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Changes in Soil Hydrological Retention Properties and Controlling Factors on Shaded and Sunny Slopes in Semi-Arid Alpine Woodlands

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Abstract: Slope orientation significantly influences soil's physicochemical properties and the soil hydrological environment. However, the regulatory mechanisms and effects, particularly in semi-arid highlands, remain poorly understood. This study investigated soil physicochemical and hydrological properties on shaded and sunny slopes. Results indicated that in the 0–20 cm soil layer, the water-holding capacity was higher on sunny slopes, while water retention in the 10–20 cm layer was significantly higher on shaded slopes. This suggests that vegetation on shaded slopes experiences less soil erosion due to higher topsoil water retention. Additionally, slope orientation altered soil properties: the electrical conductivity (EC) of the 0–20 cm soil layer was significantly higher on shaded slopes. Nutrient elements such as Ca, Cu, and Zn were also relatively higher on shaded slopes, whereas soil organic matter was significantly lower compared to sunny slopes. Overall, soil water-holding capacity and supply were primarily controlled by EC, followed by capillary porosity and nutrient elements like Ca, Mn, and Fe. Therefore, slope orientation has a significant effect on soil hydrological properties, with stronger topsoil water retention on shaded slopes. These findings offer valuable insights for vegetation restoration in semi-arid highland ecosystems.

Keywords: semi-arid woodlands; shaded and sunny slope; soil hydrological characteristics; soil properties

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1. Introduction

Understanding the spatial dynamics of soil moisture and hydraulic properties is crucial for studying various hydrological and ecological processes [1]. Soil hydrological properties play a crucial role in soil hydrological processes [2], controlling mechanisms such as infiltration, water availability, and evapotranspiration [3]. Nevertheless, factors such as vegetation type [4,5], the degradation of grasslands [3,6], soil properties [7,8], topography [9], and slope aspect [10] influence hydrological characteristics. Key soil hydrological parameters, such as water retention and hydraulic conductivity, also regulate multiple soil hydrological functions, including water storage, supply purification, and runoff regulation [8,11]. The aspect of slope, whether regarding south-facing (SF) or north-facing (NF) slopes [12], notably impacts temperature, vegetation growth, energy, and water equilibrium [13–15], consequently shaping soil hydrological characteristics. Numerous studies have explored the impact of slope orientation on infiltration, employing theoretical equations from infiltration kinetics and models like Philip, Green–Ampt, and Brooks–Corey models [16,17]. However, most models focus exclusively on horizontal or low-slope soil surfaces, neglecting their influence on the infiltration process. The infrequent consideration of diverse slope orientations [18] restricts the comprehensive understanding of how slope affects soil hydrological processes. Therefore, exploring the variations in soil hydrological properties among various slope aspects and their driving mechanisms can provide valuable insights for managing semi-arid mountainous woodlands and improving hydrological models.

The influence of slope aspect on soil hydrological properties has been largely neglected, significantly hampering the thorough assessment of soil hydrological processes in intricate landscapes. Typically, microclimatic conditions and vegetation attributes vary between NF and SF slopes. For instance, SF slopes receive three times more solar radiation than NF slopes, resulting in higher soil temperatures and lower humidity on SF slopes compared to NF slopes [9]. As a result, differences in vegetation status and soil characteristics between SF and NF slopes are expected to impact soil hydrological properties. Sun et al. [9] observed that the soil moisture content was 20.9% higher on NF slopes compared to SF slopes, while SF slopes exhibited greater soil water retention, attributed to higher levels of soil organic carbon and available nitrogen on NF slopes [19]. Additionally, studies have also found that soils on north-facing (NF) slopes have higher organic matter (SOM) and clay content [20]. These findings highlight the variability of soil hydrological properties influenced by slope orientation.

