Soil Water Holding Capacity and Influencing Factors under Different Land Use Patterns in the Qinghai Alpine Region: Postprint

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Abstract

Along a 550 km north-south transect in eastern Qinghai Province, three land use types (cropland, forestland, and grassland) were selected to analyze the variation characteristics of soil water holding capacity and its influencing factors under different land use types by measuring soil maximum water holding capacity (MC), capillary water holding capacity (CC), field water holding capacity (FC) at different depths (0–10 cm, 10–20 cm, 20–30 cm) and basic soil physicochemical properties. The results showed that: (1) The mean values of MC, CC, and FC for 0–30 cm soil in forestland and grassland were 526.83 g · kg-1, 469.75 g · kg-1, 408.29 g · kg-1 and 506.17 g · kg-1, 446.37 g · kg-1, 384.89 g · kg-1, respectively, which were significantly higher than those in cropland (306.62 g · kg-1, 254.25 g · kg-1, 227.12 g · kg-1) ($P<0.05$). (2) The soil water holding capacity (MC, CC, FC) in forestland and grassland gradually decreased with increasing soil depth, whereas no obvious variation pattern was observed for 0–30 cm soil water holding capacity in cropland due to compaction effects. (3) Principal component analysis results indicated that soil bulk density, porosity, and particle composition contributed cumulatively 79.07%–94.79% to the soil water holding capacity (MC, CC, FC) in cropland, forestland, and grassland. (4) Redundancy analysis results showed that the explanatory power of different environmental factors on soil water holding capacity in cropland, forestland, and grassland, from high to low, was: mean annual evaporation, elevation, mean annual precipitation, and latitude. The research findings can provide a basis for soil quality assessment and water management under different land use types in alpine regions.

Full Text

Soil Water Holding Capacity and Influencing Factors under Different Land Use Patterns in the Qinghai Alpine Region

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Abstract

This study measured the maximum soil water holding capacity (MC), capillary water capacity (CC), field capacity (FC), and basic soil physicochemical properties across different soil layers (0–10, 10–20, and 20–30 cm) under three land use patterns—agriculture, forestry, and grassland—along a 550 km north-south transect in eastern Qinghai Province. Results showed that: (1) The mean MC, CC, and FC in the 0–30 cm soil layer of forestland were 526.83 $g \cdot kg^{-1}$, 469.75 $g \cdot kg^{-1}$, and 408.29 $g \cdot kg^{-1}$, respectively. For grassland, the corresponding values were 506.17 $g \cdot kg^{-1}$, 446.37 $g \cdot kg^{-1}$, and 384.89 $g \cdot kg^{-1}$, respectively. All these values were significantly higher than those of farmland (306.62 $g \cdot kg^{-1}$, 254.25 $g \cdot kg^{-1}$, and 227.12 $g \cdot kg^{-1}$, respectively; $P < 0.05$). (2) The MC, CC, and FC of forestland and grassland decreased gradually with increasing soil depth, whereas farmland showed no obvious changes in these parameters with depth due to soil compaction. (3) Principal component analysis revealed that soil bulk density, porosity, and particle composition cumulatively contributed 79.07%–94.79% to the variation in soil water holding capacity (MC, CC, and FC) across farmland, forestland, and grassland. (4) Redundancy analysis indicated that the explanatory power of different environmental factors on soil water holding capacity, from highest to lowest, was: annual evaporation, altitude, annual rainfall, and latitude. These findings provide a scientific basis for soil quality assessment and water management strategies under different land use patterns in alpine regions.

Keywords: alpine region; land use pattern; soil water holding capacity; influencing factors; Qinghai

1. Introduction

Soil water holding capacity is a critical indicator for evaluating soil water conservation functions and plays a vital role in ecological community restoration and reconstruction. Maximum water holding capacity (MC), capillary water capacity (CC), and field capacity (FC) directly reflect soil water retention capabilities while indirectly indicating water redistribution capacity. Soil water holding capacity is influenced by multiple factors, including soil bulk density, porosity, organic matter content, environmental conditions, and vegetation type [?]. Clarifying the variation characteristics of soil water holding capacity and its influencing factors in different regions provides essential references for soil quality assessment, regional water regulation, and improved understanding of vegetation water utilization in alpine zones.

