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Organic matter controls of soil water retention in an alpine grassland and its significance for hydrological processes

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SUMMARY

Soil water retention influences many soil properties and soil hydrological processes. The alpine meadows and steppes of the Qilian Mountains on the northeast border of the Qinghai-Tibetan Plateau form the source area of the Heihe River, the second largest inland river in China. The soils of this area therefore have a large effect on water movement and storage of the entire watershed. In order to understand the controlling factors of soil water retention and how they affect regional eco-hydrological processes in an alpine grassland, thirty-five pedogenic horizons in fourteen soil profiles along two facing hillslopes in typical watersheds of this area were selected for study. Results show that the extensively-accumulated soil organic matter plays a dominant role in controlling soil water retention in this alpine environment. We distinguished two mechanisms of this control. First, at high matric potentials soil organic matter affected soil water retention mainly through altering soil structural parameters and thereby soil bulk density. Second, at low matric potentials the water adsorbing capacity of soil organic matter directly affected water retention. To investigate the hydrological functions of soils at larger scales, soil water retention was compared by three generalized pedogenic horizons. Among these soil horizons, the mattic A horizon, a diagnostic surface horizon of Chinese Soil Taxonomy defined specially for alpine meadow soils, had the greatest soil water retention over the entire range of measured matric potentials. Hillslopes with soils having these horizons are expected to have low surface runoff. This study promotes the understanding of the critical role of alpine soils, especially the vegetated surface soils in controlling the eco-hydrological processes in source regions of the Heihe River watershed.

1. Introduction

Soil water retention is an important soil hydraulic property which governs soil water storage, redistribution, availability and potential evaporation, and thus has profound influences on hydrological processes and ecological functions in terrestrial ecosystems. Since direct measurement of soil water contents at different matric potentials is costly and time-consuming, it is desirable to be able to estimate soil water retention through its relation to easily-obtained soil properties. Among the factors that affect soil water retention soil particle size distribution, soil organic matter and soil bulk density are generally recognized as the most important ones, which are widely used in pedotransfer functions (PTFs) for predicting soil water retention (Kern, 1995; Wösten et al., 2001; Saxton and Rawls, 2006). Other soil properties, such as soil structure, cation exchange capacity, carbonate content, plastic limit and specific surface area are also related to soil water retention and are often used as additional factors in the PTFs (Pachepsky et al., 2006; Hong et al., 2013; Khlosi et al., 2013). PTFs are empirical functions, which do not give much insight into the underlying mechanisms on how the included factors affect soil hydrology. There is no universal PTF, and perhaps none can be expected, considering the diversity of world soils. How soil water retention is conditioned by its functional factors varies from site to site according to local conditions (Kern, 1995; Wösten et al., 2001; Pachepsky et al., 2006).

Although PTFs are generally built for practical purposes, i.e. to compute hydrological properties from available soil properties, they can also be used to gain insight into soil hydrology. The soil properties that enter a PTF and their relative statistical significance reveal the controls on soil hydrology. In particular, different PTFs for water retention at different matric potentials can reveal what

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controls retention as water potential changes. This process can feed back to practical purpose: to know how and to what extent soil water retention is affected by various soil properties in diverse environments would promote our recognition of the applicability and limitations in building or selecting PTFs.

Soil particle size distribution or soil texture is the most commonly used soil property used in predicting soil water retention (Wösten et al., 2001). Clay content is believed to increase soil water retention, especially at lower matric potentials because of its adsorptive effects while silt and sand components usually function to reduce water retention (Khlosi et al., 2013; McBride and Mackintosh, 1984). Soil bulk density is in large part a function of soil structure, and so has a close correlation with soil porosity and water retention (Ruehlmann and Körschens, 2009). Soil organic matter affects soil water retention because of its affinity to water and also its influence on soil structure and bulk density. However, effects of soil organic matter on soil water retention have been shown to depend on the proportions of textural components and the amount of soil organic matter (Rawls et al., 2003).

On the Qinghai-Tibetan Plateau, alpine grassland (alpine meadow and alpine steppe) is the most widespread ecosystem (Yang et al., 2008). Soils of the alpine grasslands typically have a grass-roots intertwined surface horizon, which have been recognized in Chinese Soil Taxonomy as the 'mattic' diagnostic epipedon (Gong, 1999; Kaiser et al., 2008; Zeng et al., 2013), so named because it appears as a mat on the soil surface. The Chinese name for this horizon is directly translated as "grass felt", which gives another impression of its nature. This surface soil layer is only found in high altitude cold environments. For much of the year surface soils in these environments are frozen and so have low biological activity, while during the mild rainy summer season water often stagnates in the topsoil (Chinese Academic Expedition Group, 1985; Bao, 1992). Both of these conditions reduce organic matter decomposition, so that it is extensively accumulated in the mattic horizon. This is usually combined with a sharp decrease in soil organic matter contents with soil depth (Yang et al., 2008; Liu et al., 2012). Consequently, soils of the alpine grasslands on the Qinghai-Tibetan Plateau have a large storage of organic matter in different decomposition stages, and also a great variation at profile scale. Recently, a great deal of research focusing on soil organic carbon had been carried out on the Qinghai-Tibetan Plateau. Several studies conclude that soil moisture, rather than temperature, has the most significant influence on soil organic matter (Yang et al., 2008, 2009; Liu et al., 2012; Baumann et al., 2009). Soil water contents and distribution patterns control the storage and the patterns of soil organic matter both at regional and soil profile scales. However, in this cold alpine region, little attention has been paid to the inverse relation, i.e., the effect of soil organic matter on soil water retention that could profoundly influence soil water regime.

