Variation Characteristics of Soil Moisture under Different Land Use Patterns in the Loess Hilly Region: Postprint

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Abstract

This study investigated different land use types in the Zhuan Yaogou watershed of the loess hilly region. Soil water content in the 0-300 cm soil layer was monitored from June to November 2016 to analyze the vertical profile distribution and seasonal variation characteristics of soil water storage under six land use types: Robinia pseudoacacia forest, grassland, Caragana shrubland, Populus simonii forest, Malus micromalus forest, and abandoned farmland. The results indicated: (1) Soil water content exhibited an S-shaped vertical distribution from top to bottom, showing a trend of initial increase followed by decrease with depth, demonstrating distinct vertical variability. (2) Different land use types exhibited distinct soil moisture profiles, with varying depth ranges for the soil water active layer, sub-active layer, and relatively stable layer. (3) Soil water storage in each layer under all six land use types showed significant seasonal variation. Malus micromalus forest had the highest soil water storage at 258.21 mm, followed by Populus simonii forest, abandoned farmland, grassland, and Robinia pseudoacacia forest, while Caragana shrubland had the lowest. During the monitoring period, soil water storage increased over time, reaching its maximum in November. The coefficient of variation of soil water content decreased gradually with soil depth, with seasonal variation stabilizing in the deep soil below 100 cm. The study concluded that arbor and shrub forests consume more deep soil water, Caragana shrubland is prone to soil desiccation, Malus micromalus forest has favorable soil water conditions, and abandoned farmland and grassland have relatively stable soil water conditions.

Full Text

Preamble

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Water Characteristics of Soil Under Different Land-Use Types in the Loess Plateau Region

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Abstract

This study investigated soil moisture characteristics under different land-use types in the Loess Plateau hilly region, using the Zhuanyaogou watershed as the research area. Soil water content was monitored from June to November 2016 across six land-use types: *Robinia pseudoacacia* forest, *Caragana korshinskii* shrubland, *Populus simonii* forest, *Malus micromalus* Makino, grassland, and abandoned land. Sampling was conducted at 20 cm intervals within the 0–300 cm soil profile. The results showed that: (1) Soil water content initially increased then decreased with depth across all land-use types. (2) The depth ranges of the active layer, secondary active layer, and relatively stable layer varied among land-use types. (3) Soil water storage capacity in each layer exhibited distinct seasonal variation patterns. The highest water storage capacity (258.21 mm) was observed in *Malus micromalus* Makino, followed by *Robinia pseudoacacia*, *Populus simonii*, abandoned land, grassland, and *Caragana korshinskii* (lowest). During the monitoring period, soil water storage generally increased over time, reaching its maximum in November. The coefficient of variation for soil water content gradually decreased with depth, stabilizing below 100 cm. Trees and shrubs consumed more deep soil water, potentially causing soil desiccation. *Malus micromalus* Makino maintained favorable soil water conditions, while abandoned land and grassland showed relatively stable soil moisture regimes.

Keywords: Loess Plateau; soil water content; soil water storage; soil depth; land-use type

Introduction

Soil moisture is a critical factor linking soil-atmosphere interactions and serves as an essential carrier for material and energy cycling within soil systems, significantly influencing vegetation growth, distribution patterns, and regional ecosystems. The Loess Plateau hilly region is characterized as an arid and semi-arid area with scarce precipitation resources, severe soil erosion, and challenging vegetation restoration. Climate conditions and natural selection have resulted in sparse natural forests, with major artificial plantation species including *Populus simonii*, *Robinia pseudoacacia*, *Larix principis-rupprechtii*, and various hybrid poplars, sea buckthorn, and *Caragana* shrubs. Large-scale vegetation restoration efforts have led to excessive soil water depletion, indicating potential issues in ecological restoration processes. Soil moisture is affected by multiple factors including precipitation, vegetation type, and land-use patterns, and understanding its dynamics under different land-use scenarios is crucial for improving the ecological environment and water resource utilization efficiency in the Loess Plateau region.

