameter in controlling soil water retention capacity (Dai et al., 2020a;Yang et al., 2014). In recent year, numerous studies have been examined the variations and controls of soil water retention capacity in alpine ecosystems. For example, Pan et al. (2017) found that soil water retention capacity was strongly affected by grassland degradation, and that the soil moisture content and field capacity both decreased as the degree of alpine grassland degradation increased. Dai et al. (2020b) documented that soil water retention capacity in degraded grassland is strongly determined by soil organic matter, while soil texture exerts only weak impacts on soil water retention. However, yet most of these previous studies have focused on the effect of grassland degradation on soil water retention capacity. It was widely reported that the soil water retention capacity varies between different vegetation types (Li et al., 2015; Pariente, 2002; Zhang et al., 2011). For instance, Li et al. (2015) found that alpine *Potentilla fruticosa* shrub has higher soil water retention than alpine *Kobresia humilis* meadow. Zhang et al. (2011) reported that forested ecosystems display greater soil water retention capacity than shrub ecosystems owing to the thick humus in forests. Thus, there is an urgent need to examine soil water retention variations in different vegetation types in QTP, to provide a better understanding of the sustainable management of water and land resources and to support the management of soil–water conservation in alpine ecosystems.

To investigate the variation in soil water retention across different vegetation types in QTP, three vegetation types (i.e. *Potentilla fruticosa* shrub, *Kobresia pygmaca* meadow, and *Kobresia humilis* meadow) were selected. Furthermore, the soil water retention curve (SWRC) was used to depict the soil water retention capacity by capturing the relationship between soil water potential and soil water content (Or et al., 2002). In this study, we aim to (1) compare soil water retention capacity among three vegetation types (2) explore the mainly factors controlling soil water retention capacity.

2. Materials and methods

2.1. Study area

The study was conducted at Haibei National Field Research Station, Qinghai, China (101°19′E, 37°37′N, 3200 m a.s.l.) in the northeastern Qinghai-Tibet Plateau (Fig. 1). Climate in the study area is classified as a plateau continental monsoon climate. The mean annual precipitation at the study site is approximately 562 mm, of which 80% falls during the growing season (i.e., from May to September), the mean annual air temperature is approximately −1.7 °C, with a maximum monthly temperature of 9.8 °C in July and a minimum monthly temperature of −14.8 °C in January (Dai et al., 2019). The soil belongs to Mollic Gryic Cambisols, the thickness of the soil layer is approximately 50–70 cm and the surface layer contains abundant soil organic matter. In this study, three representative vegetation types (*Potentilla fruticosa* shrub meadow, *Kobresia humilis* meadow and *Kobresia pygmaca* meadow) were selected to examine differences in soil water retention across different vegetation types. The *Potentilla fruticosa* shrub vegetation type was dominated by

