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

Tao Pan[1,3], Shuai Hou[1,2], Shaohong Wu[1], Yanhua Liu[1], Xintong Zou[1,2], Anna Herzberger[3], Jianguo Liu[3]

[1]Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[2]University of the Chinese Academy of Sciences, Beijing 100049, China
[3]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48824, USA

*Correspondence to*: Tao Pan (pantao@igsnrr.ac.cn)

**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 are still poorly understood, and exiting findings were inconsistent. 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 analysed. 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 hydrologic 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 variation within FC and Ks and their contributing 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, and given the intimate interactions between vegetation and soil (Wen et al., 2010). Some efforts have been devoted to revealing the effects of vegetation degradation on soil hydraulic properties across scales and ecosystem types (Hallema et al., 2015; Krummelbein et al., 2009; Lal, 1996). 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. This is highlighted in remote areas such as alpine mountainous regions as its cold and adverse environment, where fieldwork is time-consuming and extremely labour intensive, indicating the need for additional research on soil hydrological effects of vegetation degradation.

Alpine mountainous regions around the globe often include headwaters that are responsible for recharging freshwater to the lower reaches but are vulnerable to external disturbances (Bernhardt et al., 2014; Kormann et al., 2015). Therefore, the hydrological responses of alpine ecosystems to climate changes and human activities have recently become a hot research topic (Laghari et al., 2012). For example, variations in Ks and land flow with land use change have been conducted in Nepal (Ghimire et al., 2014; Prasad et al ,2013); changes in Ks along an alpine slope (Wienhöfer et al, 2009)and the response of soil moisture dynamics and retention characteristics to grazing intensity in the inner Mongolia (Zhao et al, 2011) were also explored, and etc. 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 3$^{rd}$, 5$^{th}$ and 7$^{th}$ longest rivers, respectively. The hydrologic cycling of this region has great effects on the energy and water processes of Eastern Asia. Alpine meadow is a widely distributed vegetation type on the Tibetan Plateau (Wang et al., 2007). Although hydrological effects of alpine meadow changes over Tibetan Plateau have been 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 and knowledge gap remains. Some researchers have found that Ks generally decreased with increasing degradation (Zeng et al., 2013) while other studies have shown that Ks increase with degradation (Wang et al., 2007), or decreased initially and then increased (Wang et al., 2010). FC has been reported to generally decreased with degradation (Yi et al., 2012), but has also been reported to first increase and then decrease (Li et al., 2012). These inconsistencies show the high variability of FC and Ks in alpine region, even under similar vegetation type. In addition, the relationships between basic soil properties and hydraulic properties are complex and ambiguous (Fu et al., 2015). In order to acquire robust conclusions, further investigations into soil hydraulic properties associated with grassland degradation on Tibetan Plateau are needed.

Alpine swamp meadow, a special grassland type in the eastern Tibetan Plateau, is featured with unique terrestrial-aquatic soil and vegetation characteristics, which is converted from alpine swamp mainly distributed in the eastern Tibetan Plateau (Zedler et al., 2005; Wu et al., 2010; Huo et al., 2013). Unfortunately, alpine swamp meadow has been severely degraded due to climate change, overgrazing, human activities and rodents (Shang et al., 2013). Vegetation degradation impacts soil physical and chemical properties, hence influencing soil hydraulic properties as well as soil moisture. However, few studies have paid attention to the effects and influencing mechanism of alpine swamp meadow degradation on soil hydraulic properties (Wei et al., 2007; Xiong et al., 2010). To fill this knowledge gap, further investigations and studies concerning the effects of alpine swamp meadow degradation on soil hydraulic properties in this region are urgently needed to improve predictive ability of hydrologic models and reduce uncertainties.

This research is comprised of a series of plots in eastern Tibetan Plateau that represent the degradation process of a typical alpine swamp meadow, and seeks 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°C, 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. Kobresia tibetica, Blysmus sinocompressus and Carex muliensis, 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, DS and NS 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 analysed by wet sample dispersion and laser diffraction method using a laser-scattering particle analyser (Microtrac S3500, Microtrac Inc. USA) (Cooper et al., 1984).

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 °C 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:

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

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

$$\mathbf{N}\boldsymbol{CP} = \frac{\mathbf{m2 - m1}}{\boldsymbol{\rho}\cdot\mathbf{V}} \tag{3}$$

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

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

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 sites. 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), and 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. 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 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 reflect the correlation between variables. Monte-Carlo permutation test was used to identify the contribution of each factor to the total variance.