However, previous studies have seldom focused on arid and semi-arid regions, particularly the Loess Plateau. The physicochemical characteristics of soil have a significant impact on how roots spread within the soil and on the plant's capacity to draw in water and nutrients from its surroundings [21]. We hypothesize that due to the unique climatic conditions of the Loess Plateau, such as large temperature differences between morning and evening, high evaporation rates, and low precipitation, soil water retention may yield significantly different results.

In arid and semi-arid regions, afforestation leads to exposed soil surfaces that are more susceptible to wind and water erosion [22]. When surface water is inadequate, numerous trees planted in such regions initially access deep soil moisture [23–25]. However, this approach can have detrimental effects, including the demise of naturally occurring, shallow-rooted vegetation or the obstruction of vegetation-restoration. Furthermore, apart from afforestation, climate change represents an additional adverse influence on vegetation development in the Loess Plateau [26–28]. Prior research indicates that the climate of the Loess Plateau has experienced a shift towards warmer and drier conditions over the past few decades [29,30]. Due to global warming, both the frequency and severity of droughts on the Loess Plateau are increasing [31]. These harsh environmental conditions limit tree density and result in woodlands with larger spacing between trees [32]. A typical pattern observed under scattered trees in these areas is an increase in organic matter, total N, S, K, and soluble salts within the uppermost soil layers, leading to improved soil quality [33]. Investigations have revealed that trees scattered in harsh environments tend to expand their root systems to procure additional resources, which are subsequently redistributed, thereby generally bolstering the accessibility of water and nutrients in the topmost soil layers [34]. Indeed, semi-arid mountainous ecosystems are very vulnerable due to their unique climatic conditions, making their ecosystem services extremely important [35]. The soils in mountainous areas are particularly prone to degradation due to these unique climatic conditions.

While the significance of hydraulic properties in soils with different slope aspects is widely acknowledged, research specific to semi-arid montane forests remains limited in the current literature, and even fewer studies delve into the controlling factors, particularly soil nutrients, in these regions. Based on the above, the following research hypothesis is proposed: the soil and vegetation conditions on shaded and sunny slopes exhibit significant differences induced by topographic variations, which, in turn, alter the soil hydrological properties. Therefore, this study aims to (1) examine the differences in soil hydrological properties, including water retention capacity and water storage capacity, between shaded and sunny slopes, and (2) explore the driving factors behind these hydrological changes. The findings of this research will aid in the better management of semi-arid montane forests, contributing to soil moisture conservation in semi-arid ecosystems and informing more effective and targeted management strategies for these environments.