Numerous studies have investigated soil moisture issues in this region. Wang et al. examined soil water variation characteristics and replenishment/consumption depths under different land-use types in the Changwu Loess Tableland. Mo et al. analyzed soil moisture distribution patterns on different slopes in mature *Caragana* shrublands in semi-arid Loess areas. Liu et al. studied soil hydraulic properties and their impacts on soil moisture in the Liudaogou watershed. Bai et al. investigated slope soil moisture characteristics in the wind-water erosion crisscross zone, while Zhang et al. used grey correlation analysis to examine soil moisture status and monthly dynamics under various land-use types including terraces and sea buckthorn plantations. Wang et al. analyzed influencing factors such as slope gradient, stable infiltration rate, crop transpiration, and biomass in the Zhifanggou watershed. Gao et al. compared soil water infiltration patterns using double-ring and artificial rainfall methods. Cheng et al. studied soil profile texture, water-holding characteristics, and their relationships with soil moisture distribution. Xia et al. summarized that both forest composition and land-use type significantly affect soil infiltration, with shrublands showing the strongest improvement in infiltration capacity by influencing soil physical properties like porosity. Jia et al. conducted quantitative evaluations of soil erosion under different land-use scenarios using the AnnAGNPS model, providing a foundation for further soil moisture research in the Zhuanyaogou watershed.

Despite extensive research, comprehensive studies combining forest and grassland vegetation to examine soil moisture conditions under typical land-use types in the Loess Plateau hilly region remain limited. This study addresses this gap by systematically analyzing soil moisture conditions across six representative land-use types in the Zhuanyaogou watershed, aiming to clarify water activity layer distribution characteristics and reveal vertical distribution and seasonal variation patterns of soil moisture, thereby providing scientific basis for water resource utilization and theoretical guidance for vegetation restoration and allocation in the Loess Plateau hilly region.

1. Study Area Overview

This study was conducted in the Zhuanyaogou watershed, located in central-west Hequ County, Shanxi Province, adjacent to Huangpuchuan in Shaanxi to the north, Nanqugou to the south, and connected to the Xianchuan River. The geographic coordinates are 39°11 06 N–39°13 47 N, 111°12 03 E–111°19 28 E, covering an area of 28.7 km². The region belongs to the Loess Plateau hilly area with a warm temperate continental monsoon climate. The average annual precipitation is 447 mm, with more than half concentrated in July–September. The average annual temperature is 8.8°C, with 10°C accumulated temperature of 3360°C. The elevation ranges from 840–1243 m, with an average annual wind speed of 1.64 m/s and prevailing southwest winds. The soil is primarily chestnut soil with loess as the parent material, featuring granular and fragmented structures with certain water-holding capacity.

2. Sample Plot Selection

Based on existing research and analysis of remote sensing imagery combined with field surveys of major land-use types in the Zhuanyaogou watershed, different forest and shrub plots were selected. Grassland plots represented well-growing native grasslands dominated by *Artemisia sacrorum* and *Heteropappus altaicus*. Artificial forests included *Robinia pseudoacacia*, *Populus simonii*, and *Malus micromalus* Makino. Shrubland consisted of *Caragana korshinskii*. Abandoned land (15 years) served as the control, dominated by *Artemisia sacrorum* and *Stipa bungeana*. Sample plot locations are shown in [Figure 1: see original paper] and basic plot information is provided in .

3. Experimental Design

Soil water content was measured using the oven-drying method. From June to November 2016, soil samples were collected from each plot during the last ten days of each month. In each 0–300 cm profile, samples were taken at 20 cm intervals. Five random samples were collected per plot, placed in aluminum boxes, and oven-dried at 105-108°C to determine water content. The arithmetic mean was calculated for each layer. Bulk density was measured using the ring knife method for the 0-100 cm layer. Precipitation was recorded using rain gauges during the study period. In 2016, total precipitation was 471 mm, with 118 mm (25.05%) concentrated in July.