## 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. Compared to LD, mean CP value of all depths decreased by 5.5% and 13.6% for MD and SD, respectively. Mean values of NCP decreased from LD to MD by 6.6% while increased from MD to LD 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 (0-80 cm 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 70-80 cm (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 0-20 cm layers for FC, and the 0-10 cm 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. According to the statistical analysis in section 3.2, data of samples in 0-10 cm layer and 10-20 cm layer were selected to analyze the relationships between basic soil properties and hydraulic properties associated with degradation. From Fig.6, 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 first ordination axis (horizontal) mainly reflects the influence of all the basic soil properties and the second axis (vertical) mainly reflects that of CP and NCP. 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 (Fig.7): 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.

Monte-Carlo permutation test 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; Zeng et al., 2013). This study showed that SMC decreased consistently from LD to SD, quite responsive 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), and Wang et al (2007), In fact, decrease in vegetation coverage, SOC, and increase in sand content will negatively impact on soil water retention, 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 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). On the contrary, basic soil properties will improve consistently during the restoration processes (Li et al., 2006;Wu et al., 2010). The particle distribution of soil samples in the soil texture triangle (Fig.4) clearly show the sandification trend with increasing degradation. In fact, as degradation increased root activity and litter fall input vanish significantly, thus the decomposition process and organic matter accumulation in soil are hindered with increased 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. 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.**4.2 Influencing factors of degradation on soil hydraulic properties** 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 (Gao et al., 2015;Pagliai et al., 2002), and non-capillary pores belongs to macro-pores.

Our results demonstrate that CP decreases consistently with degradation (Fig.3-i), and similar conclusions were obtained by some other studies conducted in alpine ecosystems (Xiong et al., 2011;Yi et al., 2012). 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 and health. 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). It essentially depends on capillary effects, therefore FC is closely associated with CP. Li, et al. (2012) contended that FC first increase but then decrease with degradation, but pointed out that the soil porosity is positively correlated with FC.

Changes of NCP are more complex. First decreasing from LD to MD and then increasing 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. The similar “high-low-high” trends were observed in some studies conducted for alpine meadow (Wang et al., 2010;Wei et al., 2010), but the magnitude and change is different, which may be due to the difference of soil and vegetation factors in different regions. In summary,

our results (Table.2,3) are in accordance with the well-identified relationships between soil porosity and hydraulic properties. 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 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;Lipiec et 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

In summary, this study mainly investigated the changes of field capacity (FC) and saturated hydraulic conductivity (Ks) with alpine swamp meadow degradation, and analyzed the influencing mechanism of grassland degradation on these two hydraulic properties. With increasing degrees of alpine swamp meadow degradation, soil moisture content, basic soil properties and hydraulic properties changed significantly, especially for the rhizosphere (0-20cm layer). 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). 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 | *Kobresia tibetica*, *Kobresia humilis*, *Stipa aliena* |
| MD | 59.7±4.5 | 15-20 | *Kobresia pygmaea*, *Agropyron cristatum*, *Carex tristachya* |
| SD | 13.7±8.6 | 5-12 | *Kobresia robusta*, *Leymus chinensis*, *Potentilla bifurca* |