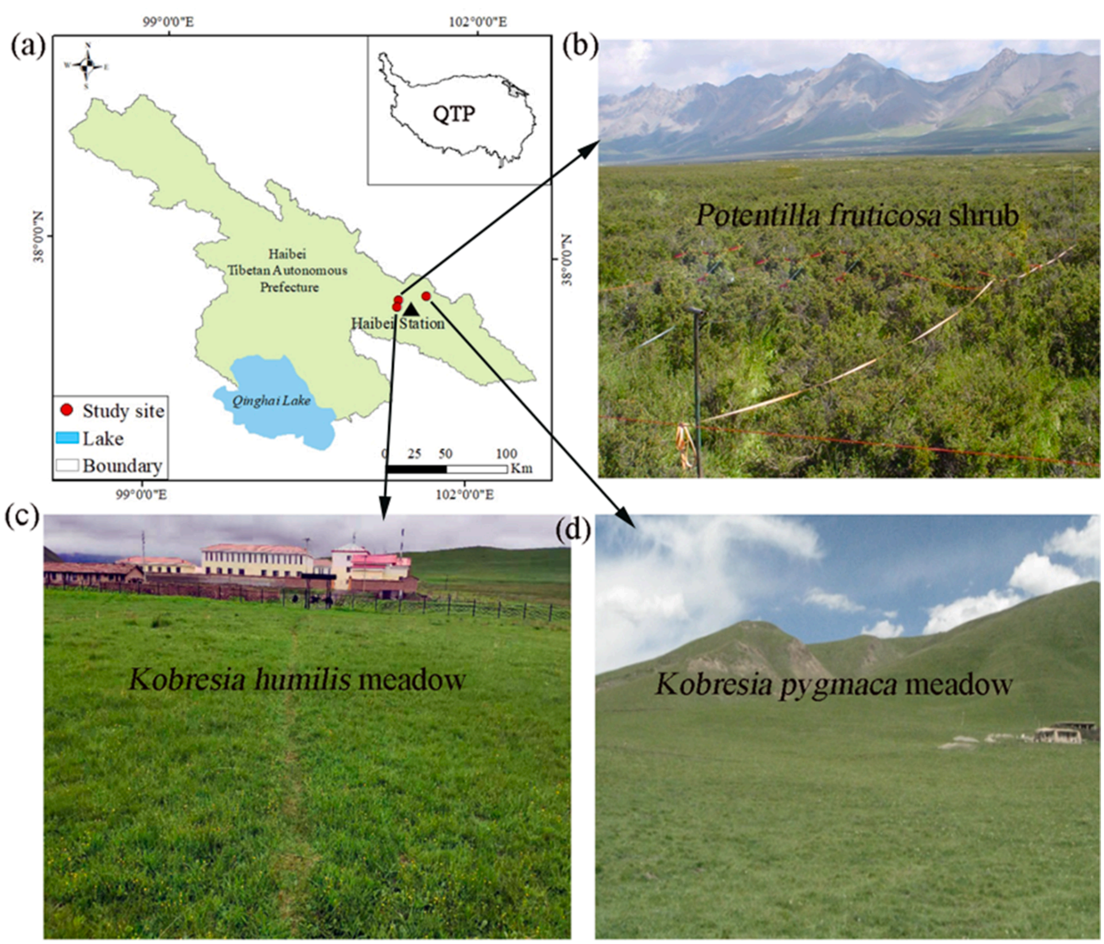

Fig. 1. The study sites and three vegetation types.

Potentilla fruticosa, covering 70 ~ 80%, and reached an average height of about 30 ~ 50 cm, the *Kobresia humilis* meadow vegetation type was dominated by *Kobresia humilis*, and auxiliary species included *Stipa aliena*, *Elymus nutans*, *Poa annua*, *Gentiana straminea*, and others, the *Kobresia pygmaca* meadow was dominated by *Kobresia pygmaca*, and auxiliary species included *Stipa aliena, Saussurea pulchra, Elymus nutans and Leontopodium nanum* (Li et al., 2021).The three vegetation types were grazing exclusion by through the use of mesh fencing, and all located in relatively flat ground and sunny slopes to avoid other factors effect on soil water retention capacity.

2.2. Soil and plant sampling

Given that the root systems of the three vegetation types are mainly distributed in the soil layer above 50 cm, undisturbed soil samples were collected from the 0 to 50 cm layer at depths of 0–10, 10–20, 20–30, 30–40 and 40–50 cm, at four points randomly distributed across each of the three vegetation types, at the end of August 2019. Undisturbed soil was collected by a soil bulk sampler with a stainless steel cutting ring (5.0 cm diameter × 5.0 cm high), and analyzed for soil bulk density (BD), soil porosity and hydraulic properties such as saturation moisture capacity (SMC) and capillary moisture capacity (CMC). First, undisturbed soil samples (collected as ring cores) were taken back to the laboratory, saturated with tap water for 48 hr, and weighed to give M1 (g). The samples were then placed in a flat container filled with dry sand at the bottom, left for 2 hr, and weighed again to give M2 (g). The samples were saturated again, and transferred to a pressure plate apparatus (1500 F1, Soil Moisture Equipment Corp., SEC, U.S.) to obtain the soil water content at −30, −50, −100, −200, −300, −450, −800, −1200 and −1500 kPa. Next, the samples were oven dried at 105 °C for 72 hr to constant mass, and weighed again to give M3 (g). Finally, the dried soil was washed through 0.25 and 2 mm sieves, impurities were picked out, and the samples were analyzed for their soil physical and chemical properties such as soil organic matter (SOM), carbon nitrogen ratio, and soil particle size distribution. The SOM was determined by the Walkley & Black procedure (Nelson, 1996), and the soil particle distribution was measured using a MasterSizer 2000 to obtain the clay (<0.002 mm), silt (0.002–0.02 mm) and sand (0.02–2 mm) contents based on the International Classification Standard (Peng et al., 2014).

To investigate the impact of plant biomass on soil water retention, both aboveground biomass (AGB) and belowground biomass (BGB) were collected across the three vegetation types at the end of August 2019. The AGB was measured following the standard harvesting method, by randomly throwing three 25 cm × 25 cm quadrats for alpine meadow and 1 m × 1 m quadrats for alpine shurb. The BGB was measured by extracting soil cores (diameter 7 cm) in each quadrat at depths of 0–10, 10–20, 20–30, 30–40 and 40–50 cm; these were washed with clean water to remove all soil particles. Finally, both ABG and BGB samples were oven-dried to constant weight at 65 °C.

2.3. Laboratory measurements and analyses

The soil bulk density (BD, g cm^3), saturation moisture capacity (SMC, %) and capillary moisture capacity (CMC, %) were calculated by the following equations (Cui et al., 2019):

$$BD = \frac{M_3 - M}{V}$$

$$SMC = \frac{M_1 - (M_3 - M)}{M_3 - M}$$

$$CMC = \frac{M_2 - (M_3 - M)}{M_3 - M}$$

where V is the volume of the steel ring core (cm^3), and M is the weight of the empty steel ring core (g).

The soil total porosity (TP; %), soil capillary porosity (CP; %), and soil non-capillary porosity (NCP; %) were calculated as follows (Jiao et al., 2011):

$$TP = \left(1 - \frac{BD}{ds}\right) \times 100$$

$$CP = CMC \times \frac{BD}{V} \times 100$$

$$NCP = TP - CP$$

where BD is soil bulk density, ds is the soil particle density (2.65 g cm^{-3}), CMC is capillary moisture capacity (%), and V is the volume of the steel ring core (cm^3).