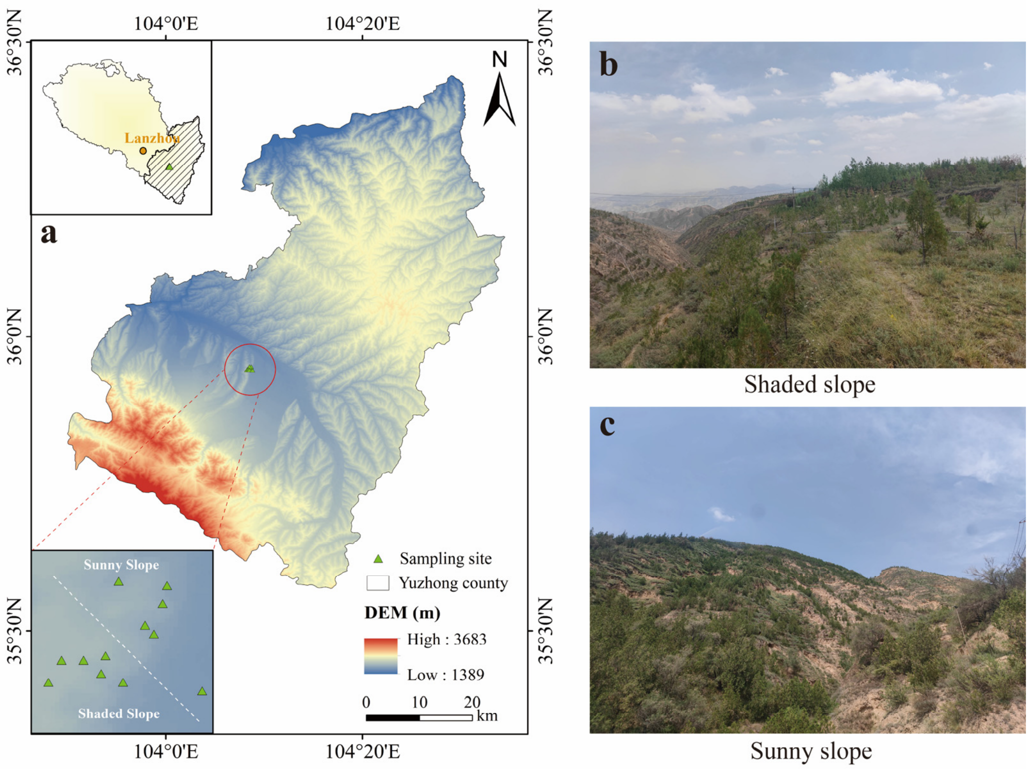
2. Materials and Methods

2.1. Study Area

This study was conducted on Cuiying Mountain (35.95° N, 104.14° E, elevation 1968 m) in Yuzhong County, Lanzhou City, Gansu Province, China. The site is located at the junction of the Loess Plateau, the Inner Mongolia Plateau, and the northeastern Qinghai–Tibet Plateau. It serves as a transitional zone between the eastern monsoon region, the arid region of northwest China, and the alpine zone of the plateau, making it regionally representative. The underlying surface features typical Loess Plateau topography with primary forests, shrubs, and grassland vegetation, under a temperate continental climate. The surrounding environment is minimally impacted by human activities, reflecting the average conditions of semi-arid regions within a few hundred kilometers.

2.2. Experimental Design and Soil Sampling

Field experiments were carried out in April 2023 on Cuiying Mountain, at an elevation of approximately 1968 m. Sampling was carried out along a transect from the mountain top to the foot, on both shady and sunny slopes (Figure 1a). Six sampling points were selected on each slope (Figure 1b,c). At each sampling point, three 1 m × 1 m square plots were established and quartered. Soil samples, including both undisturbed and disturbed ones, were gathered from these designated areas. Undisturbed soil samples (100 cm^3) were collected from two soil layers (0–10 cm and 10–20 cm) in each of the three plots using a core ring sampler and then preserved in sealed aluminum boxes. These samples were used to measure soil water content (SWC), bulk density (BD), and other hydraulic properties. Disturbed soil samples were obtained by using a soil auger at the different depths (0–10 cm and 10–20 cm) vertically. These samples were sealed in bags, with plant roots, residues, and other debris removed. The samples were air-dried, ground, and sieved through 2 mm and 0.149 mm sieves for physicochemical property analysis. Table 1 provides basic information about the sampling sites.



Shaded slope

Sunny slope

Figure 1. The study site (**a**) and the two slopes in this study: shaded slope (**b**) and sunny slope (**c**).

Table 1. Basic information about the research sites.

Aspect	Latitude	Longitude	Altitude (m)	Vegeration Coverage (%)	Woodland Type
Shaded slope	35°56′40″ N	104°8′27″ E	1925	95	Cupressus funebris forest
	35°56′45″ N	104°8′38″ E	1923	90	Mixed deciduous forest
	35°56′47″ N	104°8′36″ E	1909	90	Mixed deciduous forest
	35°56′52″ N	104°8′40″ E	1913	85	Mixed deciduous forest
	35°56′56″ N	104°8′41″ E	1861	85	Shrubbery
	35°56′57″ N	104°8′30″ E	1752	85	Shrubbery
Sunny slope	35°56′39″ N	104°8′17″ E	1931	95	Platycladus orientalis forest
	35°56′34″ N	104°8′14″ E	1928	88	Populus alba forest
	35°56′39″ N	104°8′22″ E	1885	85	Shrubbery
	35°56′36″ N	104°8′26″ E	1844	90	Shrubbery
	35°56′34″ N	104°8′31″ E	1793	85	Shrubbery
	35°56′32″ N	104°8′49″ E	1721	85	Populus alba forest