Note: *:standard deviation

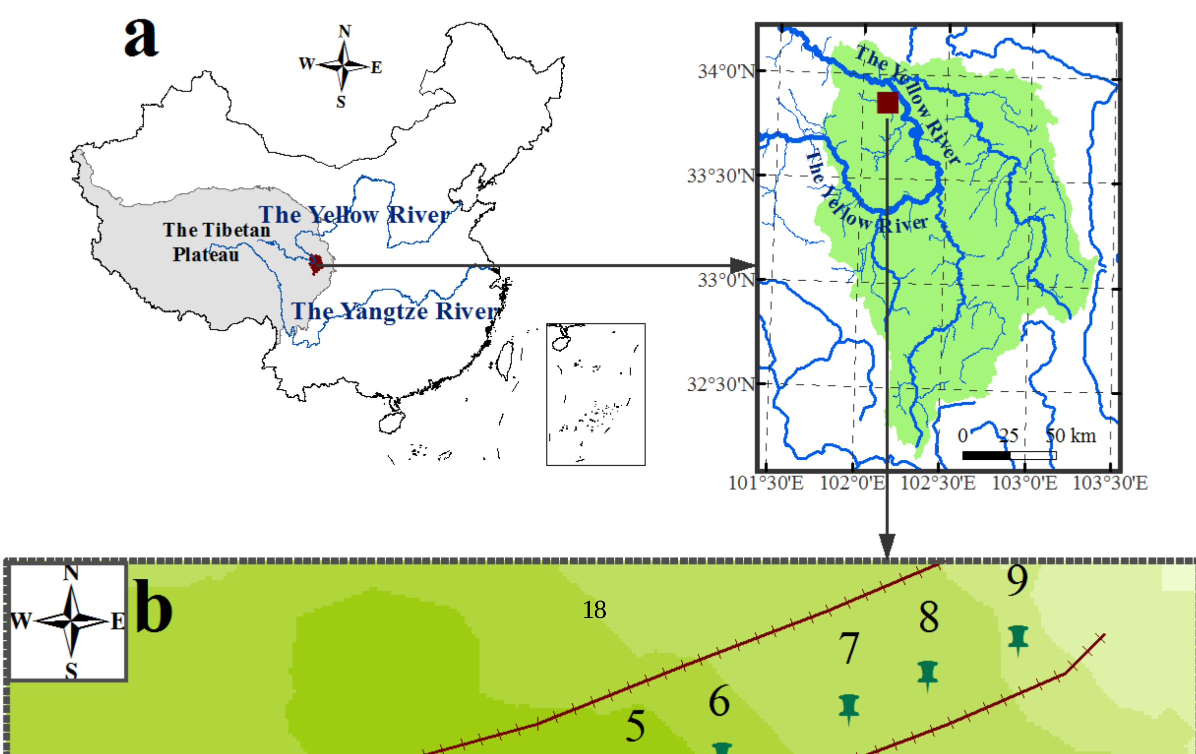
**Table 2: Pearson correlation coefficient between Ks, FWC and soil properties of soil in layers above 20cm depth.**

| 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 3: 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 |



a
N
W
E
S
The Yellow River
The Tibetan Plateau
The Yangtze River
34°0'N
33°30'N
33°0'N
32°30'N
The Yellow River
The Yellow River
0 25 50 km
101°30'E
102°0'E
102°30'E
103°0'E
103°30'E
b
N
W
E
S
9
8
7
6
5