The soil water storage (SWS; mm) was calculated as follows (Wu et al., 2019):

$$SWS = h \times \theta \times BD \times 10^{-1}$$

where h is the soil depth (Hejcman et al., 2010), θ is the soil gravimetric water content (%), BD is the soil bulk density (g cm^{-3}), and 10^{-1} (mm/cm) is a unit conversion factor.

The soil water characteristic curves (SWCCs) describe the relationship between soil water potential and soil water content at −30, −50, −100, −200, −300, −450, −800, −1200 and −1500 kPa pressure. In this study, the field capacity (FC) and wilting water content (WC) can be regarded as the soil water content at −30 and −1500 kPa, respectively. Thus, the plant available water content (PAWC) is the difference between field capacity (FC) and wilting water content (WC). To quantitatively compare the soil water retention among the three vegetation types, the Gardner model was used to fit the soil water retention curve (Gardner et al., 1970). The formula is as follows:

$$h = A\theta^{-B}$$

where θ is matric potential (kPa), h is the soil water content (%), and A and B are the fitting parameters; a higher value of A indicated a higher soil water retention .

2.4. Statistical analysis

Multi-way ANOVA analysis was used to analyze the effect of root biomass and soil characteristics on soil water retention capacity, the differences in plant biomass and soil characteristics among the different vegetation types was examined by one-way ANOVA analysis, then followed by the least significant difference (LSD) test to analyze when the results of ANOVA were significant at $P < 0.05$. Furthermore, Pearson correlation and partitions variance were used to examine the correlation between hydraulic properties and soil characteristics, with aim of revealing the dominant factors controlling soil water retention across three vegetation types. All data analysis was carried out using R software version 3.4.3 (R Development Core Team, 2006), and all graphs were produced using Origin (OriginPro 19, USA) and was presented as mean ± SE (standard error).

3. Results

3.1. Aboveground biomass and root biomass

The aboveground biomass in KHM (377.80 ± 27.01 g m^{-2}) was significantly higher than that in PFS (245.74 ± 10.74 g m^{-2}) and KPM (194.51 ± 9.84 g m^{-2}) (Fig. 2a). However, the 0–10 cm root biomass in KPM (4353.89 ± 510.83 g m^{-2}) was significantly higher than that in PFS (2126.42 ± 291.38 g m^{-2}) and KHM (1791.68 ± 176.95 g m^{-2}), whereas 20–40 cm root biomass was higher in PFS than in KPM and KHM. Furthermore, the root biomass declined sharply with depth, with most root biomass distributed in the top 0–10 cm (Fig. 2b).

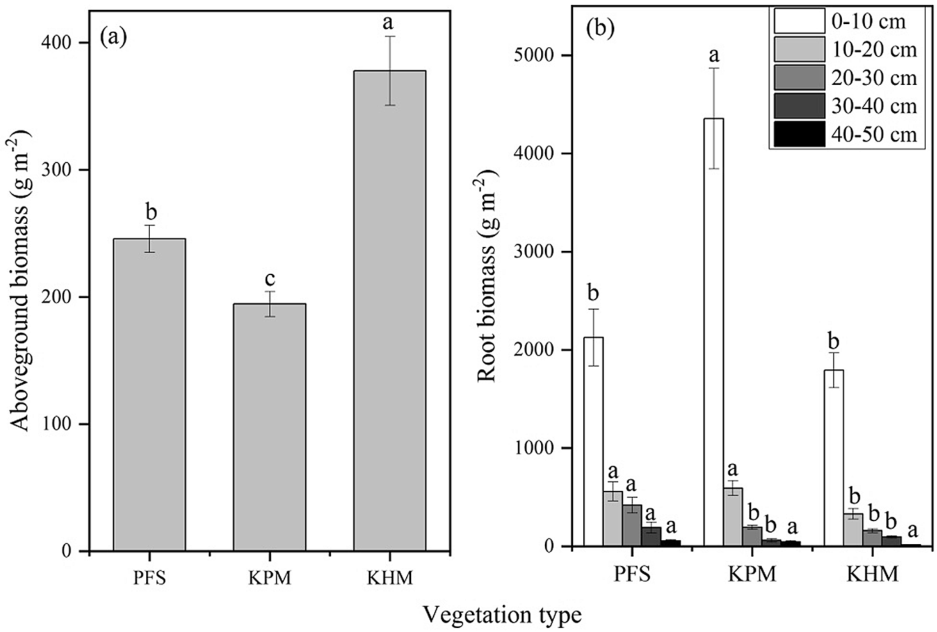

Fig. 2. Aboveground biomass (a) and root biomass (b) across three vegetation types.Values are in the form of the Mean ± SE, and the sample size n = 4, different lowercase mean significant differences in the same soil layers at different vegetation, the same below.

