Variation of soil hydraulic properties with alpine grassland degradation in the Eastern Tibetan Plateau

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Abstract. Ecosystems in alpine mountainous regions are usually more vulnerable and easily be disturbed by environmental change globally. Alpine swamp meadow, a unique grassland type in the eastern Tibetan Plateau which provides important ecosystem services to the upstream and downstream regions of international rivers of Asia even the world, is undergoing severe degradation, which can dramatically alter the soil hydraulic properties and water cycling processes. However, the effects of alpine swamp meadow degradation on soil hydraulic properties and the corresponding influencing mechanisms are still poorly understood. In this study, soil moisture content (SMC), field capacity (FC) and saturated hydraulic conductivity (Ks) together with several basic soil properties under light degraded (LD), moderate degraded (MD) and severe degraded (SD) alpine swamp meadow were investigated. Then the variation of SMC, FC and Ks with alpine swamp meadow degradation and their dominant influencing factors were analyzed. The results show that SMC and FC decreased consistently from LD to SD, while Ks decreased from LD to MD and then increased from MD to SD, following the order of LD > SD > MD. Significant differences of soil hydraulic properties between degradation degrees were found at upper soil layers (0-20cm), indicating that the influences of degradation were most pronounced in the top soils. FC was positively correlated with capillary porosity (CP), water-stable aggregates (WSA), soil organic carbon (SOC), silt and clay content, and Ks were positively correlated with non-capillary porosity (NCP). Relative to other soil properties, soil porosity is the dominant influencing factor of FC and Ks. CP explained the 91.1% total variance of FC, and NCP explained that by 97.3% for Ks. The combined effect of vanishing root activities and increasing sand content was responsible for the inconsistent patterns of NCP and Ks. Our findings suggest that alpine swamp meadow degradation would inevitably lead to reduced water holding capacity and rainfall infiltration. This study gives out a more comprehensive understanding of the soil hydrological effects of vegetation degradation. Further hydrological modelling researches in Tibetan Plateau and similar regions are recommended to understand the effects of degraded alpine swamp meadow on soil hydraulic properties.

Key words. Soil hydraulic properties; Field Water Capacity; Saturated Hydraulic Conductivity; Alpine Swamp Meadow Degradation; Influencing factors; Tibetan Plateau

1 Introduction

Soil moisture plays a critical role in land surface processes and hydrological cycles. It not only directly participates in soil hydrological processes, but also influences vegetation growth and even modifies weather processes and local climate (Legates et al., 2011; Shein, 2010; Vereecken et al., 2015). Field capacity (FC) and saturated hydraulic conductivity (Ks) are two key soil hydraulic properties that jointly affect soil water storage, transmission and distribution (Cassel et al., 1986; Marshall et al., 2014). Knowledge of how FC and Ks vary and their influencing factors is essential for better understanding of soil hydrological processes. FC and Ks are also key parameters in most hydrological, climate and land surface models (Boluwade et al., 2013; Reszler et al., 2016; Tatsumi et al., 2015). Therefore, understanding the effects of vegetation changes on FC and Ks are necessary for model parameterization and reducing the uncertainty of simulation (Sun et al., 2016).

Soil hydraulic properties are highly heterogeneous both spatially and temporally and could respond swiftly to external changes and disturbances (Ma et al., 2016; Strudley et al., 2008). FC and Ks are mainly influenced by vegetation, soil (Pachepsky et al., 2015), topography (Leij et al., 2004), climate (Jarvis et al., 2013) and human activities (Mubarak et al., 2009; Palese et al., 2014), etc. In recent years, vegetation degradation has been widespread due to natural environmental changes and anthropogenic influences. Efforts have been devoted to revealing the effects of vegetation degradation on soil hydraulic properties across scales and ecosystem types. For forest, Lal (1996), Niemeyer et al. (2014) and Zimmermannet al. (2008) analyzed the variations of Ks along the gradient of disturbance and confirmed the increasing trend of Ks with forestation process. Krummelbein et al. (2009) investigated the effects of grazing intensity on soil hydraulic properties and revealed the variations of soil porosity and soil retention characteristics in Inner Mongolia grasslands. Recently, Fu et al. (2015) and Price et al. (2010) explored the variations of Ks with land use changes and demonstrated the decrease of Ks and the subsequent increase of overland flow resulted from deforestation or cultivation. Despite these advances, exiting studies mostly focused on low altitude areas. There are still many other regions where effects of vegetation degradation on soil hydraulic properties are inadequately studied (Vereecken, et al., 2015). This is highlighted in remote areas such as alpine mountainous regions as the cold and adverse environment, where fieldwork is time-consuming and extremely labour intensive (Bernhardt, et al., 2014; Wang, et al., 2012).

Alpine mountainous regions are widely distributed around the world, such as the Rocky Mountain Range in North America, the Andean mountain range in South America, the Alps in Europe, Mt. Kilimanjaro in Africa, the Himalayans in Tibet, and Mt. Fuji in Japan etc. These regions are often the headwaters of great rivers and supply a large amount of water to the lower reaches (Bernhardt et al., 2014; Kormann et al., 2015). Alpine grassland is one of the main ecosystem types which plays an important role for the water supply service of these regions. As the extreme environmental conditions of alpine mountainous regions, the alpine ecosystems are very vulnerable to environmental changes. Due to global climate warming and human disturbances, alpine grasslands are experiencing intense changes especially degradation, which have great influences on the soil hydrological processes. Therefore, understanding the responses of soil hydraulic properties to alpine grassland variations is of great importance (Laghari et al., 2012). For example, in central Nepal, south of the Himalayas, Ghimire et al. (2014) and Prasad et al. (2013) investigated variations in Ks with land use changes and found that reforestation of degraded pasture could substantially increase Ks in surface and subsurface layers. Leitinger et al. (2010) studied FC and soil infiltration rate of alpine pasture in the Alps and found that grazing significant decreased FC and soil infiltration rate in 0-20 cm layer, and thus altered surface runoff generation. In the Tibetan Plateau, Wang et al. (2012) confirmed that changes in alpine grassland vegetation cover will greatly altered infiltration process and hill slope runoff coefficient. Although these studies contributed to a better understanding of the effect of alpine ecosystem variations on soil hydraulic properties, they primarily addressed the change patterns of hydraulic properties. Moreover, it has been confirmed that soil physical and chemical properties, such as soil porosity, texture and organic matter content, are closely interacted with soil hydraulic properties (Fu et al., 2015; Jarviset al., 2013; Strudley et al., 2008). However, researches about the quantitative relationships between soil hydraulic properties and physiochemical properties are still relatively limited.