2.3. Laboratory Measurements and Analysis

Soil physicochemical properties were determined following the guidelines outlined in "Soil Agricultural Chemistry Analysis" [36]. Soil pH and electrical conductivity (EC) were measured using a pH meter (PHS-3E, Leici, Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China) and an EC meter (HI 98311, HANNA Instruments, Villafranca, Italy) at a soil-to-water ratio of 1:2.5 at room temperature. Soil organic carbon (SOC) was assessed using the potassium dichromate oxidation method [37]. Soil carbonate ($CaCO_3$) content was measured using the volumetric titration method [38]. Total potassium (TK) was determined using a flame photometer. The concentrations of Ca, Fe, Cr, Mn, Ni, Cu, Zn, and Pb in the soil were quantified using atomic absorption spectrophotometry (Thermo Fisher, Waltham, MA, USA, SOLAAR M6). To ensure accuracy, soil samples from the China National Standard Material Center (GSS-8) were used as standard samples, with one analysis performed for every 20 samples, achieving recovery rates between 80 and 120%. All the reagents and chemicals employed in the process were of analytical grade. Soil water content (SWC) and bulk density (BD) were determined using the 105 °C drying method. Total porosity (TP; %) was calculated using soil BD and particle density (PD), with an average PD value of 2.65 $g \cdot cm^{-3}$. The formulas used to derive soil capillary porosity (CP; %), non-capillary porosity (NCP; %) [39], and soil water storage (SWS; mm) [40] were as follows:

$$BD = \frac{\text{mass of soil (g)}}{\text{volume of soil (cm}^3\text{)}} \quad (1)$$

$$TP = 1 - \frac{BD}{PD} \quad (2)$$

$$CP = CMC \times BD \quad (3)$$

$$NCP = TP - CP \quad (4)$$

$$SWS = SWC \times BD \times h \times 10^{-1} \quad (5)$$

where CMC is the capillary moisture capacity (%), h is soil depth (cm), and 10^{-1} (mm/cm) is the unit conversion factor.

2.4. Statistical Analysis

Statistical analysis, data visualization, and normalization were performed using Microsoft Excel 2021 (Microsoft, Redmond, WA, USA). Statistical analyses were performed using R software version 4.3.2 (R Development Core Team 2006) and utilized the "vegan" package. Redundancy analysis (RDA) and Pearson correlation were utilized to investigate the relationships between hydrological characteristics and basic soil properties, aiming to ascertain the primary factors influencing soil water retention. All graphs and charts were generated using Origin 2024b (OriginLab, Northampton, MA, USA). The sampling location map was created using ArcMap 10.8.1.

3. Results and Discussion

3.1. Soil Hydrological Characteristics of Shaded and Sunny Slopes

Figure 2 illustrates the soil hydrological properties at different soil layers on the two slopes. There was a greater difference in soil hydrological properties between the 10–20 cm and 0–10 cm layers. The soil water content (SWC) (Figure 2a) and bulk density (BD) (Figure 2b) at 10–20 cm on the shady slope were significantly higher than those on the sunny slope, consistent with the soil water storage (SWS) results, with the shady slope having notably higher SWS (Figure 2g). At various soil depths, the total porosity (TP) (Figure 2c) and non-capillary porosity (NCP) (Figure 2f) of the shady slope soil were higher than those of the sunny slope, while the capillary porosity (CP) (Figure 2e) was higher on the sunny slope. The capillary moisture capacity (CMC) (Figure 2d) tended to be higher on the sunny slope, with the difference being more pronounced in the 10–20 cm soil layer.