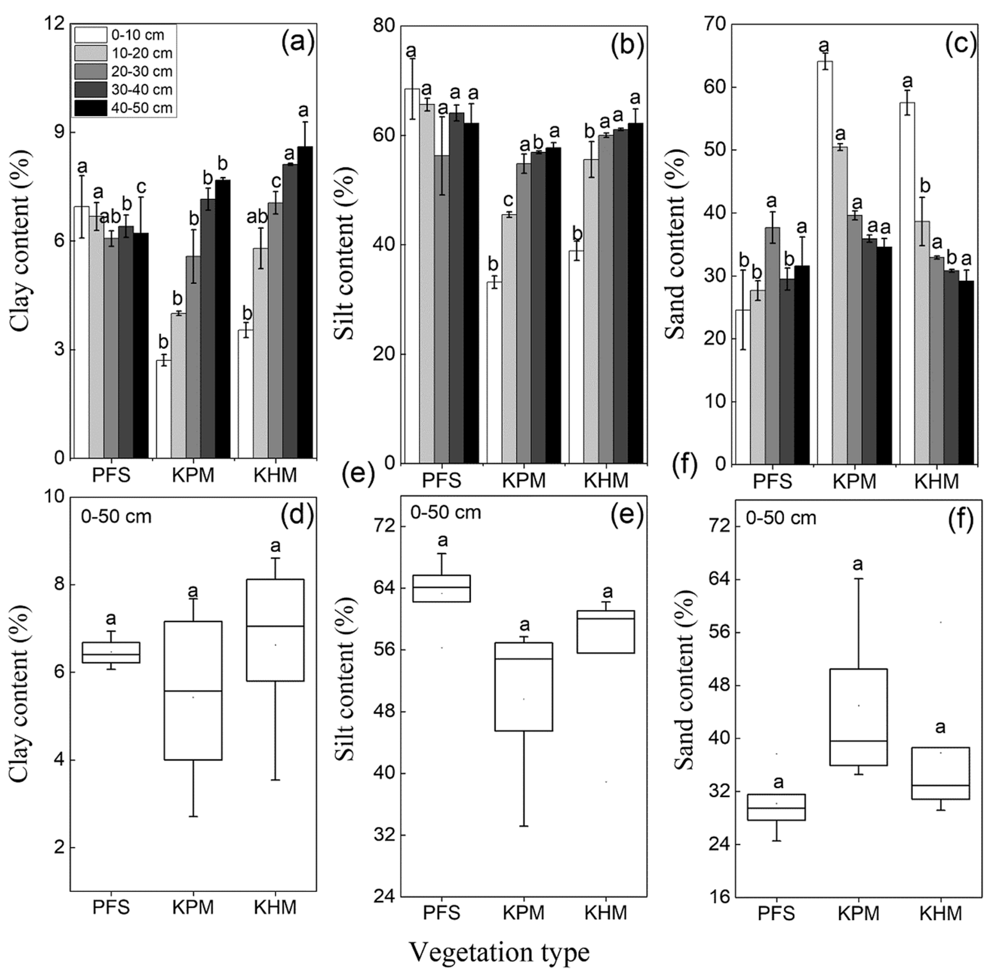

Fig. 3. The content of clay (<0.002 mm), silt (0.002–0.02 mm) and sand (0.02–2 mm)across three vegetation types at different soil layers.

3.2. Soil particle size distribution

Silt (0.002–0.02 mm) was the dominant component in the top 0–50 cm across all three vegetation types (mean 56.17%), followed by sand (0.02–2 mm; mean 37.64%) and clay (<0.002 mm; mean 6.19%), which was classified into silt loams(Fig. 3). There was no significant difference amongst the three vegetation types when analyzing the complete 0–50 cm soil profile, but the clay, silt and sand contents within the individual soil layers varied significantly between vegetation types (Fig. 3). Specifically, the 0–20 cm clay and silt content was higher in PFS than in KHM and KPM, especially for 0–10 cm ($P < 0.05$), while the 0–20 cm sand content was lower in PFS than in KHM and KPM. However, the 20–50 cm clay content was higher in KHM than in KPM and PFS. Overall, the clay and silt contents in KHM and KPM increased sharply with soil depth, while sand content decreased (Fig. 3), whereas in PFS the clay and silt contents decreased with soil depth while sand content increased.

3.3. Soil physicochemical properties

The soil properties within the different soil layers varied significantly between vegetation types (Fig. 4). The 0–50 cm soil bulk density was lower in PFS (0.89 g cm^{-3}) than in KHM (0.99 g cm^{-3}) and KPM (1.02 g cm^{-3}) (Fig. 4a), whereas 0–50 cm soil total porosity in PFS (66.22%) was higher than KHM (62.55%) and KPM (61.54%) (Fig. 4b). Furthermore, the 0–50 cm soil capillary porosity was significantly higher in PFS than in KHM and KPM, except for 0–10 cm (Fig. 4c), whereas 0–50 cm non-capillary porosity was significantly lower in PFS than in KHM and KPM (Fig. 4d).