As the third pole and the highest place in the world, Tibetan Plateau is the headwaters region of Yangtze River, Yellow River and Mekong River, which are the world's 3rd, 5th and 7thlongest rivers, respectively. The hydrological cycling of this region has great influences on the energy and water processes of eastern Asia. Due to climate change, overgrazing, human activities and rodents, alpine meadow on the Tibetan Plateau has been severely degraded (Wang et al., 2007). Although hydrological effects of alpine meadow degradation over Tibetan Plateau have been extensively explored (Li et al., 2012; Wang et al., 2007; Wang et al., 2010; Zeng et al., 2013), large discrepancies still exist in the obtained conclusions. For example, Zeng et al. (2013) analyzed the effect of alpine meadow degradation on soil hydraulic properties using tension infiltrometers in the centre of the Tibetan Plateau and found that Ks generally decreased with degradation for both 0-10 cm and 40- 50 cm layers, but Wei et al. (2010)investigated the impact of alpine meadow degradation on soil infiltration by double-ring infiltrator in the eastern Tibetan Plateau and reported that Ks of 0-20 cm layer decreased initially and then increased. Wang et al. (2007) measured Ks of alpine steppe and alpine meadow in the source of the Yangtze River and found that Ks of the surface layers increased significantly with degradation. Yi et al. (2012) reported that FC of 0-20 cm layer was highest for non-degraded alpine meadow while Li et al. (2012) found the highest value of FC occurred at light degradation degree. These inconsistencies showed the high variability of soil hydraulic properties on the Tibetan Plateau and called for further investigations. To date, however, comparison of different change patterns of those previous studies and the underlying mechanisms are rarely reported. Besides, as a main grassland type in the eastern Tibetan Plateau, alpine swamp meadow is featured with unique terrestrial-aquatic soil and vegetation characteristics (Shang et al., 2013; Zedler et al., 2005). However, little attention has been paid to the effects of alpine swamp meadow degradation on soil hydraulic properties and the influencing mechanism. This circumstance might serve as a bottleneck for a thorough understanding of the hydrological effect of alpine grassland degradation on Tibetan Plateau.

In this research, we measured Ks, FC along with several key basic soil properties based on a series of experimental sites that represent the degradation process of alpine swamp meadow in eastern Tibetan Plateau. Several statistical methods such as redundancy analysis were used to quantitatively analyze the variation of soil hydraulic properties and its influencing factors. This study aimed to (1) investigate changes in FC and Ks associated with degradation, and (2) analyze the dominant factors and reveal the influencing mechanism of degradation on FC and Ks for alpine swamp meadow.

2 Material and methods

2.1 Site description

The experimental field (102°12'45″E, 33°46'28″N, 3435m above sea level) is located in the Zoige Wetland in the east of Tibetan Plateau(Fig.1-a). This region contains the largest area of alpine swamp in China and is the main recharge area of the Yellow River (Bai et al., 2013). In recent decades, however, a large proportion of wetland area has been converted from swamp to meadow and in some cases resulting in desertification (Hu et al., 2015). The mean daily air temperature is 1.2℃, ranging from −10.7°C in January to 11.7°C in July, and the average annual precipitation is 620 mm, 85% of which falls during the summer. The principal main vegetation is *Kobresia*-dominated alpine meadow (e.g. *Kobresiatibetica*, *Blysmussinocompressus* and *Carexmuliensis*, etc.) and the corresponding soil is silt loam, an alpine meadow soil type (Huo et al., 2013).

The experimental field is relatively flat with no perceivable slope and an elevation difference of 20m between the highest and lowest points (Fig.1-b). Due to variation in grazing intensity, rodent activities and topographic conditions, patches of grassland from initial degradation to almost completely barren emerge across the field, making it possible to choose sites in various degrees degradation in small areas without large-scale soil spatial heterogeneity coming into play.

Based on the survey of herbage growth and dominant species, a total of nine investigated sites representing various degradation degrees were selected along the strip of the enclosed experimental field (Fig.1-b) using a strategy of space-for-time substitution (Zeng et al., 2013). To assess degradation degree of each site, several key vegetation characteristics including total vegetation coverage (VC), dominant species, number of species, above-ground biomass (MA), and underground biomass (MB) were determined in mid-late July, 2014. Average field plant height was recorded at 10-15cm.

For the classification of alpine degradation, various qualitative and semi qualitative indicators are present in the literature (Gao et al., 2010; Wang et al., 2007; Zeng et al., 2013). In this study, we chose VC, dominant species and number of species as indicators of degradation, and the nine sites are classified into three groups: lightly degraded(LD), moderately degraded (MD), and severely degraded (SD), corresponding to site 1,2,4, site 5,6,8 and site 3,7,9. Characteristics of the three degradation degrees of alpine meadow are shown in Table 1, and MA and MB of each degree are shown in Fig. 2.

2.2 Soil sampling and measurements

Both disturbed and undisturbed soil samples were obtained from 0 to 80cm depths at 10cm intervals at three points randomly distributed on each investigated site mentioned above. Disturbed samples were collected using a soil auger, and samples of the same layer were thoroughly mixed and then air-dried. After being sieved by 2-mm and 0.15-mm mesh, the composite samples were stored in plastic bags and transported to the laboratory for analysis. Soil organic carbon (SOC) was determined by dichromate oxidation with an external heat source (also cited as Walkley-Black wet combustion method)(Nelson et al., 1996); 1-2 mm water-stable aggregates (WSA) was measured using a routine wet-sieve method with mechanical sieving procedure described by ISSAS(1978); soil particle composition (sand >0.05mm, silt 0.002mm-0.05mm, and clay<0.002mm) was analyzed by wet sample dispersion and laser diffraction method using a laser-scattering particle analyser (Microtrac S3500, Microtrac Inc. USA)(Cooper et al., 1984; Zhang, 2014).

Undisturbed samples were collected using cylinder cores (50.46mm in diameter and 50mm in height) to determine soil physical and hydraulic properties including bulk density (BD), capillary porosity (CP), non-capillary porosity (NCP), field water capacity (FC) and saturated hydraulic conductivity (Ks). In laboratory, all these parameters were determined in proper sequence with water suction method (Fu et al., 2015). First, the cylinder cores were dipped in 5mm-depth water to absorb water through capillary action for roughly 8 hours before a constant weight was reached; the corresponding weights were recorded as m1. Second, the cores were soaked in 4.8cm-depth water for approximately 24 hours until saturated, and the respective weights were recorded as m2. Third, soil samples were put on dry sand for 48h and the resulting weights were recorded as m3. Subsequently, cylinder cores were linked to a Mariotte’s bottle to measure Ks using constant head method based on Darcy’s Law (Klute et al., 1986). Finally, the cores were oven-dried at 105 ℃ for approximately 24h and the weights were recorded as m4. No perceivable swelling was detected for all the cores during the soaking process, and the parameters were calculated by the following formulas:

$$\mathrm{BD} = \frac{m4}{V} \tag{1}$$

$$\mathrm{CP} = \frac{m1 - m4}{\rho \cdot V} \tag{2}$$

$$\mathrm{NCP} = \frac{m2 - m1}{\rho \cdot V} \tag{3}$$

$$\mathrm{FC} = \frac{m3 - m4}{\mathrm{BD} \cdot V} \tag{4}$$

$$\mathrm{Ks} = \frac{10 \cdot Q \cdot L}{A \cdot \Delta H \cdot t} \tag{5}$$

where V is the volume of the cylinder core(100cm^3); ρ is the water density(1g•cm^{-3}); t is the time interval(10min); Q is the volume of the outflow through the soil cores during the time interval t(ml); L is the length of the soil core(5 cm); ΔH is the difference of the hydraulic head(10 cm); A is the cross sectional area of the cylinder core(20cm^2).