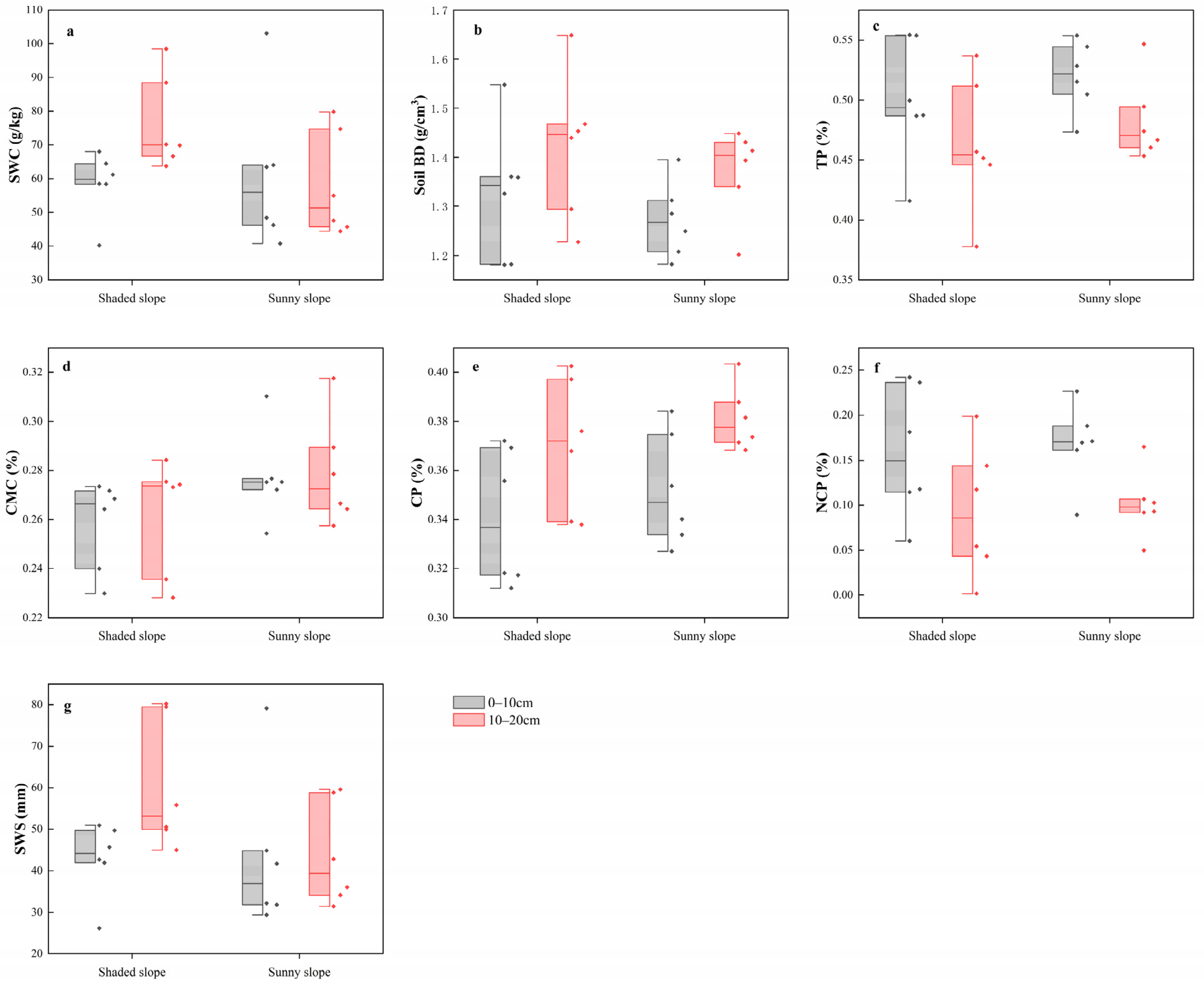


Figure 2. The soil hydrological indicators on two slope aspects. SWC: soil water content (**a**), BD: soil bulk density (**b**), TP: soil total porosity (**c**), CMC: capillary holding capacity (**d**), CP: soil capillary porosity (**e**), NCP: non-capillary porosity (**f**), SWS: soil total carbon (**g**).