In addition, the soil organic matter and C: N ratio varied significantly between vegetation types. The 0–10 cm soil organic matter (142.47 g kg^{-1}) in KPM was higher than in KHM (108.84 g kg^{-1}) and PFS (129.05 g kg^{-1}), whereas the 10–50 cm soil organic matter washigher in PFS than in KPM (Fig. 4e). The C: N ratio of the 0–20 cm soil layer showed no significant difference between vegetation types, whereas the 20–50 cm C: N ratio was significantly lower in PFS than in KPM and KHM (Fig. 4f). Overall, the soil bulk density increased with soil depth, while soil total porosity and soil capillary porosity decreased with soil depth, the soil organic matter was mainly distributed in the top 10 cm soil layer and decreased sharply with soil depth across all three vegetation types.

3.4. Soil water retention across three vegetation types

The Gardner model was sufficient for simulating the soil moisture curves across three vegetation types, and yielded a high correlation coefficient R^2 (Fig. 5). Parameter A indicated the soil water retention capacity. Soil water retention capacity decreased in the order PFS > KHM > KPM in the 0–10 cm layer, PFS > KPM > KHM in the 10–40 cm layer, and KPM > PFS > KHM in the 40–50 cm layer. The rate of decrease in 0–20 cm soil water content capacity with decreasing soil suction, as quantified by parameter B, decreased in the order KPM > KHM > PFS. Overall, the PFS had stronger soil water retention capacity than KPM and KHM, except at 40–50 cm. Furthermore, the 0–50 cm saturated water storage, capillary water storage and field water storage in PFS were higher than those in KPM and KHM, whereas the 0–30 cm plant available water storage was much lower in PFS than in KPM and KHM (Fig. 6).

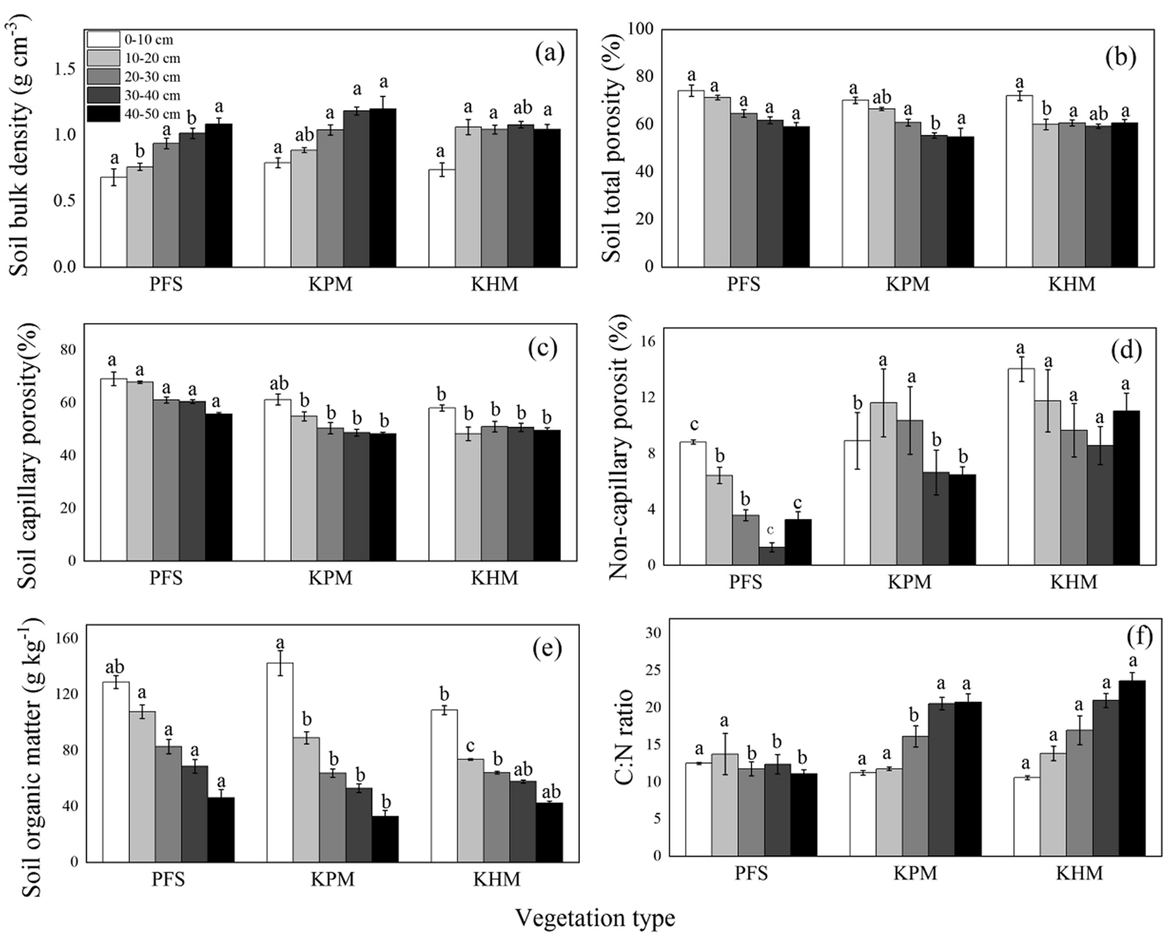

Fig. 4. Soil bulk density(a), soil total porosity (b), soil capillary porosity (c) and non-capillary porosity (d) , soil organic matter (e) and C: N ratio (f) across three vegetation types at different soil layers.