In recent years, numerous scholars have investigated the spatiotemporal variability of soil water holding capacity and its influencing factors [?], yielding significant advances. For instance, Wang et al. [?] found that capillary porosity and organic matter content were the primary factors affecting soil water holding capacity in the Qinghai alpine region. Gao et al. [?] examined how different fertilization practices affected water holding capacity in the Loess Plateau dryland region, demonstrating that organic fertilizer application increased soil organic matter and improved water retention performance. Zhao et al. [?] reported that land use patterns significantly influenced soil water holding capacity in the eastern Qilian Mountains alpine region. Li et al. [?] identified slope aspect, gradient, bulk density, soil texture, and organic carbon content as key factors affecting soil water holding capacity in Xinjiang' s arid region. Collectively, these studies reveal that dominant controlling factors vary significantly across different regions and spatial scales.

Despite extensive research on soil water holding capacity and its influencing factors, few studies have examined variation characteristics under different land use patterns in alpine regions, limiting understanding of water transport processes and runoff mechanisms in alpine ecosystems. To address this knowledge gap, this study selected three land use types—agriculture, forestry, and grassland—along a 550 km north-south transect in eastern Qinghai. By measuring soil water holding capacity (MC, CC, FC) and basic physicochemical properties across different depths (0-10, 10-20, and 20-30 cm), we analyzed variation characteristics and influencing factors under different land use patterns, aiming to provide a scientific basis for soil quality assessment and water management in alpine regions.

1.1 Study Area

The study area is located in eastern Qinghai Province (98°23 -102°29 E, 32°52 -36°13 N), situated in the transition zone between the Tibetan Plateau and the Loess Plateau, with elevations ranging from 1894 to 4547 m and a general west-to-east downward slope. The region features a plateau continental climate with long sunshine hours (average annual sunshine duration: 2553 h), mean annual temperatures between -9.2 and 7.3 °C, and annual precipitation ranging from 395 to 943 mm. Precipitation is unevenly distributed, concentrated primarily in June–September. Annual evaporation ranges from 395 to 1097 mm. Dominant soil types include mountain brown-cinnamon soil, chestnut soil, black loam, gray-cinnamon soil, and meadow soil. Major tree species include *Populus cathayana*, *Picea crassifolia*, and *Sabina przewalskii*. Primary shrubs are *Hippophae rhamnoides*, *Potentilla fruticosa*, and *Berberis thunbergii*. Dominant herbaceous species include *Stipa capillata* and *Elymus nutans*.

1.2 Sample Collection and Analysis

In July 2019, after investigating the topography, vegetation types, and elevation in eastern Qinghai, we established a 550 km north-south transect using a high-density sampling strategy (approximately 10 km between sample points). Based on representativeness and typicality principles, we selected 55 sampling sites across three land use types: farmland, forestland, and grassland [Figure 1: see original paper]. At each site, we collected three undisturbed soil cores and three disturbed soil samples from three depths (0–10, 10–20, and 20–30 cm), totaling 165 undisturbed and 165 disturbed samples.

Undisturbed samples were used to determine soil bulk density, porosity, and water holding capacity. Soil bulk density was measured by oven-drying the cores at 105 °C to constant weight. For water holding capacity measurements, saturated cores were weighed immediately after soaking to determine MC. These saturated cores were then placed on sand-filled trays for 2 hours before weighing to determine CC. After an additional 24 hours on sand-filled trays, the cores were weighed again to determine FC. Disturbed soil samples were air-dried, cleared of debris, roots, and gravel, ground, and passed through 2 mm and 0.25 mm sieves. Soil organic matter content was determined using the potassium dichromate oxidation-external heating method [**?**]. Soil particle size distribution was measured using a Mastersizer 2000 laser particle size analyzer and classified according to the international system: clay (<0.002 mm), silt (0.02–0.002 mm), and sand (2–0.02 mm).

1.3 Data Analysis

Statistical analyses, including one-way ANOVA, correlation analysis, and principal component analysis (PCA) of soil water holding capacity and basic physicochemical properties, were performed using SPSS 25.0. Graphs were created using Origin 9.65. Redundancy analysis (RDA) was conducted using Canoco 5.0 to examine relationships between environmental factors and soil water holding capacity.