Above all, soil moisture content (volumetric) of all investigated sites was measured by Time Domain Reflectometry (TDR) (TRIME-PICO-IPH,TDR, IMKO,Inc., Ettlingen, Germany) from 0-80cm soil depth at 10 cm intervals from June 20th to July 20th, 2014. The TDR was calibrated in the local alpine region in advance, and the determination accuracy was ±3%. Soil moisture was measured three times for each layer of each site. There is no rainfall events recorded within 2 days before the data collection, and each measurement of all sites were finished within one day.

2.3 Statistical analysis

Data in this study were presented as mean±SD (standard deviation). Comparison analysis was performed using SPSS 19.0. A one-way analysis of variance (ANOVA), followed by least significant difference (LSD) method was used to test the differences between average values of all parameters at each degradation degree. Pearson correlation coefficient was employed to reflecting the effects of vegetation degradation on soil properties.

In addition, redundancy analysis (RDA) was applied to study the relationship between basic soil properties and hydraulic properties by using CANOCO software version 4.5 (Biometris). RDA is a type of constrained ordination method combining multiple regression and principal component analysis (PCA). It aims to represent a multivariate data set (generally a collection of samples with more than two properties) along a reduced number of orthogonal axes, and visualize the data set in a two-dimensional scatter diagram, hence enabling an easier interpretation of the structure of multivariate data and relationships among variables (Borcard et al., 2011). The projections of the arrows onto the axes represent the contribution of corresponding variables to the extracted axes. The cosine of the angle between the arrows reflects the correlation between variables. Monte-Carlo permutation test was used to rank the importance of each explanatory variable, and then the contribution of each variable to the total variance is determined by multiple regression (Leps, 2003).

3 Results

3.1 Variation of basic soil properties and porosity characteristics under different degrees of degradation

Changes in basic soil properties and porosity characteristics with alpine swamp meadow degradation were obvious (Fig.3). Statistical analysis showed that SOC and WSA decreased significantly (p<0.05) with degradation (Fig.3-b, c), while BD increased significantly (p<0.05) (Fig.3-a). Soil texture was altered remarkably with sand content increasing significantly (p<0.05) (Fig.3-f) while significant decreases were observed in silt and clay content (p<0.05) (Fig.3-d, e). The majority of all soil samples were classified as loam and sand (Fig.4). Half of the LD samples belonged to loam, while vast majority of MD (17 of 24 samples) and SD (22 of 24 samples) belonged to sand. Compared to LD, SOC, WSA, silt and clay content of MD decreased by 17.9%, 15.7%, 5.1% and 23.1% respectively, and those of SD decreased by 61.5%, 32.8%, 44.0%, 75.8%, respectively. BD and sand content of MD increased by 2.3% and 2.9%, respectively, and those of SD increased by 7.2% and 19.6%, respectively.

Soil porosity altered drastically with degradation (Fig.3-g, h). CP decreased consistently with increasing degree of degradation. Comparing to LD, mean CP value of all depths decreased by 5.5% and 13.6% for MD and SD, respectively. Mean value of NCP decreased from LD to MD by 6.6% while increased from MD to SD by 4.4%, following the order of LD>SD>MD.

All properties differed most distinctly in surface (0-10 cm) and subsurface layer (10-20 cm) among different degradation degrees. The differences gradually diminished with increasing soil depth despite some exceptions (e.g.40-50cm for clay and 70-80cm for silt). Almost all basic soil properties showed strong depth dependence. For each degradation degree, BD and sand content showed increasing trend while SOC, WSA, silt and clay content decreased consistently, from depth of 0 to 80cm. CP of MD experienced parabolic change with the highest value at 20-30cm layer. NCP was an exception, showing decreases in the upper-40cm layers while increasing slightly in the lower-40cm layers. For each property, slope of the vertical variations decreased with degradation.

3.2 Changes of SMC, FC and Ks with degradation

Fig.5 showed that SMC in the profile decreased consistently with degradation for all soil layers. Compared with LD, the mean SMC (0-80cm layer) of MD and SD decreased by 21.8%, 33.5%, respectively, and SMC decreased more greatly from LD to MD than from MD to SD.SMC of different degradation degrees always showed an increasing trend with depth. For MD and SD, SMC increased consistently with depth, while for LD, SMC showed no clear trend in both 0-30 cm and 40-80 cm layers, increasing sharply at 40cm depth.

Changes of FC and Ks associated with alpine swamp meadow degradation are displayed in Fig.6. Both of these properties responded quickly to degradation and showed notable vertical distribution. Mean values of FC decreased consistently with degradation in upper-30 cm layers but varied irregularly below (Fig.**6**-a). Unlike FC, Ks values decreased from LD to MD and then increased from MD to SD (i.e. LD >SD >MD) except for layers 40-50 cm and 70-80cm (Fig.**6**-b). It was also evident that Ks values were more variable in the upper soil layers. FC of all degradation degrees decreased consistently with depth, and the slope of the decreasing trend decreased with degradation, while Ks decreased in the upper-40cm layers and then increased in the lower-40cm layers, reaching lowest values at 40cm. Similar patterns of change and vertical distribution were observed for NCP (see 3.1).

ANOVA showed that SMC of LD is significant higher (p<0.05) than MD in all soil layers except for 20-30 cm layer, and SMC of MD is significant higher than SD in 10-80 cm layers. In contrast with SMC, significant difference among three degradation degrees only existed at 0-20cm layers for FC, and the 0-10cm layer for Ks. These statistical analyses indicated that alpine meadow degradation did not have significant impacts on soil hydraulic properties in layers deeper than 20cm depth.

3.3 Influencing factors of degradation on soil hydraulic properties

Alpine swamp meadow degradation directly leads to deterioration of basic soil properties, and thus soil hydraulic properties are influenced. Pearson correlation analysis (Table 2) showed the effects of vegetation characteristics on soil properties. Generally, SOC, WSA, CP, clay and silt content were positively correlated with VC, MA and MB, while BD and sand content were negatively correlated with vegetation characteristics. The correlation between NCP and vegetation characteristics was not significant due to its inconsistent change pattern with degradation. Compared with those in 40-80 cm layers, soil properties in 0-40 cm layers were all significantly (p<0.05 or 0.01) correlated with vegetation characteristics, indicating that the effects of vegetation degradation on soil properties were mostly confined in upper soil layers.

According to the statistical analysis in section 3.2, data of samples in 0-10cm layer and 10-20cm layer were selected to analyze the relationships between basic soil properties and hydraulic properties associated with degradation. Fig.7 illustrates relationships between soil basic and hydraulic properties ascertained by the redundancy analysis (RDA). It can be seen that FC was positively correlated with CP, WSA, SOC, silt and clay content, but were negatively correlated with BD and sand content. NCP had no impact on FC, but served as the only factor that determined Ks. FC and Ks are independent of each other, which can be further supported by Pearson correlation analysis (Table 2).The two axes explain 60.2% and 29.0% of the total variance of FC and Ks, respectively.