Our study was carried out on a grassland within an alpine watershed in the northeast border of the Qinghai-Tibetan Plateau, the source region of the Heihe River, the second largest inland river in China, draining an area of about 150,000 km^2. The eco-hydrological characteristics of the grassland ecosystem, such as water infiltration, water consumption by evapotranspiration, water storage in soil, runoff generation as well as plant growth and soil development, determine to a great extent the discharge of the Heihe River.

The aim of this study is to determine soil water retention characteristics of alpine grassland soils and their determining soil properties as evidenced by PTFs, especially the role of soil organic matter. As part of this, we develop site and matric-potential specific PTFs with possible predictors soil organic matter, bulk density and particle-size fractions. We include the evidence of previous works on watershed hydrology and soil hydrological behaviors in the same or adjacent regions (Yang et al., 2011, 2012; He et al., 2012; Zeng et al., 2013) to discuss the role of soils in conditioning hydrological processes at watershed scale.

2. Materials and methods

2.1. Study site and soils

The study site is situated in the Qilian Mountains, northeast border of the Qinghai-Tibetan Plateau (Fig. 1). Two opposing hilly slopes with contrasting landscape and hydrologic conditions were selected for soil sampling. The north-facing one (sites N1–N9) named Hulugou is a representative catchment in the upper reach of the Heihe River, which has a diverse landscape, including (from upper to lower) a glacier-snow zone, alpine cold desert, marsh meadow, alpine shrub and meadow mixed zone, and alpine steppe (Yang et al., 2011). The south-facing one (sites S1–S5) consists mainly of alpine meadow and alpine steppe landscape. Overall, the north-facing hillslope has higher vegetation coverage than the south-facing one. Many researches have demonstrated that soils on north-facing slopes generally have greater organic matter content than south-facing soils; solar radiation is assumed to be the driving force of these differences (Franzmeier et al., 1969; Geroy et al., 2011). However, in our study area, such differences may be enhanced by the water supplied by melting glaciers and permafrost above the north-facing hillslope (Yang et al., 2011, 2013).

In this study, we only consider soils within alpine grassland where the dominant herb species are *Carex melantha*, *Kobresia capillifolia* and *Polygonum viviparum*. The altitude of the watershed ranges from 2960 m to 4800 m, and our sampling sites from 2978 m to 3642 m, the altitude belt of alpine grassland. Meteorological data were measured by the Heihe Upstream Watershed Ecology-Hydrology Experimental Research Station, which is situated at the junction of these two contrasting hillslopes near the lowest elevation. The mean annual temperature was about 0.2 °C, with a highest mean monthly temperature of 19.0 °C in July and the lowest of -18.4 °C in January. Mean annual precipitation was 495.1 mm, with 80–93% concentrated in the period from June to October.

Soils in the study area are relative young and mostly poorly-developed. Entisols, Inceptisols and Mollisols are the dominant US Soil Taxonomy (Soil Survey Staff, 2014) orders, Gelisols only appear above 3600 m and Histosols are sporadically distributed in depressions. Our samples cover Mollisols, Inceptisols, and Histosols. Typically soils have an Ao–Bw–2C horizon sequence in the north facing hillslope, but an Ao–Bk–C sequence in the south facing hillslope, due to the accumulation of carbonates as a result of the higher evaporation on the south-facing slope (Fig. 2). Mattic horizons (Ao) are characterized by dense grass roots, high organic matter content, low bulk density and granular soil structure; genetic B horizons (Bw, Bk) have a weak blocky structure and low density of grass roots; C horizons have no structure, very little organic matter and essentially no roots. Lithological discontinuity is widespread in this area and is usually formed by silty materials covering glacial debris (2C). The silt-enriched surface soil horizons are thought to have aeolian origins, as in some other alpine soils (Muhs and Benedict, 2006; Phillips and Lorz, 2008; Lehmkuhl, 1997; Lawrence et al., 2013).

2.2. Field methods

Fourteen sites were selected along these two hillslopes (nine in the north, five in the south) (Fig. 1) considering altitude, slope gradient, slope aspect and slope form. Soil profiles were excavated and described in the field using standard soil survey methods. Bulk