2. Results

2.1 Soil Bulk Density and Porosity under Different Land Use Patterns

Soil bulk density and porosity are key indicators of soil compaction, governing water flow and storage. Land use patterns significantly affect these properties. Figure 1 and Table 1 show the distribution characteristics of soil bulk density and porosity under different land use patterns. Across 0–30 cm depth, mean bulk density was highest in farmland (1.46 $g \cdot cm^{-3}$) and lowest in forestland (1.12 $g \cdot cm^{-3}$). Except for the 0–10 cm layer, all depths showed significant differences in bulk density among land use types ($P < 0.05$), with farmland > grassland > forestland. Within each land use type, bulk density increased significantly with depth in forestland and grassland ($P < 0.05$) but showed no significant differences across depths in farmland ($P > 0.05$).

Mean capillary porosity and total porosity (0–30 cm) followed the order: forestland > grassland > farmland, with significant differences among all land use types ($P < 0.05$). Non-capillary porosity was highest in farmland at 0–10 cm but lowest at 10–20 cm and 20–30 cm. In forestland and grassland, capillary and total porosity decreased significantly with depth ($P < 0.05$), while non-capillary porosity showed no clear pattern.

2.2 Soil Water Holding Capacity under Different Land Use Patterns

Soil water holding capacity varied significantly among land use types. Figure 2 shows that mean MC, CC, and FC (0–30 cm) were highest in forestland (526.83, 469.75, and 408.29 $g \cdot kg^{-1}$, respectively) and lowest in farmland (306.62, 254.25, and 227.12 $g \cdot kg^{-1}$, respectively), with forestland and grassland values significantly exceeding farmland ($P < 0.05$). Forestland and grassland showed no significant differences between them ($P > 0.05$).

In forestland and grassland, MC, CC, and FC decreased gradually with increasing soil depth, consistent with findings from the eastern Qilian Mountains [?]. Farmland showed no clear pattern with depth, likely due to compaction effects. At 0–10 cm, MC, CC, and FC were significantly higher in forestland and grassland than farmland ($P < 0.05$). At 10–20 cm and 20–30 cm, the order was: forestland > grassland > farmland.

2.3 Relationships between Soil Physicochemical Properties and Water Holding Capacity

Soil water holding capacity exhibited strong heterogeneity due to influences from soil texture, porosity, bulk density, and nutrients. Figure 3 shows correlation coefficients between soil water holding capacity (MC, CC, FC) and soil properties (bulk density, non-capillary porosity, total porosity, clay content, silt content, sand content). Correlation patterns were generally consistent across land use types. In farmland, MC, CC, and FC were significantly negatively correlated with bulk density and sand content but positively correlated with total porosity, clay content, and silt content ($P < 0.05$). In forestland and grassland, water holding capacity was significantly positively correlated with total porosity, clay content, and silt content but negatively correlated with bulk density and sand content ($P < 0.05$).

Because soil properties are inherently autocorrelated, simple correlation analysis cannot fully capture these relationships. Therefore, we conducted PCA using significantly correlated factors (Table 2). For farmland, two principal components explained 91.87% of variance, with PC1 (71.82% variance) dominated by total porosity, clay content, and silt content. For forestland, three components explained 94.79% of variance, with PC1 (52.53% variance) dominated by total porosity and clay content. For grassland, two components explained 79.07% of variance, with PC1 (64.10% variance) dominated by total porosity, clay content, and silt content. Overall, soil bulk density, porosity, and particle composition were the dominant factors controlling soil water holding capacity across all land use types in the Qinghai alpine region.

2.4 Relationships between Environmental Factors and Soil Water Holding Capacity

Redundancy analysis examined relationships between soil water holding capacity and environmental factors (annual rainfall, annual evaporation, NDVI, surface roughness, altitude, latitude). The first two axes explained 51.99% and 1.24% of variance in water holding capacity, respectively, with a cumulative explanation of 99.73% for the relationship between water holding capacity and environmental factors. Monte Carlo permutation tests confirmed the reliability of the ordination ($F = 2.10$, $P < 0.05$).

Figure 4 shows the two-dimensional ordination. Longer arrows for altitude, annual evaporation, and annual rainfall indicate greater explanatory power. The acute angle between water holding capacity and altitude/annual rainfall indicates positive relationships, while the obtuse angle with annual evaporation indicates a negative relationship. Monte Carlo tests (Table 3) ranked environmental factors by importance: annual evaporation (33.60%), altitude (29.30%), annual rainfall (20.40%), and latitude (16.90%).