Additionally, all the samples could be divided into two groups: one includes all the samples from LD and two samples from SD, while the other includes all the samples from MD and four samples from SD. It is clear that the group including LD samples showed a close relationship with all the soil properties except BD and sand, while the second group mainly including MD and SD was just the opposite.

Above all, soil basic properties were treated as explanatory variables to explain the total variance of Ks and FC. Monte-Carlo permutation test was first used to rank the importance of each explanatory variable, and then the relative contribution of each variable to the total variance of Ks and FC were determined by multiple regression. The result showed (Table 3) that CP is the dominant factor for FC that explains 91.9% of the variance of FC. NCP is the dominant factor for Ks that explains 97.0%

of the variance of Ks. As these properties explain large proportion of the variance in FC and Ks the relative influence of other soil properties can be dismissed.

4 Discussion

4.1 Effects of alpine swamp meadow degradation on soil moisture content and basic soil properties

Soil moisture content (SMC) is a comprehensive indicator of soil quality and can directly reflect soil water holding capacity (Palese et al., 2014; Zenget al., 2013)**.** This study showed that SMC decreased consistently from LD to SD, responded swiftly to degradation. And unlike soil properties, significant difference of SMC among three degradation degrees can be found at all soil layers. Similar changing patterns with vegetation degradation in alpine regions were observed by Zeng et al. (2013), Wang et al. (2007) and Li et al. (2012). In fact, decrease in vegetation coverage, SOC, and increase in sand content will negatively impact on soil water retention (Strudley et al., 2008;Yi et al., 2012), leading to SMC loss with degradation. Moreover, due to the root uptake in summer, SMC of all degradation degrees in the 0-30 cm layers are lower than that in deeper layers.

Changes in basic soil properties, such as increases in BD and sand content, decrease of SOC, WSA , silt and clay content with degradation (Fig.2 a-f) align closely with the hypothesized results and are in agreement with much of the literature (Gao et al., 2010;Wang et al., 2007;Wei et al., 2010). Along the degradation gradient, trends of these basic properties are almost uniform regardless of soil types and vegetation traits (Guo et al., 2013; Zeng et al., 2013). On the contrary, basic soil properties will improve consistently during the restoration processes (Li et al., 2006; Wu et al., 2010). Moreover, changes in basic soil properties with degradation were mostly confined in the upper layers (0-40cm), and the contrasts were most remarkable in the surface layer (0-10cm). Similar change patterns as to soil depth have been confirmed in many other studies (Fu et al., 2015; Hallema et al., 2015; Wang et al., 2007; Zeng et al., 2013). Correlation analysis showed that soil properties, especially in the upper layers (0-40 cm), were closely associated with vegetation characteristics (Table 2).Vegetation factors are indispensable to the stability of soil status, such as the formation of SOC, porosity and structure. In fact, root activity and litter fall input vanish significantly as degradation degree increases, thus the decomposition process and organic matter accumulation in soil are hindered with degradation. Depletion of SOC greatly alters the soil micro-environment and may trigger a series of changes in soil physical, chemical and biological processes (Nelson et al., 1996). For instance, it has been confirmed that clay and silt contents are largely dependent on a release of organic acid from soil organic matter, which can corrode coarse minerals and transfer large grains into fine particles (Fan et al., 2015). Besides, organic matter can also act as “glue” in soil aggregates formation and determine water-stability (Lipiec et al., 2009). Therefore, a decrease in SOC will strongly influence soil structure, and thus bring about overall changes of soil physical and chemical properties. Furthermore, the absence of plant coverage and root grasp will cause topsoil to become vulnerable to wind, raindrops, surface flow and compaction, directly resulting in soil erosion and degradation, and the particle distribution of soil samples in the soil texture triangle (Fig.4) clearly shows the sandification trend with increasing degradation. Insignificant correlations between vegetation characteristics and soil properties of the lower layers (40-80 cm) (Table 2) were in accordance with the fact that no significant differences of soil basic properties were found between degradation degrees at the lower layers.

4.2 Influencing factors of degradation on soil hydraulic properties

With increasing degradation degree, our results demonstrated that FC decreased consistently (Fig.6-a), which was in accordance with some previous studies conducted in other alpine ecosystem types (Xiong et al., 2011; Yi et al., 2012). However, there were other studies reported different change patterns of FC. Li et al. (2012) and Wei et al. (2010) found that FC first increased but then decreased with alpine meadow degradation. This might be caused by different degradation classification. Li et al. (2012) and Wei et al. (2010) classified the sampling plots into four and five degradation degrees according to succession stages, respectively, and the initial degree of the sampling plots in both studies was non-degraded degree, However, the highest values of FC in both studies corresponded to the light degree, and FC of the most severe degradation degree were much lower than of non-degraded degree. These traits were in line with our results. What's more, Wei et al. (2010) pointed out that CP changed similarly with degradation, i.e., CP was positively correlated with FC, which was consistent with the definition of FC (OttoniFilho et al., 2014).

Ks decreased initially and then increased with degradation (Fig.6-b), and similar "high-low-high" trend of Ks was also observed in some studies conducted for alpine meadow despite the change amplitude was different (Wang et al., 2010; Wei et al., 2010). However, Zeng et al. (2013) reported a decreasing trend while Wang et al. (2007) reported an increasing trend of Ks. These discrepancies may be attributed to the difference of soil and vegetation factors in different regions and also the degradation classification. In the study conducted by Zeng et al. (2013), the root density consistently decreased averagely by 97% from light to extreme degree, which indicated a substantial decrease of soil macro-pores and thus resulted in lower values of Ks; in the study conducted by Wang et al. (2007), the gravel (size>2mm) content increased by nearly 100-fold, which will greatly increase soil infiltration.

Soil pores are empty space active in soil water storage, retention and movement, therefore soil porosity is closely related to soil hydraulic properties(Lipiec et al., 2006). Increases in BD indicate a reduction in soil total porosity (TP) since TP is generally calculated using the following equation: TP=1-BD/2.65 (Li et al., 2006; Price et al., 2010). TP can be divided into CP (pore size <0.1mm) and NCP (pore size>0.1mm). Water that fills capillary pores can be suspended by capillary effect, making CP key for soil water retention. However, in non-capillary pores soil water can move freely by gravity making NCP critical for soil water infiltration and transmission. Generally, soil pores with pore size larger than 75μm are defined as macro-pores, and non-capillary pores belongs to macro-pores (Gao et al., 2015; Pagliai et al., 2002). Soil porosity mainly depends on soil texture and aggregates (i.e. the finer texture of the soil, the smaller the pore size). Applying this logic, increasing degradation would increase sand content and decrease WSA, and thus lead to a decrease in CP (Fu et al., 2015; Lipiec et al., 2006). Moreover, the positive correlation between CP and SOC was detected in many studies (Gao et al., 2015; Price et al., 2010;Yu et al., 2015), concluding that CP can be an indicator of soil quality. By definition, FC is the maximum water content held in soils when excess water has drained away and the downward flux is negligible (Ottoni Filho et al., 2014). Therefore, FC is essentially depends on capillary effect, and decrease in FC is resulted from decrease in CP.