In view of the influence of slope aspect on soil temperature and moisture [41,42], one can deduce that soil hydrological characteristics will also undergo changes accordingly. The increased solar radiation on the sunny slope enhances soil evaporation, leading to greater water consumption. Studies in arid and semi-arid regions have also reported higher soil evaporation rates on sunny slopes compared to shady slopes [43,44], ultimately resulting in lower soil moisture content on sunny slopes under the same precipitation conditions. This is consistent with our research findings, where we observed higher soil water storage on shady slopes than on sunny slopes in the 0–20 cm layer (Figure 2g), with significant differences, particularly at the 10–20 cm soil depth. This contrasts sharply with earlier findings indicating that the field capacity of sunny slope soils is higher than that of shady slope soil [20,45]. Generally, soil bulk density (BD) and total porosity are the main factors affecting plant traits [46]. The higher soil water retention capacity on sunny slopes may be attributed to greater vegetation height and above-ground biomass, as well as a lower rainfall infiltration capacity.

3.2. Soil Physicochemical Properties and Trace Element Contents on Shaded and Sunny Slopes

The general soil physicochemical properties and trace element contents (K, Ca, Fe, Cr, Mn, Ni, Cu, Zn, Pb) of the two slope aspects are shown in Table 2. The pH values of the soils on both slopes are slightly alkaline, which is consistent with the calcareous soil background of the area. The electrical conductivity (EC) of the shady slope soil is significantly higher than that of the sunny slope. Since electrical conductivity reflects the soil's ability to conduct an electric current, the increase in EC is likely influenced by changes in soil hydrology and chemical substances [47]. The soil organic matter (SOM) content on both slopes is significantly lower than the background value for Gansu Province, with the sunny slope showing notably higher SOM compared to the shady slope. The average $CaCO_3$ content is higher than the background value for Gansu soils, indicating an alkaline soil environment, which can improve soil structure and stability but may also affect nutrient supply and soil fertility in complex ways.

The trace element contents on both slopes are significantly lower than the background values for Gansu Province, possibly due to low availability and the rapid consumption of trace nutrients by plants, leading to deficiencies. However, Cr and Pb concentrations are higher, reaching risk levels according to screening standards, which may be related to irrigation with reclaimed water, indicating a risk of heavy metal pollution in the study area. Additionally, the concentrations of nutrients such as K, Ca, Fe, and Mn are relatively high on both slopes, with Fe concentrations being 11.7–16.8 times higher and Mn concentrations 1.4–1.9 times higher than the background values for Gansu soils. Iron is a major limiting factor for sustainable crop growth in soils with coarse texture, low organic matter content, high $CaCO_3$ content, and high pH [48]. The concentrations of other trace elements (Ni, Cu, Zn) show little difference from the background values.

Soil exhibits considerable heterogeneity and variability in its physical and chemical characteristics. Soil characteristics vary by soil type and location, reflecting differences in parent material, climate, and land use. Understanding soil property variations is crucial as they determine the productivity and utilization of the area [49]. Forest stands composed of different tree species have varying litter quality and root exudates, which ultimately lead to changes in soil properties [50]. Soil physicochemical properties can effectively improve various soil functions during vegetation restoration [51]. Soil EC is considered the most important property distinguishing constant land use types [52], with the higher electrical conductivity in the surface soil of abandoned lands possibly due to enhanced capillary action from vegetation removal or loss. This further increases salt accumulation in the surface soil due to reduced precipitation and increased evaporation from deeper soil layers [53]. Compared to EC, soil pH and BD show minor differences with soil depth across land use types, consistent with previous studies conducted in similar areas on the Chinese Loess Plateau [54–56]. Soil organic matter is the most discriminative variable with soil depth. Soil organic carbon is the largest carbon pool in terrestrial ecosystems, playing a crucial role in balancing soil multifunctionality and serving as a key indicator of soil functions [57,58]. The low organic matter content in these soils is due to the prevailing arid and semi-arid climate conditions, limiting the contribution of soil organic matter to the total and available trace nutrients [59]. The presence of calcium carbonate affects the availability of certain nutrients. For instance, $CaCO_3$ can enhance the availability of calcium and magnesium but may reduce the availability of phosphorus and some trace nutrients (such as Fe, Mn, Zn, Cu) due to higher pH levels. While moderate $CaCO_3$ content benefits soil fertility, excessively high levels can lead to low soil fertility, particularly in arid and semi-arid regions, where excessive $CaCO_3$ can cause soil hardening and reduced nutrient supply [60].