4. Data Processing

Soil mass water content and water storage were calculated using the following formulas:

Soil mass water content (%) = (wet soil + box weight - dry soil + box weight) / (dry soil + box weight - empty box weight) × 100

Soil water storage (mm) = soil bulk density (g/cm³) × soil water content (%) × soil layer depth (cm) / 10

All data were analyzed and plotted using Microsoft Excel, SPSS 17.0, and Origin

2017. Standard deviation methods were applied to analyze seasonal variation characteristics.

1. Vertical Profile Distribution Characteristics of Soil Moisture Under Different Land-Use Types

The vertical distribution of soil water content in June–November showed that soil moisture changed dramatically with depth in the 0-100 cm layer across all six land-use types. A common pattern emerged: soil water content initially increased then decreased with depth. The variation attenuated significantly below 100 cm.

Robinia pseudoacacia forest showed consistent monthly trends, with substantial variation in the 0-120 cm layer. Soil moisture increased with depth initially, then decreased rapidly below 120 cm, stabilizing in the 120-300 cm layer. *Populus simonii* forest exhibited consistently high water content across months, with maximum values in the 0-140 cm layer and stabilization below 140 cm. *Malus micromalus* Makino maintained higher water content than other land-use types, with relatively uniform vertical variation patterns. In the 0-60 cm layer, water content increased with depth, while it decreased rapidly below 60 cm. Abandoned land (control) showed decreasing water content with depth in the 0-140 cm layer, stabilizing below 140 cm.

2. Distribution of Soil Water Active Layers Under Different Land-Use Types

Based on standard deviation (SD) values, soil layers were classified as: active layer (SD $>$ 1.5%), secondary active layer (1% $<$ SD $<$ 1.5%), and relatively stable layer (SD $<$ 1%). All land-use types shared common characteristics: the upper profile showed dramatic water content fluctuations while lower layers remained relatively stable.

The active layer depth varied among land-use types: *Robinia pseudoacacia* (0-80 cm), *Caragana korshinskii* (0-100 cm), *Populus simonii* (0-60 cm), *Malus micromalus* (0-60 cm), grassland (0-60 cm), and abandoned land (0-120 cm). The secondary active layer thickness was generally 20 cm, except for *Malus micromalus* (60 cm) and abandoned land (none). The relatively stable layer began at 80-120 cm depth, with *Robinia pseudoacacia* showing the deepest stable layer (100-300 cm). provides detailed ranges for each plot.

3. Seasonal Variation Characteristics of Soil Moisture Under Different Land-Use Types

Monitoring of 0-300 cm soil water storage from June to November revealed distinct seasonal patterns. The ranking of water storage capacity from highest to lowest was: *Malus micromalus* Makino, *Robinia pseudoacacia*, *Populus simonii*, abandoned land, grassland, and *Caragana korshinskii* (lowest). *Malus micromalus* showed the highest water storage (258.21 mm), reaching 275.52 mm in July, 273.92 mm in August, 278.57 mm in September, and peaking at 316.58 mm in November.

All land-use types exhibited clear seasonal variation in soil water storage, with an overall increasing trend over time that lagged behind precipitation patterns. Water storage peaked in November following the rainy season, demonstrating a hysteresis effect due to the time required for water infiltration and transport through the soil profile. [Figure 2: see original paper] and [Figure 3: see original paper] illustrate these dynamics.

4. Stratified Characteristics of Soil Moisture Seasonal Variation Under Different Land-Use Types

The coefficient of variation (CV) for soil water content decreased progressively with depth across all land-use types, stabilizing in deeper layers. Surface layers (0–20 cm) showed the highest variability, with CV values declining continuously through the 0–140 cm layer. Below 160 cm, seasonal variation remained low and stable.