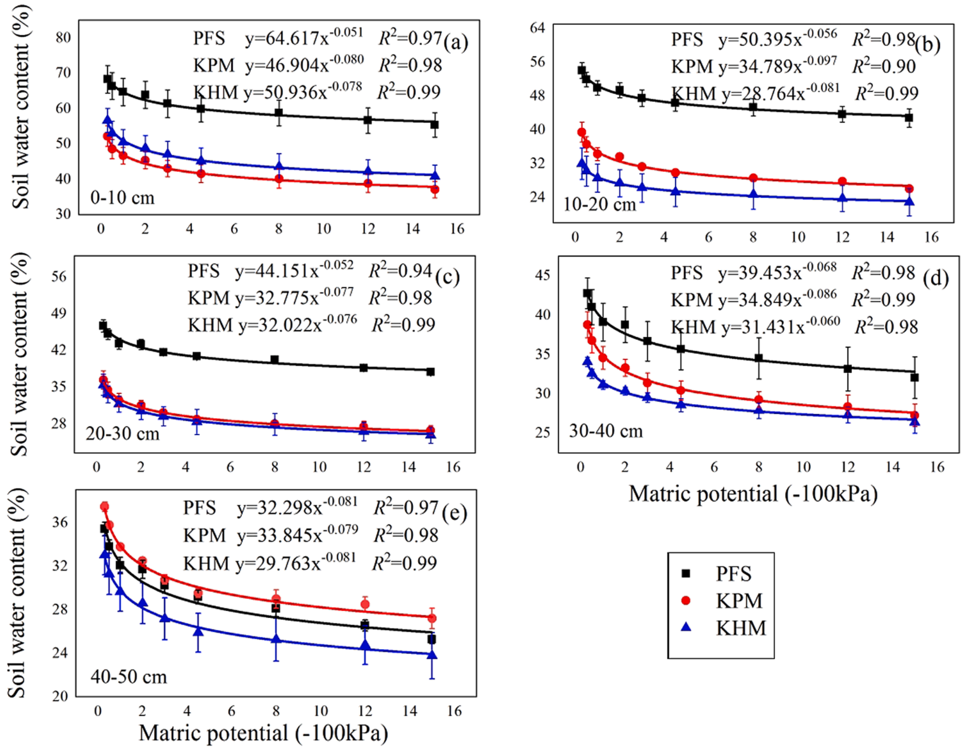

Fig. 5. Soil water retention curve of different soil layer across three vegetation types at different soil layers.

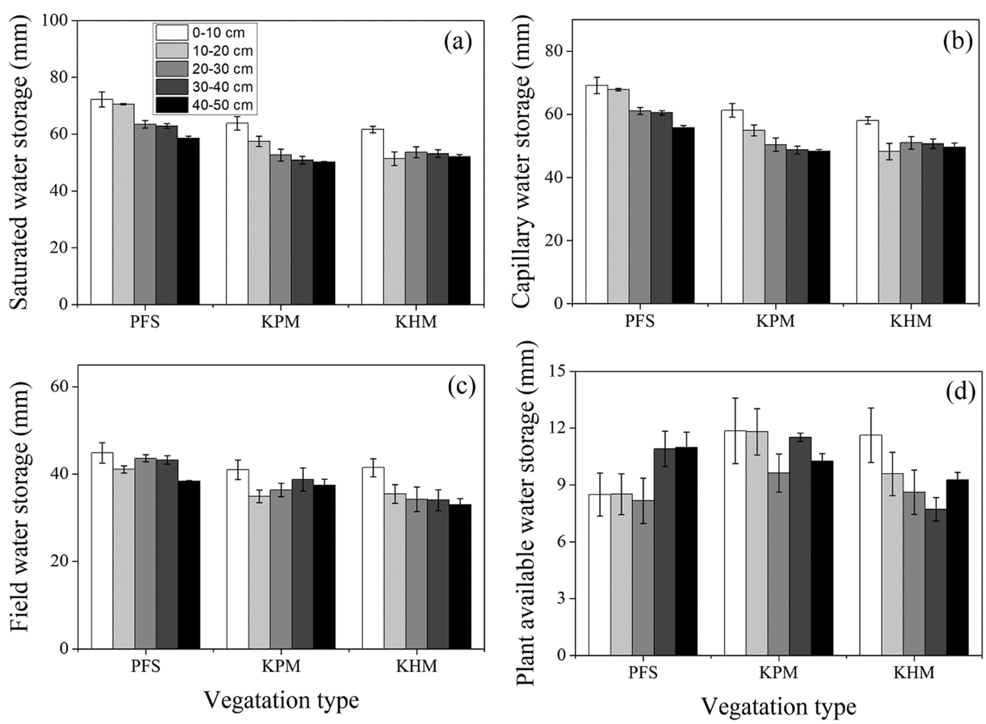

Fig. 6. Saturated water storage, capillary water storage, field water storage and plant available water storage across three vegetation types at different soil layers.