Table 2. Soil physicochemical properties and heavy metal content statistics for two slopes.

	Slope	Min	Max	Mean	SD	CV (%)	Background Value [a]
pH	Shaded	8.02	9.04	8.58	0.25	2.93	8.4
	Sunny	7.98	9.95	8.68	0.34	3.88	
EC (µS/cm)	Shaded	143.4	1822.0	802.9	506.0	63.0	NA
	Sunny	107.8	1871.0	323.1	333.9	103.3	
SOM (g/kg)	Shaded	0.002	0.042	0.023	0.011	48.0	8.0
	Sunny	0.031	0.087	0.055	0.012	21.1	
$CaCO_3$ (%)	Shaded	13.77	16.07	15.50	0.0072	4.67	11.8
	Sunny	13.84	16.11	15.42	0.0057	3.68	
K (mg/kg)	Shaded	173	246	212.7	13.7	6.4	NA
	Sunny	192	252	215.3	12.6	5.8	
Ca (mg/kg)	Shaded	656	1229	867.1	121.3	14.0	NA
	Sunny	648	1031	793.4	78.2	9.9	
Fe (mg/kg)	Shaded	330	438	387.1	26.1	6.7	28.1
	Sunny	332	473	384.9	26.3	6.8	
Cr (mg/kg)	Shaded	64.2	79.0	71.1	4.8	6.8	70.2
	Sunny	55.9	113.0	74.4	10.1	13.6	
Mn (mg/kg)	Shaded	647.8	760.6	719.0	32.6	4.5	464
	Sunny	639.7	872.3	736.2	51.3	7.0	
Ni (mg/kg)	Shaded	30.3	46.2	37.7	3.3	8.7	35.2
	Sunny	31.2	47.1	37.0	3.4	9.2	
Cu (mg/kg)	Shaded	24.7	44.5	31.4	3.5	11.2	20.1
	Sunny	25.4	36.2	29.9	2.6	8.5	
Zn (mg/kg)	Shaded	58.2	121.7	71.5	8.7	12.1	68.5
	Sunny	62.0	97.1	72.8	5.2	7.1	
Pb (mg/kg)	Shaded	19.0	45.1	23.1	3.7	16.0	18.8
	Sunny	20.3	39.6	23.5	3.0	12.9	

CV: Coefficient of variation, SD: standard deviation, NA: no data. [a]: Gansu Province soil background value (CNEMC, 1995).

The slope aspect causes changes in environmental factors, significantly influencing soil properties [20,55,61]. We found that the soil organic matter (SOM) content in the 0–20 cm soil layer was significantly higher on sunny slopes compared to shady slopes. This finding is consistent with previous studies, where the SOM on north-facing slopes was lower than that on south-facing slopes [20,55]. In relatively dry regions, plant growth is more constrained by soil moisture than soil temperature. Therefore, the higher soil moisture on southern slopes can stimulate microbial activity and vegetation growth, promoting litter decomposition and nutrient cycling [61], ultimately leading to higher SOM on southern slopes.