Robinia pseudoacacia and *Caragana korshinskii* showed the most dramatic decreases in CV with depth, stabilizing below 120 cm. *Populus simonii* exhibited an anomalous pattern where CV increased with depth in the 0–80 cm layer, possibly due to steep slope conditions limiting water storage even during rainy periods. *Malus micromalus* maintained relatively stable CV values across depths. Abandoned land and grassland showed high surface variability that decreased rapidly with depth. [Figure 4: see original paper] depicts these stratified variation patterns.

Discussion

1. Vertical Profile Distribution Characteristics

The deep soil layers in the Loess Plateau hilly region experience relatively simple water cycling dominated by rainfall infiltration, surface evaporation, and plant transpiration, resulting in distinct stratification and variation patterns in soil moisture profiles. The observed trend of increasing then decreasing water content with depth aligns with previous research. Xiao et al. found similar patterns in the Loess Plateau, with 0–100 cm layers showing high moisture and large variation, while layers below 100 cm remained relatively stable. Ma et al. reported comparable vertical trends in the Liupan Mountain region, where soil moisture first increased then gradually decreased with depth.

These patterns reflect the dominant influence of precipitation in surface layers, where soil structure is looser and infiltration capacity higher. With increasing depth, soil structure becomes more compact, infiltration capacity decreases, and moisture conditions become more stable. The formation of different water activity layers is primarily controlled by precipitation and vegetation root distribution. The active layer (0–100 cm) experiences alternating wetting and drying cycles with strong influences from rainfall and evaporation. Below this layer, moisture conditions are mainly determined by vegetation water uptake patterns. The stable layer formation in abandoned land results from limited root distribution and minimal deep water utilization.

2. Seasonal Variation Characteristics

Due to seasonal precipitation variability, soil moisture exhibits typical seasonal patterns influenced not only by rainfall but also by vegetation water consumption during different growth stages and soil evaporation. All six land-use types showed clear seasonal variation in water storage, with a temporary decrease in July followed by increases through November, corresponding to seasonal precipitation patterns but with temporal lag.

This hysteresis effect results from the time required for water to infiltrate and be transported through the soil profile. Cheng et al. found similar seasonal trends in the Changwu Loess Tableland, where bare land, alfalfa fields, and apple orchards showed comparable seasonal patterns in the 0–15 m layer due to rainfall influence, while high-yield farmland variations were more crop-dependent. Wang et al. also reported that seasonal variation in soil water storage aligned with precipitation patterns in the Loess Tableland region.

3. Stratified Variation Characteristics

The consistent trend of decreasing CV with depth across land-use types matches previous Loess Plateau studies. Ma et al. found CV decreasing with depth in the Liupan Mountain region, stabilizing below 100 cm where environmental influences diminished. Xiao et al. reported active moisture changes in the 0–100 cm layer of *Caragana* shrublands, with stabilization below 100 cm.

The study area' s typical monsoon climate with distinct wet/dry seasons means shallow soil moisture is strongly affected by precipitation and temperature, while deeper layers show more stable seasonal patterns. The anomalous pattern in *Populus simonii*, where CV increased with depth in the 0–80 cm layer, may be attributed to steep slopes that prevent long-term water storage even during rainy periods. Liu et al. demonstrated that slope significantly affects soil moisture variation in karst regions, and similar multi-factor interactions likely operate in the Loess Plateau hilly region, warranting further investigation of topographic effects.

Conclusion

1. Soil water content under different land-use types shows typical vertical profile characteristics, initially increasing then decreasing with depth. Varia-

tion is dramatic in the 0–100 cm layer but attenuates significantly below this depth.

2. The depth ranges of active, secondary active, and stable layers differ among land-use types due to varying vegetation water use patterns. Tree and shrub plantations consume more deep soil water, with *Caragana korshinskii* being particularly prone to soil desiccation.
3. Soil water storage shows clear seasonal variation across all land-use types, increasing over time but lagging behind precipitation patterns. The seasonal variation trend aligns with precipitation dynamics.
4. The coefficient of variation for soil water content decreases progressively with depth, showing an inflection point around 100 cm and stabilizing in deep layers where seasonal variation becomes minimal.

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