**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.**

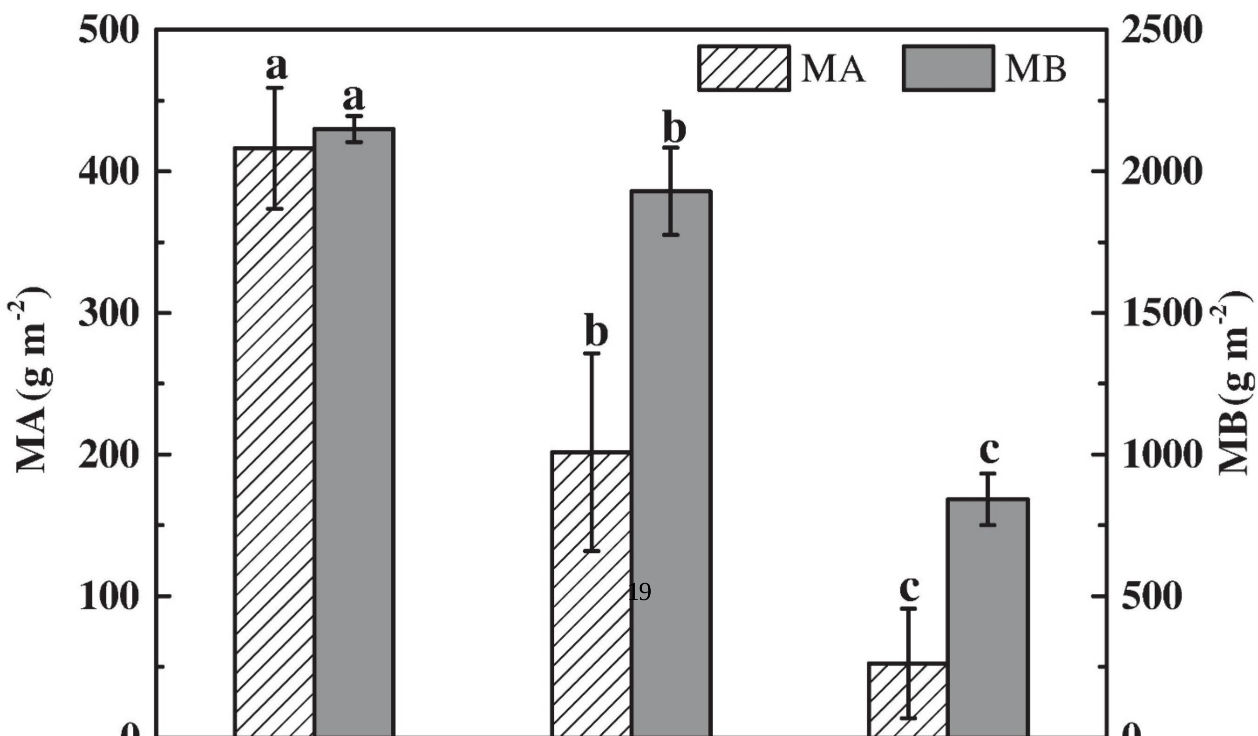


**Figure 2: The MA and MB of different degradation degrees. The error bars denote the standard deviation of the 3 sites of the same degradation degree. The letters above the bars denotes the significant difference (p<0.05) between different degradation degrees.**

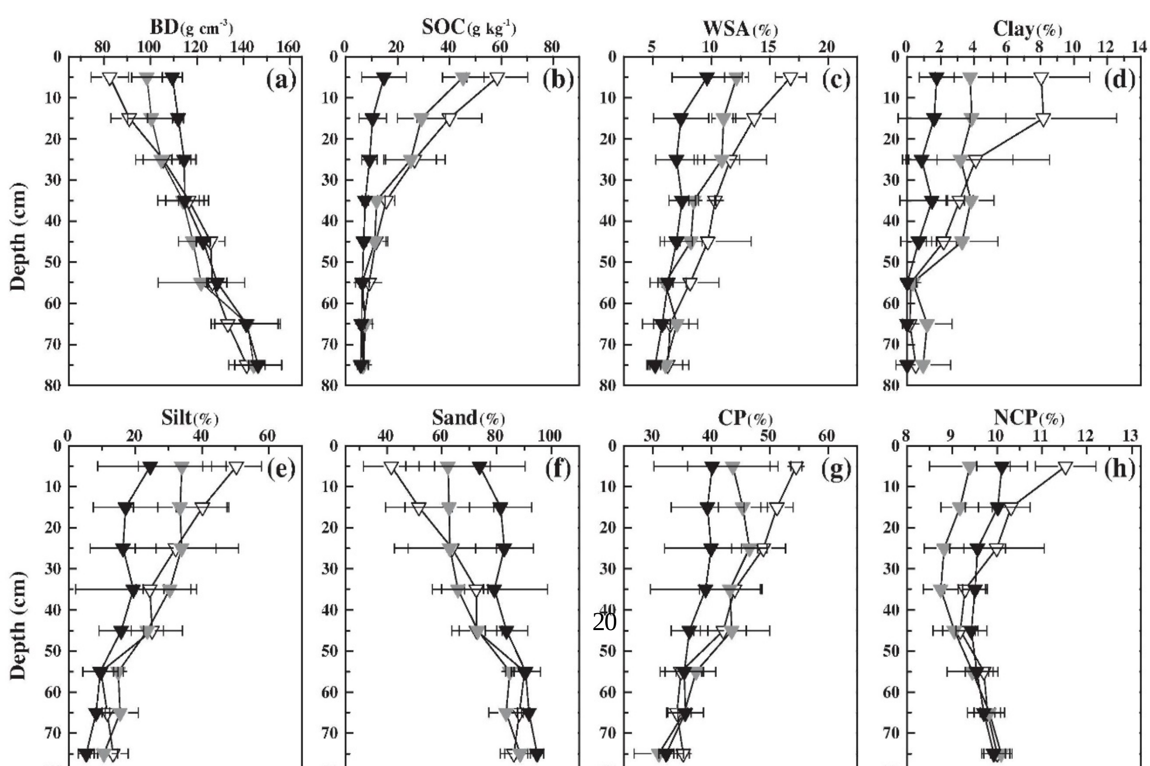


**Figure 3: The basic soil properties of different degradation degrees. The error bars denote the standard deviation of the 3 sites of the same degradation degree.**