Unlike CP, changes of NCP in this study are more complex, first decreased from LD to MD and then increased from MD to SD (i.e. MD<SD<LD) (Fig.3-h). It is widely accepted that soil macro-pores are closely related to root penetration and activities of soil fauna (Kuncoro et al., 2014; Zeng et al., 2013). NCP measured in the rhizosphere (0-10cm layer) decreased significantly as root penetration weakened with degradation. On the other hand, increases in sand content will lead to an increase in size of soil pores. Hence, the slight but observed increase in NCP from MD to SD. However, the effect is not equivalent with root penetration resulting in macro-pores, i.e., the contribution of increasing sand content to NCP could not offset the vanishing effects of vegetation on soil porosity, hence NCP of SD was higher than MD but still lower than that of LD. Ks determine soil water movement and is largely dominated by NCP, so it changed in accordance with Ks.

In summary, our study revealed that the well-identified relationships between soil porosity and hydraulic properties are applicable in alpine swamp meadow. Hence, compared with soil porosity, the contribution of other properties to the variance of FC and Ks are outweighed (Table.3). In addition, FC positively correlates with SOC, WSA, silt and clay content ($p<0.05$), and negatively correlates with BD and sand content($p<0.05$)(Table.2), these correlations are consistent with studies in other regions (Głąb et al., 2014; Price et al., 2010; Wei et al., 2010). Due to the inconsistent changing pattern, Ks only positively correlate with NCP (Table.2). In fact, arguments about the impact of soil properties on Ks and its changes are still under debate (Fu et al., 2015; Jarvis et al., 2013). Hence, further investigations about the variations of Ks are needed.

4.3 Hydrological effects of alpine swamp meadow degradation and the implication for hydrology modelling

Our results show a clear distinction of basic soil and hydraulic properties among different alpine meadow degradation degrees. Considering the important roles that FC and Ks play in soil water retention and infiltration, it can be concluded that key hydraulic processes and functions in soil such as water holding capacity, transmission as well as runoff generation mechanisms may differ significantly with alpine swamp meadow degradation. For example, high Ks seen in topsoil can form preferential flow and avoid infiltration excess runoff (Fu et al., 2015; Lipiecet al., 2006). In this study, soils of LD have relatively higher Ks and FC, indicating the robustness of soil water retention. For MD, Ks were reduced significantly; lower Ks may act as a barrier to vertical water flow reducing its capacity to intercept rainfall.

Furthermore, the results showed the effects of degradation mainly manifest in the upper soil layers. There are only a few influences of degradation in deep soil layers. Moreover, the rhizosphere lies at the interface between the atmosphere and ground surface and directly accepts precipitation, recharges deep soil layers and supplies water to plant growth (Li et al., 2012; Wu et al., 2014). In this sense, rhizosphere is of great hydrological importance to alpine ecosystem, and changes in soil hydraulic properties of this layer may greatly alter the soil hydraulic processes in local regions.

In addition, the hydrological effects of large-scale alpine meadow degradation are noticeable and serious in Tibetan Plateau (Jin et al., 2015; Wang et al., 2012). For hydrological modelling, accurate parameter acquisition is necessary for simulation accuracy (Vereecken et al., 2015). Our results indicate that hydraulic properties will be altered significantly both vertically and spatially with degradation. Therefore, to improve the performance of hydrological modelling, differences in soil hydraulic properties under different degradation degrees should be considered seriously (Jin et al., 2015).

5 Conclusion

Due to global change and anthropogenic disturbances, alpine swamp meadow on the eastern Tibetan Plateau is undergoing severe degradation. Based on nine plots representing alpine swamp meadow of different degradation degrees, this study mainly investigated the changes of soil hydraulic properties with alpine swamp meadow degradation, and analyzed the influencing mechanism of grassland degradation on field capacity (FC) and saturated hydraulic conductivity (Ks). In summary, with increasing degradation degree, SMC and FC decreased consistently from LD to SD, while Ks decreased from LD to MD and then increased from MD to SD (i.e. LD>SD>MD). Besides, BD, SOC, WSA, soil texture and porosity were also altered remarkably. Significant differences of both soil basic and hydraulic properties between different degradation degrees usually exist in the 0-20cm layer, indicating that the effect of degradation was mostly concentrated in the rhizosphere. FC were positively correlated with CP, WSA, SOC, silt and clay content, but were negatively correlated with BD and sand content; Ks only positively correlated with NCP.

Changes in FC and Ks are mainly controlled by soil porosity during degradation process. CP and NCP are dominant factors, which explained 91.1% and 97.3% of the variance of FC and Ks, respectively. Root activities attenuate with degradation and directly lead to decrease in NCP, while the contribution of sand particles to NCP comes into play for MD and SD when vegetation vanishes. The combined effect of vanishing root activities and increased sand content that is responsible for the inconsistent changes in NCP and Ks during the degradation processes. Our findings give out a more comprehensive understanding of the soil hydrological effects of vegetation degradation. Given the importance of parameterization for hydrological models, water flow simulations in Tibetan Plateau and similar regions should consider variations in soil hydraulic properties of different degraded alpine swamp meadow.

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Table 1: Vegetational characteristics of investigated sites in this study.

Degradation Degree	VC (mean±SD*, %)	Number of species	Dominant species
LD	80.5±4.9	18-25	*Kobresiatibetica, Kobresiahumilis, Stipaaliena*
MD	59.7±4.5	15-20	*Kobresiapygmaea, Agropyroncristatum, Carextristachya*
SD	13.7±8.6	5-12	*Kobresiarobusta, Leymuschinensis, Potentillabifurca*

Note: *:standard deviation

Table 2: Pearson correlation coefficient between vegetation characteristics and soil properties in 0-40cm and 40-80 cm layers

Layers	Properties	BD	SOC	WSA	Sand	Silt	Clay	CP	NCP
0-40 cm	VC	-0.710**	0.769**	0.747**	0.533*	0.472*	-0.491*	0.829**	0.155
	MA	-0.811**	0.899**	0.902**	0.838**	0.698**	-0.735**	0.808**	0.345
	MB	-0.635**	0.860**	0.800**	0.672**	0.646**	-0.662**	0.615**	0.028
40-80 cm	VC	-0.187	0.658**	0.586**	0.249	0.420	-0.405	0.321	-0.407
	MB	-0.487*	0.461*	0.464*	0.365	0.507*	-0.502*	0.544*	-0.030
	MA	-0.352	0.474*	0.461*	0.369	0.694**	-0.661**	0.412	0.010

Note: *: significant at 0.05 level;**: significant at 0.01 level (2-tailed test); n=18.