3. Discussion

Soil bulk density and porosity are critical indicators of soil compaction, directly affecting water flow and storage. Land use patterns significantly influence these properties. In our study, farmland exhibited significantly higher bulk density and lower porosity than forestland and grassland due to long-term mechanical compaction from tillage, creating a plow pan layer beneath the cultivation horizon [**?**]. This finding aligns with previous research on the Yellow River Delta [**?**].

In forestland, extensive canopy cover and biomass produce abundant litter and roots that undergo biochemical transformation into organic matter. Root systems also enmesh fine particles into larger aggregates and secrete binding agents that promote aggregate formation, thereby reducing bulk density and increasing porosity [?]. Consequently, forestland porosity significantly exceeded that of grassland and farmland. This pattern is consistent with studies on soil physical properties in the Yellow River Delta [?].

Soil water holding capacity is a crucial factor determining ecosystem water conservation and represents one of the most important soil physical properties. It is comprehensively influenced by bulk density, porosity, particle composition, environmental factors, and land use patterns [?]. Our results demonstrate that loose soils with high porosity and low bulk density exhibit stronger water holding capacity, whereas compacted soils with low porosity and high bulk density show reduced capacity. Among land use types, forestland had the lowest bulk density and highest porosity, resulting in the greatest water holding capacity. Farmland, due to long-term compaction, had the highest bulk density and lowest porosity, yielding the lowest water holding capacity. Grassland fell between these extremes, consistent with findings from other studies [?].

Correlation analysis revealed that capillary porosity exerted stronger effects on water holding capacity than non-capillary porosity in both forestland and grassland, consistent with Wang et al. [?]. The weak relationship between water holding capacity and clay content in farmland may reflect its sandy loam texture (sand content $> 50\%$, clay content $< 20\%$), where clay content has limited influence on water retention.

PCA results confirmed that soil bulk density, porosity, and particle composition were the dominant controls on water holding capacity. Wen et al. [?] reported similar findings in Hainan' s tropical region, where water holding capacity increased with total porosity and decreased with bulk density. Yang et al. [?] corroborated these relationships.

RDA identified annual evaporation, altitude, annual rainfall, and latitude as the primary environmental factors influencing water holding capacity. This differs from Li et al.' s [?] findings in Xinjiang' s arid region, likely reflecting distinct climatic conditions. Latitude and altitude are key determinants of temperature, affecting solar radiation, day length, and solar angle. In the Qinghai alpine region, higher altitudes correspond to lower temperatures despite lower latitudes, with temperature decreasing approximately 0.6 °C per 100 m elevation gain. Precipitation is the sole water source, while evaporation is the main loss pathway. Temperature strongly influences evaporation rates. Higher altitudes reduce surface temperatures, increase precipitation, decrease microbial activity, and enhance organic matter accumulation, thereby improving soil structure [?]. Consequently, soils at lower latitudes, higher altitudes, with greater rainfall and less evaporation exhibit higher water holding capacity.

4. Conclusions

Comparative analysis of soil water holding capacity under different land use types in the Qinghai alpine region yields the following conclusions:

1. Mean MC, CC, and FC (0–30 cm) across different land use types followed the order: forestland > grassland > farmland. Agricultural use significantly reduced soil water holding capacity compared to forestland and grassland.

2. In forestland and grassland, root biomass decreased with soil depth, leading to reduced porosity and water holding capacity with depth. In farmland, long-term tillage created a compacted plow pan beneath the cultivation layer, resulting in no clear depth-related pattern in water holding capacity.

3. Correlation analysis showed that capillary porosity had greater effects on water holding capacity than non-capillary porosity in forestland and grassland, consistent with previous research [**?**].

4. Soil bulk density, porosity, and particle composition were the dominant factors controlling water holding capacity across all land use types.

5. RDA revealed that environmental factors explained water holding capacity variation in the order: annual evaporation > altitude > annual rainfall > latitude.

Forestland and grassland in the Qinghai alpine region demonstrate stronger water holding capacity, while agricultural use significantly reduces this capacity. Therefore, establishing forest conservation zones, implementing appropriate grassland enclosure management, and integrating cultivation with soil conservation practices are essential pathways for improving local soil quality and water conservation.

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Note: Figure translations are in progress. See original paper for figures.