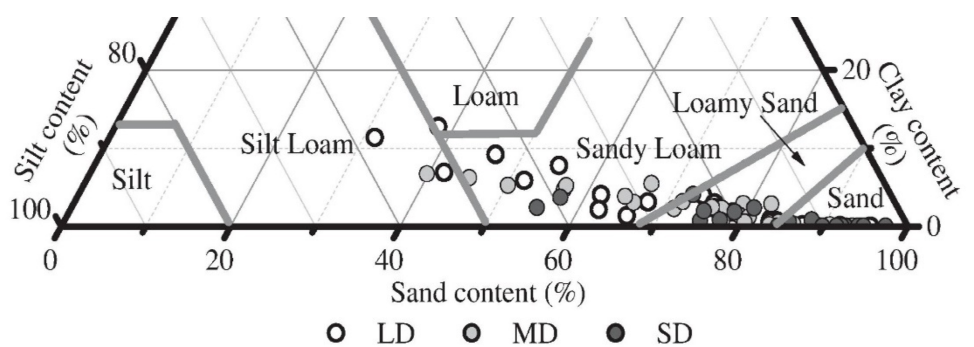



**Figure 4: Particle size distributions of LD, MD, and SD soil samples. Textural classes corresponding to particle size distributions observed in these soils are bounded by grey bold lines (e.g., loam, silt).**

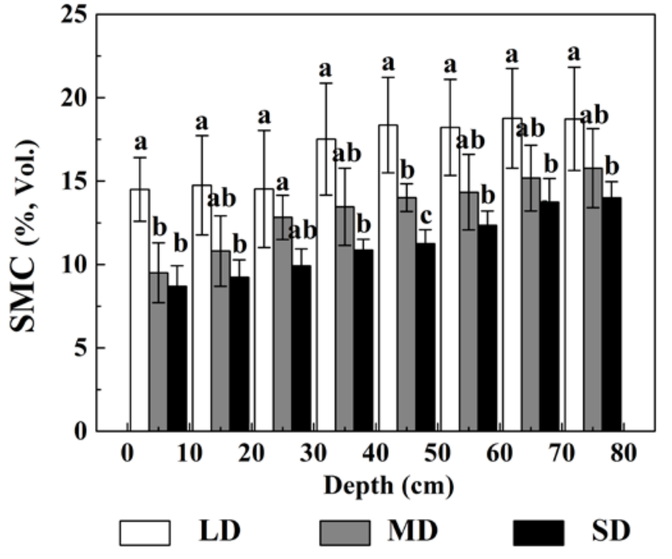



**Figure 5: Changes of soil moisture content (SMC) with increasing degradation degrees. Error bars denote the standard deviation of the 3 sites of the same degradation degree. The letters above the bars denotes the significant difference (p<0.05) between different degradation degrees.**

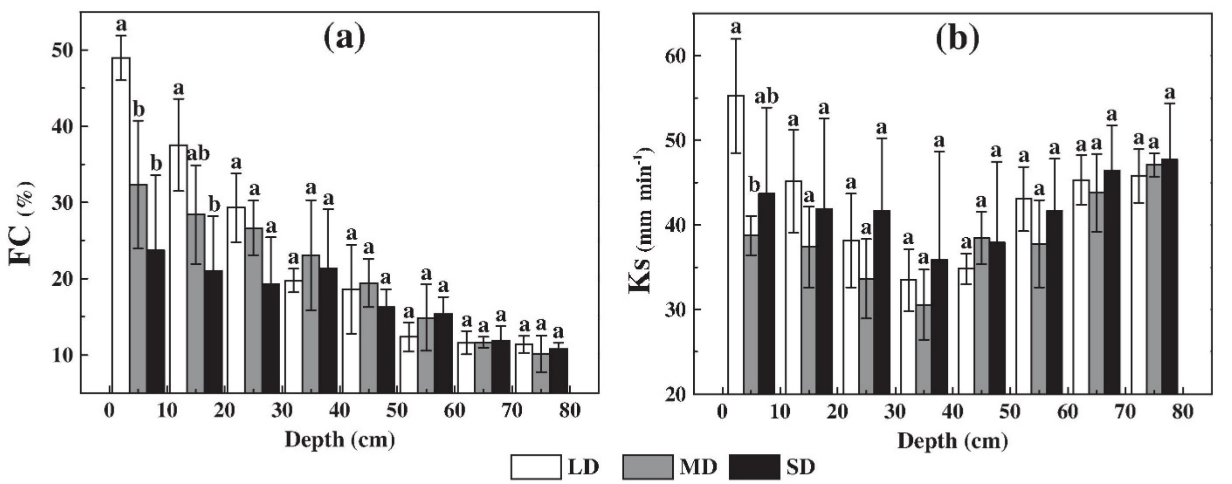


**Figure 6: Difference in degradation degree for FC and Ks. Error bars denote the standard deviation of the 3 sites of the same degradation degree. The letters above the bars denotes the significant difference ($p<0.05$) between different degradation degrees.**