Table 3: Pearson correlation coefficient between Ks, FC and soil properties of soil in layers above 20cm depth.

Properties	BD	SOC	WSA	Sand	Silt	Clay	CP	NCP
Ks	-0.447	-0.239	-0.246	-0.381	0.366	0.391	0.172	0.896**
FC	-0.912**	0.867**	0.875**	-0.803**	0.786**	0.760**	0.918**	0.361

Note: **: significant at 0.01 level (2-tailed test); n=18.

Table 4: Total variance of FC and Ks explained by basic soil properties

Ranking	FC			Ks		
	Properties	% of Variance	Cumulative%	Properties	% of Variance	Cumulative%
1	CP	91.1	91.1	NCP	97.3	97.3
2	WSA	7.5	98.6	BD	1.8	99.1
3	NCP	0.7	99.3	WSA	0.5	99.6
4	Silt	0.5	99.8	CP	0.2	99.8
5	BD	0.2	100.0	Clay	0.1	99.9
6	SOC	0.0	100.0	Silt	0.1	100.0
7	Clay	0.0	100.0	Sand	0.0	100.0
8	Sand	0.0	100.0	SOC	0.0	100.0

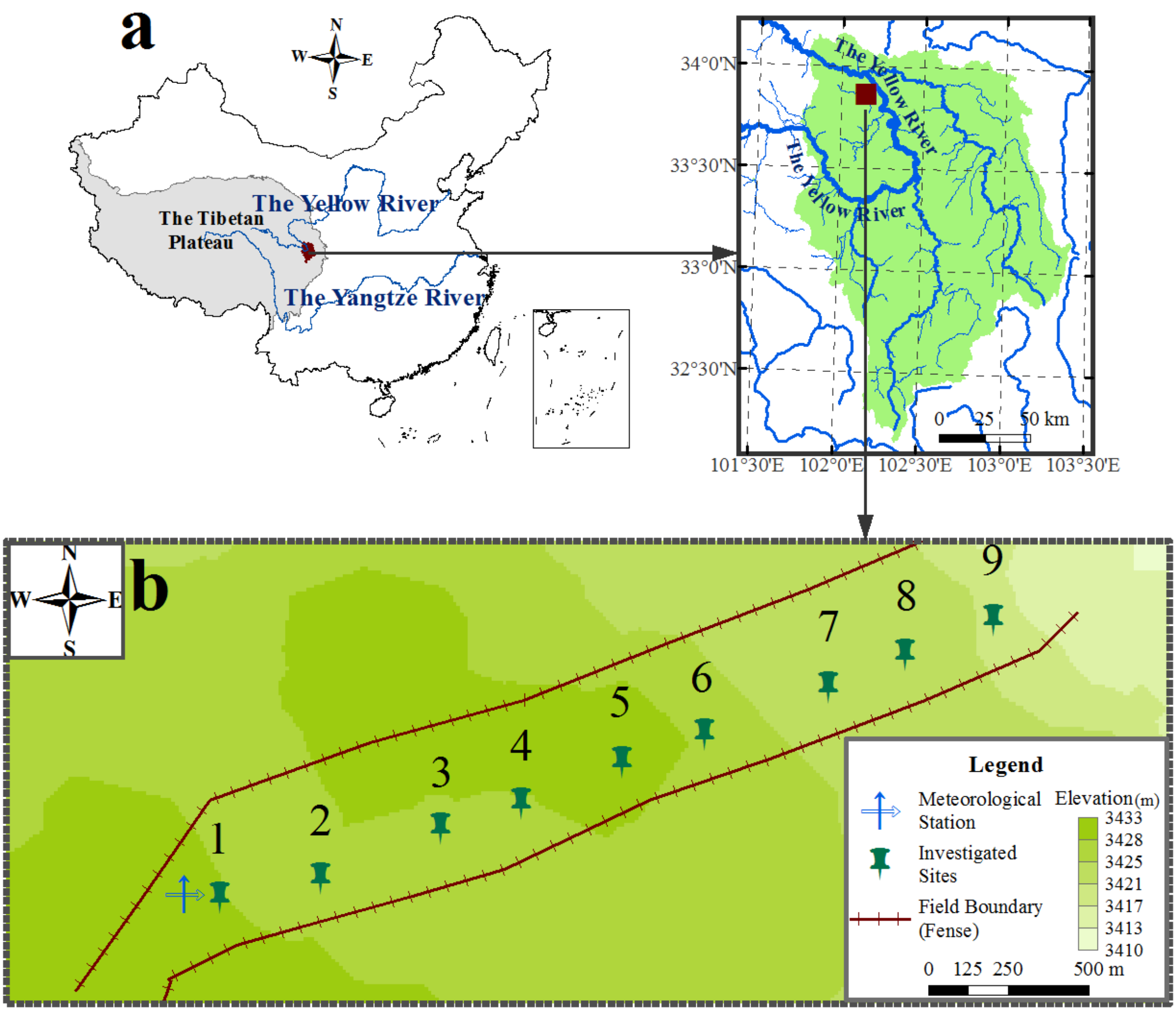

Figure 1: Location of the study area and investigated sites: a) location of the experimental field in the Zoige Wetland in the east of Tibetan Plateau, China; b) distribution of investigated sites within the experimental fields.