3.5. Relationships between soil water retention capacity and soil properties

The multi-way ANOVA analysis indicated that soil water retention capacity was significant affected by root biomass, soil organic matter and soil capillary porosity (Table 1). Pearson correlation analysis shows that soil water retention capacity (i.e., parameter A) was significantly positively related to root biomass, soil organic matter, soil total porosity and capillary porosity, but significantly negatively related to soil bulk density (Fig. 7a). Furthermore, the soil water retention capacity was mainly controlled by soil capillary porosity, which accounted for 21.30% of total variance, followed by soil bulk density (18.50%), soil

Table 1
Multi-way ANOVA analysis about effect of root biomass and soil characteristics on soil water retention capacity.

Parameter	*df*	*F*	*P*-value
RBSOM	1	24.25	0.001**
	1	17.28	0.002**
BDTPCP	1	3.78	0.084
	1	0.027	0.874
	1	5.96	0.037*

Note: RB, root biomass; SOM, soil organic matter ; BD, Soil bulk density; TP, soil total porosity; CP, soil capillary porosity.

total porosity (18.50%), soil organic matter (18.09%) and root biomass (10.54%), whereas non-capillary porosity and soil particle size distribution exerted no significant impact on soil water retention capacity (Fig. 7).

4. Discussion

4.1. Variation in soil properties among three vegetation types

We found that soil properties within the different soil layers varied significantly between vegetation types. For instance, the 0–10 cm soil organic matter was higher in KPM than in KHM and PFS (Fig. 4e), which was attributed to the specific biological characteristics (e.g., higher root: shoot ratio) in KPM, this was confirmed by the much higher 0–10 cm root biomass in KPM than in KHM and PFS (Fig. 2b), resulting in higher 0–10 cm soil organic matter in KPM. Furthermore, *Kobresia pygmaca* thrives in cold, dry climates and is a short-rhizome underground bud plant. Its dense growth readily forms a dense mattic epipedon, leading to abundant soil organic matter in the topsoil (Lin et al., 2015). In addition, the 20–50 cm soil C: N ratio was significantly lower in PFS than in KHM and KPM (Fig. 4f). Given that soil C: N ratio is an important indicator of soil organic matter type and decomposition rate (Yang et al., 2014), a lower soil C: N ratio was linked to a higher decomposition rate. We can infer that PFS has a stronger soil humification and nitrogen mineralization ability in the 20–50 cm soil layer, when compared to that in KHM and KPM. Meanwhile, the soil C:N ratio in PFS displayed only a slight decrease with depth, whereas the soil C:N ratio in KHM and KPM increased sharply with soil depth, indicating that the soil humification and nitrogen mineralization ability in deep soil were limited by N in KHM and KPM.

Furthermore, the 0–40 cm soil bulk density was lower in PFS than in KHM and KPM, whereas the soil capillary porosity was higher in PFS than in KHM and KPM (Fig. 5). Such differences may relate to the deeper roots in PFS than in alpine meadow. Our results suggested that the PFS could maintain more water during rainfall events. Besides, the soil texture also varied between vegetation types. We found the 0–20 cm clay content was much higher in PFS than in KHM and KPM, whereas the 30–50 cm clay content was much lower in PFS than in KHM and KPM. Meanwhile, the 0–20 cm sand content was significantly lower in PFS than in the other two vegetation types. Such higher clay content in PFS than in KHM and KPM might associated with its higher litter productivity, this suggests that the PFS contained finer particles when compared to that in meadow, by increasing clay content and reducing sand content.

4.2. Effect of environmental factors on soil water retention capacity across three vegetation types

In this study, we found a clear dependence of soil water retention capacity on vegetation type (Fig. 5). The soil water retention capacity was higher in PFS than in KPM and KHM, except at 40–50 cm; this pattern was consistent with a previous study in which alpine PFS had a higher soil water retention capacity than alpine KHM (Li et al., 2015). The higher soil water retention capacity in PFS may be associated with its higher soil capillary porosity than in KHM and KPM. In this study, we found that soil water retention capacity was mainly affected by the soil capillary porosity, followed by soil total porosity and soil organic matter, whereas the soil particle size distribution exerted no significant influence on soil water retention capacity (Fig. 7). Such results were also reported in previous studies conducted in degradation grassland, where soil water retention capacity was more strongly affected by soil organic matter than by soil particle size distribution (Dai et al., 2020b; Yang et al., 2014), even though soil particle size distribution is often regarded as an important driver of soil water retention properties (Zhuang et al., 2001). The weak effect of soil particle size distribution on soil water retention capacity was attributed to the lower soil clay content but higher soil organic matter. Several studies have reported that soil water retention capacity is mainly determined by soil particle size distribution when the soil organic matter is<8% (Rawls et al., 2003; Saxton and Rawls, 2006), and the soil water retention capacity is mainly controlled by soil organic matter in sandy soils with little or no clay (Jamison and Vernon, 1953). In this study, the clay content only ranged from 2.70 to