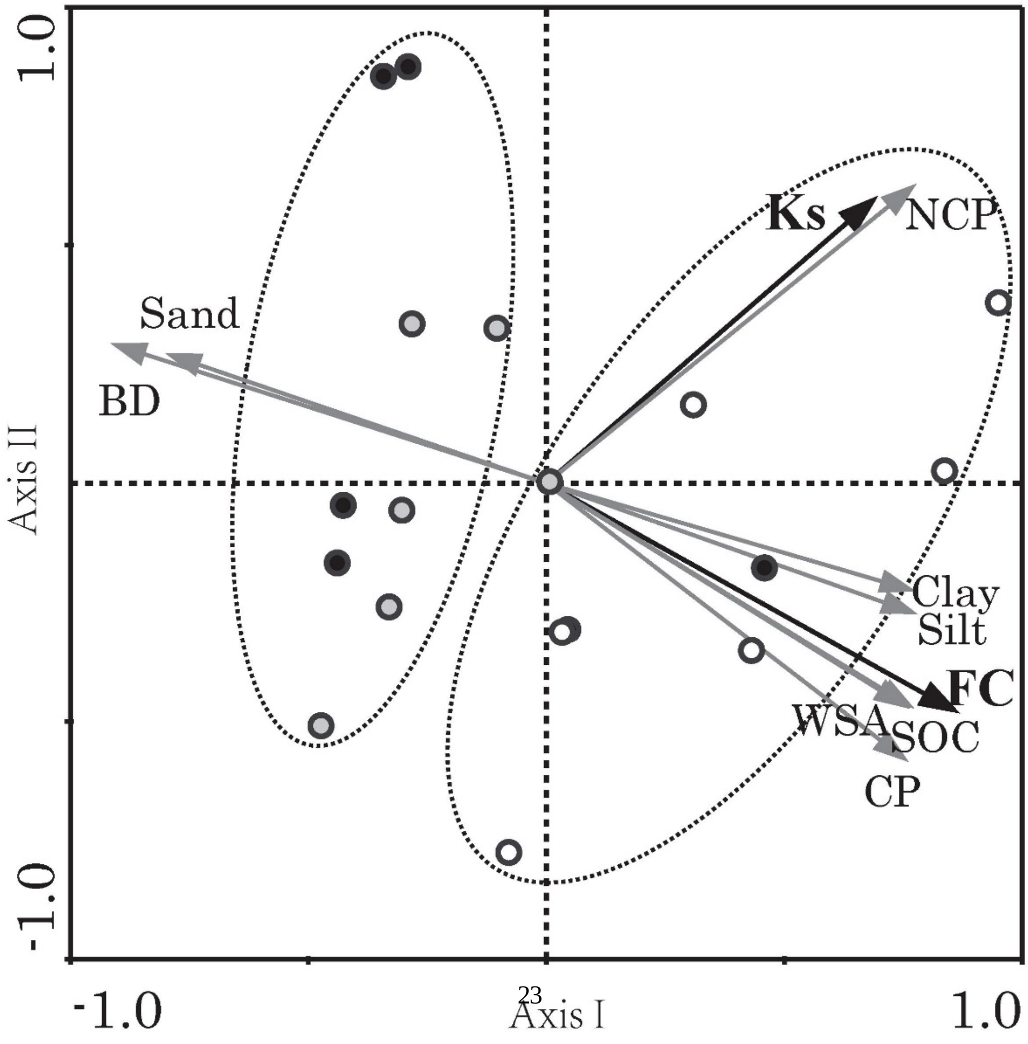


**Figure 7: Redundancy analysis of soil hydraulic properties and basic properties under different degradation stages. Symbols '○', '●' and '●' denote soil samples from LD, MD and SD, respectively.**