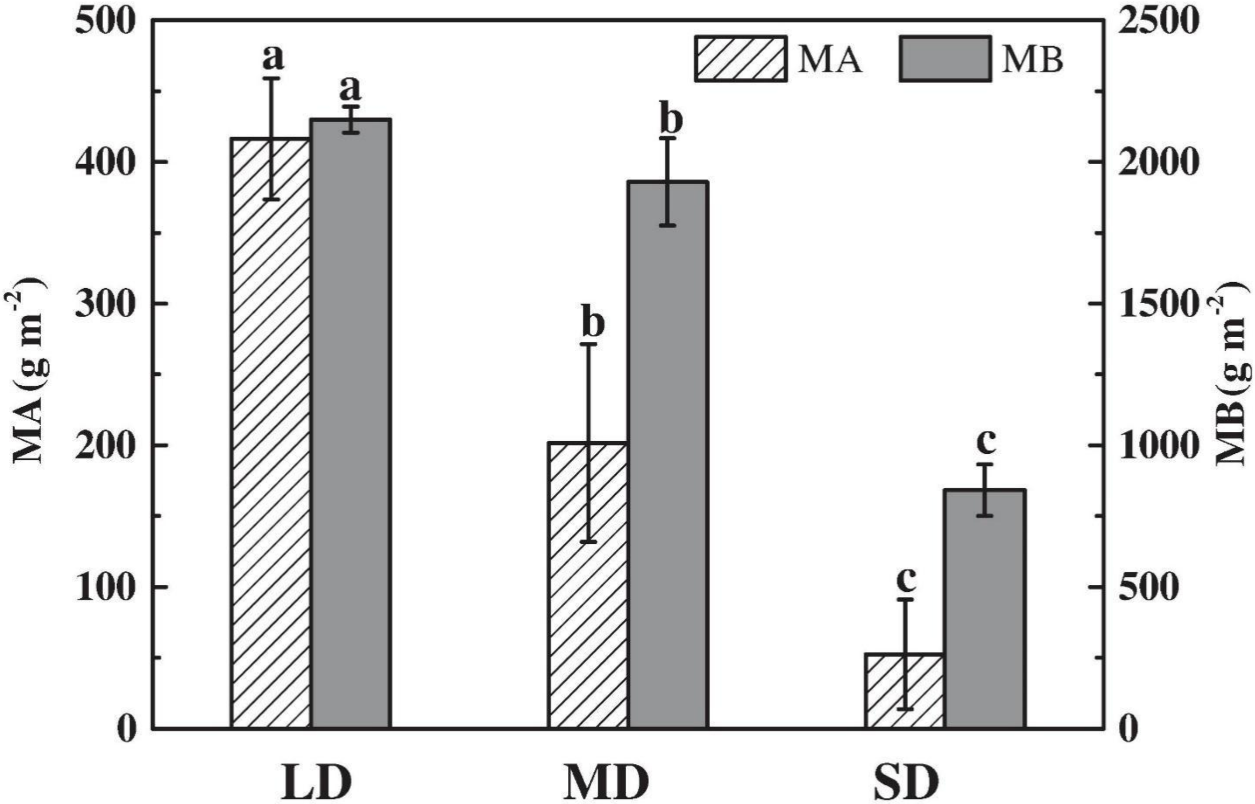

Figure 2: The MA and MB of different degradation degrees. The error bars denote the standard deviation of the 3 sites of the same degradation degree. Different successive letters above the bars denote the significant difference ($p<0.05$) between different degradation degrees.

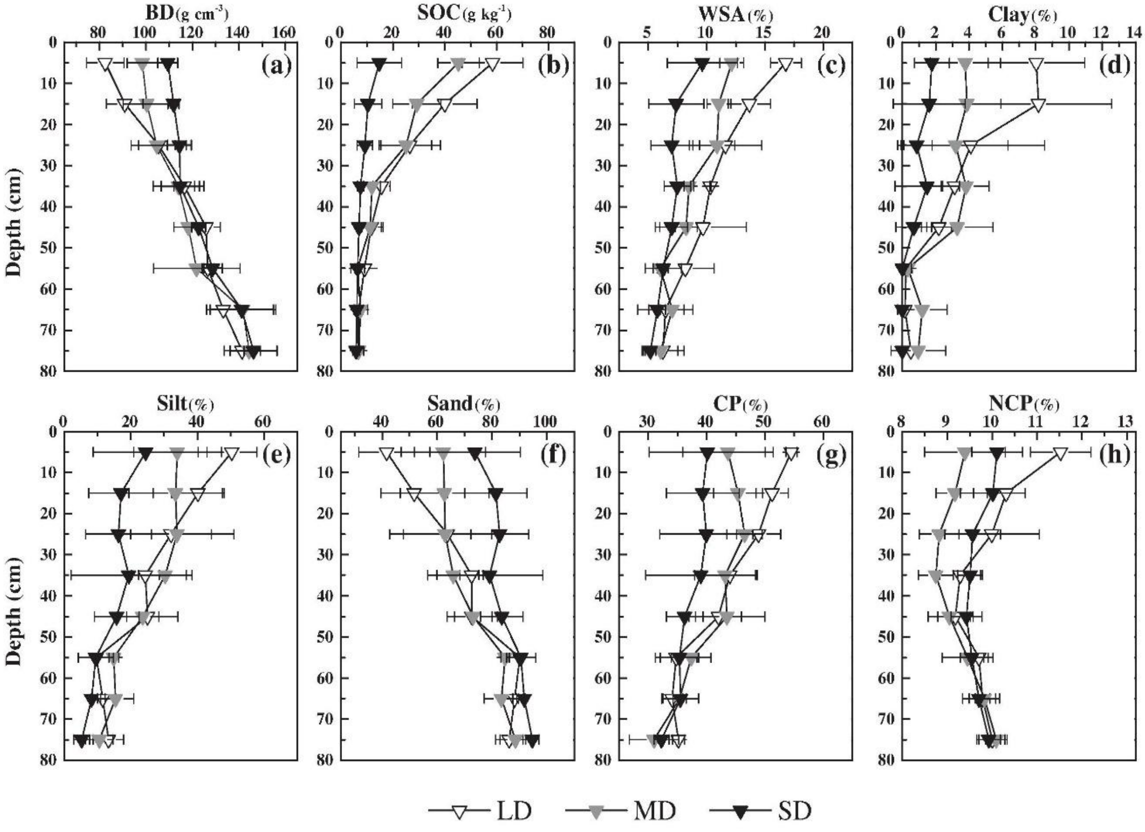

Figure 3: The basic soil properties of different degradation degrees. The error bars denote the standard deviation of the 3 sites of the same degradation degree.

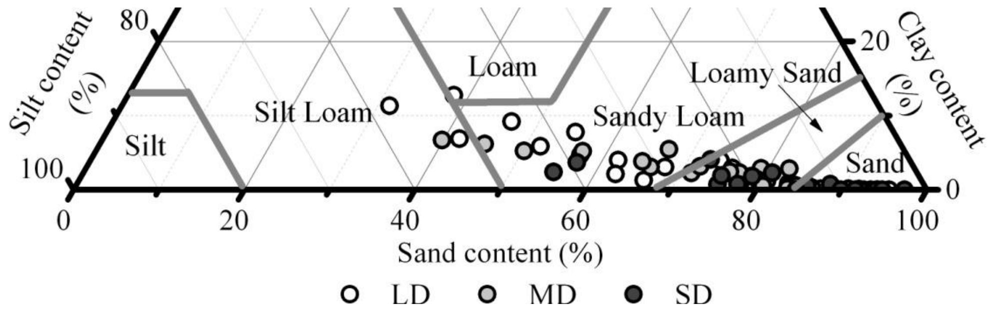

Figure 4: Particle size distributions of LD, MD, and SD soil samples. Textural classes corresponding to particle size distributions observed in these soils are bounded by gray bold lines (e.g., loam, silt).

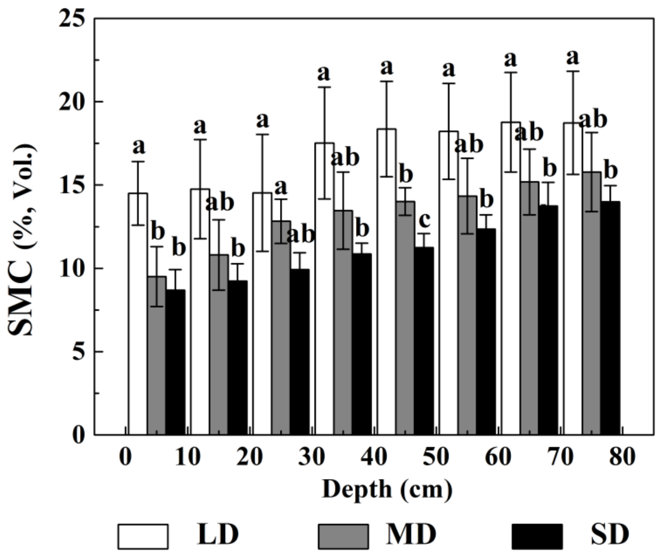

Figure 5: SMC of different degradation degrees. Error bars denote the standard deviation of the 3 sites of the same degradation degree. Bars with the same letter indicate that no significant differences (p<0.05) exist between corresponding degradation degrees.