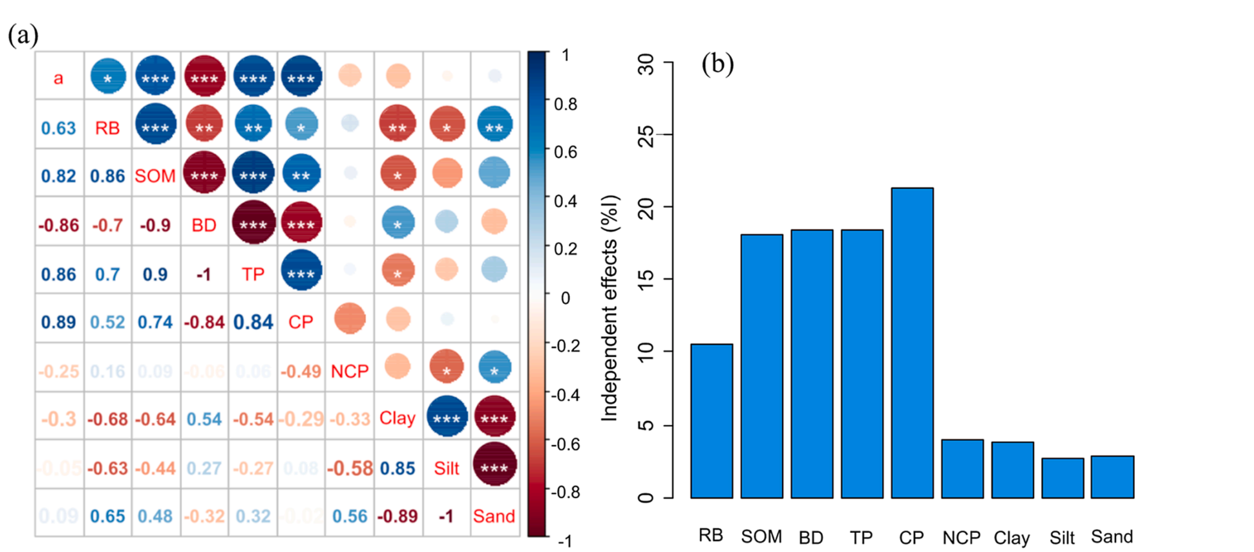

Fig. 7. Pearson correlation coefficient between soil water retention and soil properties (a), and the independent relative effects of properties on soil water retention (b). Note: A: the parameter fitted by Gardner model, represent soil water retention capacity, RB: root biomass, BD: soil bulk density, SOM: soil organic matter, TP: soil total porosity, CP: soil capillary porosity, NCP: soil non-capillary porosity, "*", "**" and "***" significant at 0.05, 0.01 and 0.001 level, respectively.

8.6% (mean 6.19%), whereas the soil organic matter was more than 10%; therefore, it was no surprise that the soil particle size distribution exerted no significant influence on soil water retention capacity while soil organic matter showed a strong influence. The impact of soil organic matter on soil water retention capacity was largely mediated by two processes. First, the soil organic matter can directly reduce soil bulk density, thereby increasing soil porosity, owing to the dilution of the soil matrix with the less dense organic material (Minasny and Mcbratney, 2018). Second, the soil organic matter can improve aggregation and soil structure, and increase soil biotic activity and water retention capacity (Lal, 2004).

Furthermore, the growth of plant roots also plays a vital role in modifing soil hydraulic conductivity via altering soil pore space and hence modified soil hydraulic conductivity (Leung et al., 2015). For instance, the formation of soil macro-pores (i.e., increase in void ratio) induced by root shrinkage upon decay was often lead to a decrease in soil water retention (Ni et al., 2019; Leung et al., 2015). Given PFS has a thicker root system and less susceptible to decay relative to the alpine meadow, thus the soil water retention capacity in PFS was higher than in KHM and KPM. In contrast, the available water content of the 0–30 cm soil layer was lower in PFS than in the other two vegetation types. Our results suggested that the plants in PFS may be more susceptible to water stress than plants in KPM and KHM, especially considering that almost 90% of the roots in PFS were confined to the 0–30 cm soil layer. The lower plant available water content in PFS was attributed to the higher wilting water content, although the soil volumetric water content was maintained at 32.81% even at −1500 kPa (wilting coefficient pressure). Considering the variations in soil hydrological properties across different vegetation types is rather complex process. In this study, we only consider root biomass and soil properties on soil water retention capacity, more root properties (e.g., root length density, root volume density, etc) and model should be considered in soil water retention capacity in future study.

5. Conclusion

The soil water retention capacity within the different soil layers varied between vegetation type, we found the soil water retention capacity was much higher in PFS than in KPM and KHM, owing to the higher soil capillary porosity in PFS. However, the 0–30 cm plant available water content was much lower in PFS than in KHM and KPM, suggesting that plants in PFS may be more susceptible to water stress than those in KPM and KHM. Overall, the soil water retention capacity was most strongly influenced by CP, followed by SOM, BD and TP, whereas the soil non-capillary porosity and soil particle size distribution exerted no significant impact on soil water retention capacity. Our results could provide new insights to support grassland management strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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