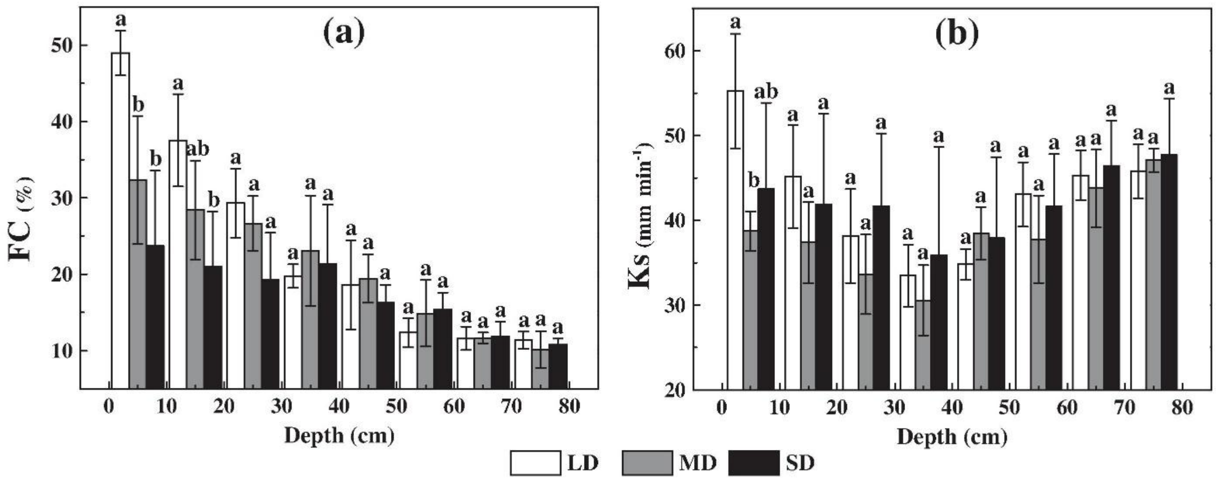

Figure 6: Difference in degradation degree for FC and Ks. Error bars denote the standard deviation of the 3 sites of the same degradation degree. Bars with the same letter indicate that no significant differences ($p<0.05$) exist between corresponding degradation degrees.

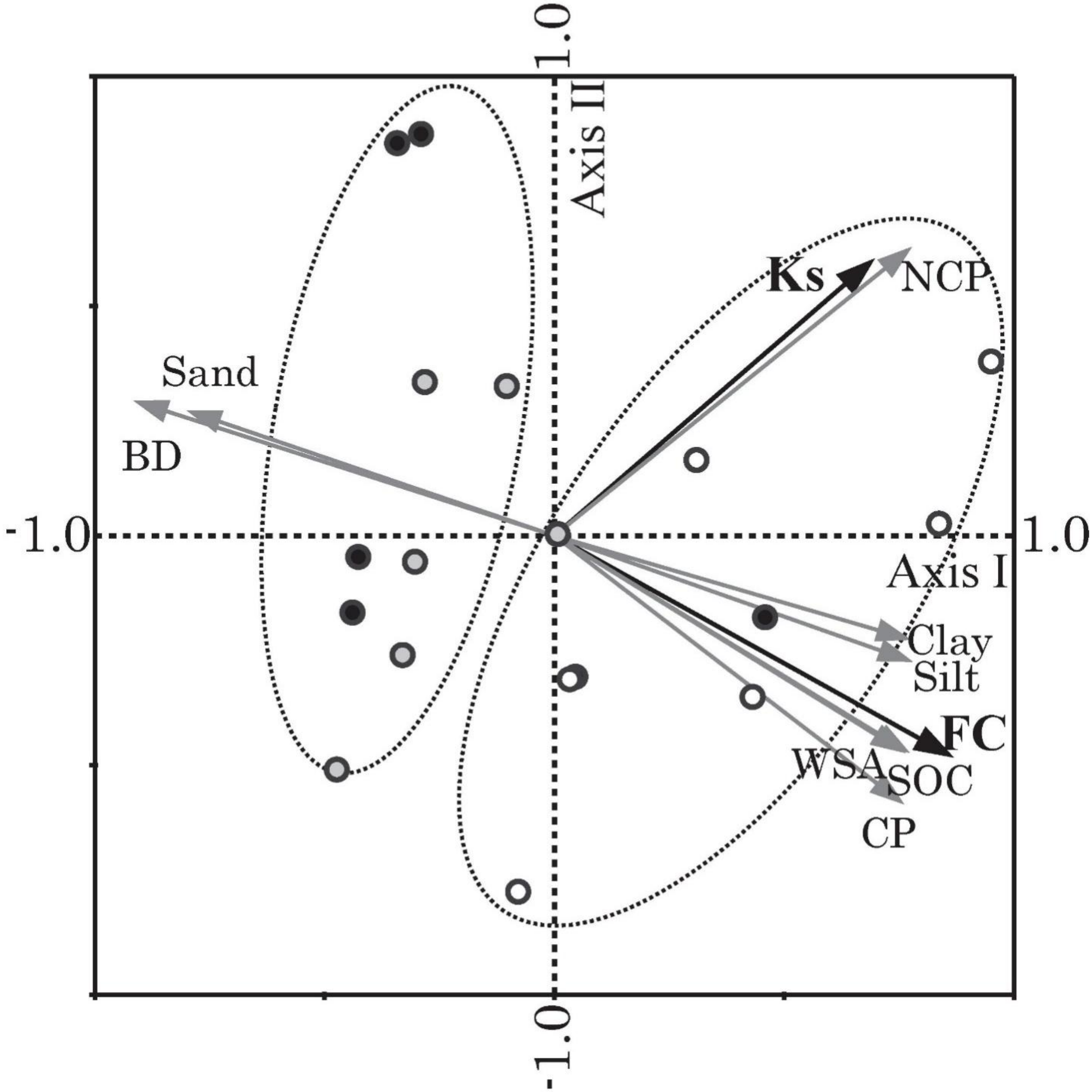

Figure 7: Redundancy analysis of soil hydraulic properties and basic properties under different degradation stages. Symbols '○', '●' and '●' denote soil samples from LD, MD and SD, respectively. The two axes represent the principal component (PC) extracted from the explaining variables (basic soil properties). The first ordination axis (axis I, horizontal) mainly reflect the influence of BD, SOC and soil texture and the second axis (axis II, vertical) mainly reflects that of CP and NCP.