In contrast, in our study, plant growth was primarily limited by temperature and soil moisture. The extended solar exposure and elevated temperatures characteristic of sunny slopes significantly stimulate plant growth, which consequently results in a substantial increase in vegetative biomass and accelerates the decomposition of organic litter. Therefore, the elevated SOM content on south-facing slopes is likely attributed to the increased vegetation biomass and the accelerated decomposition of litter, as the majority of soil carbon inputs are derived from plant biomass [62]. Additionally, aspect-induced environmental variations significantly influence SOM levels by modulating vegetation biomass. An earlier study reported that the amount of direct solar radiation received by south-facing slopes, particularly during the peak radiation period in summer, is nearly three times that of north-facing slopes [9]. Higher solar radiation can promote root biomass growth, consequently leading to higher soil carbon content on sunny slopes compared to shaded slopes [61]. Moreover, soil bulk density (BD) also undergoes changes depending on the slope aspect. The topsoil BD (0–20 cm) on shady slopes is higher than on sunny slopes (Figure 2b). The lower BD on sunny slopes might be related to the higher SOM content [63].

3.3. Relationship between Soil Hydrological Properties and Soil Characteristics on Shaded and Sunny Slopes

Redundancy analysis (RDA) was employed to detect the contributing factors of each environmental variable (soil properties). When the angle between the response variable (soil hydrological properties) and the environmental variables approached 90°, the explanatory power of the environmental variables on the response variable was minimal. Therefore, using the RDA method, irrelevant variables can be removed to improve the model and reduce variance. As shown in Figure 3, soil properties were significantly correlated with the first RDA axis (RDA1) and weakly correlated with the second RDA axis (RDA2). The RDA1 and RDA2 axes collectively accounted for a remarkable 99.99% of the total variability observed in the soil's hydrological characteristics. Pearson correlation analysis indicated that soil SWS on the shady slope (Figure 4a) was significantly positively correlated with EC and CP, and significantly negatively correlated with $CaCO_3$ content. This variation was not evident on the sunny slope (Figure 4b).

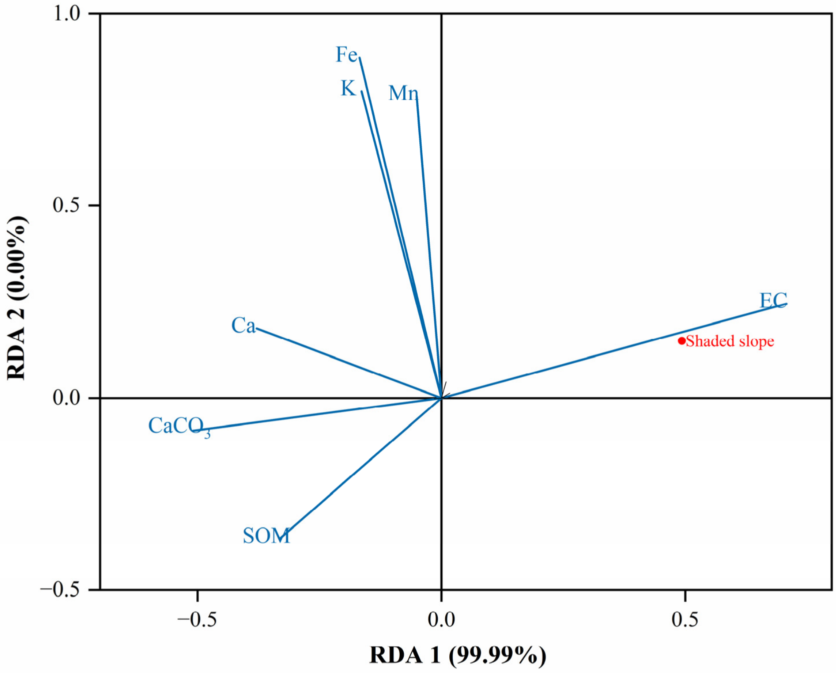


Figure 3. Redundancy analysis of soil hydraulic and physicochemical properties between shaded slope and sunny slope. Note: The environmental variable was set to soil physicochemical properties and the response variable was set to soil hydrological properties. The percentages of total variation explained by each RDA axis are indicated by the values on the respective axes.

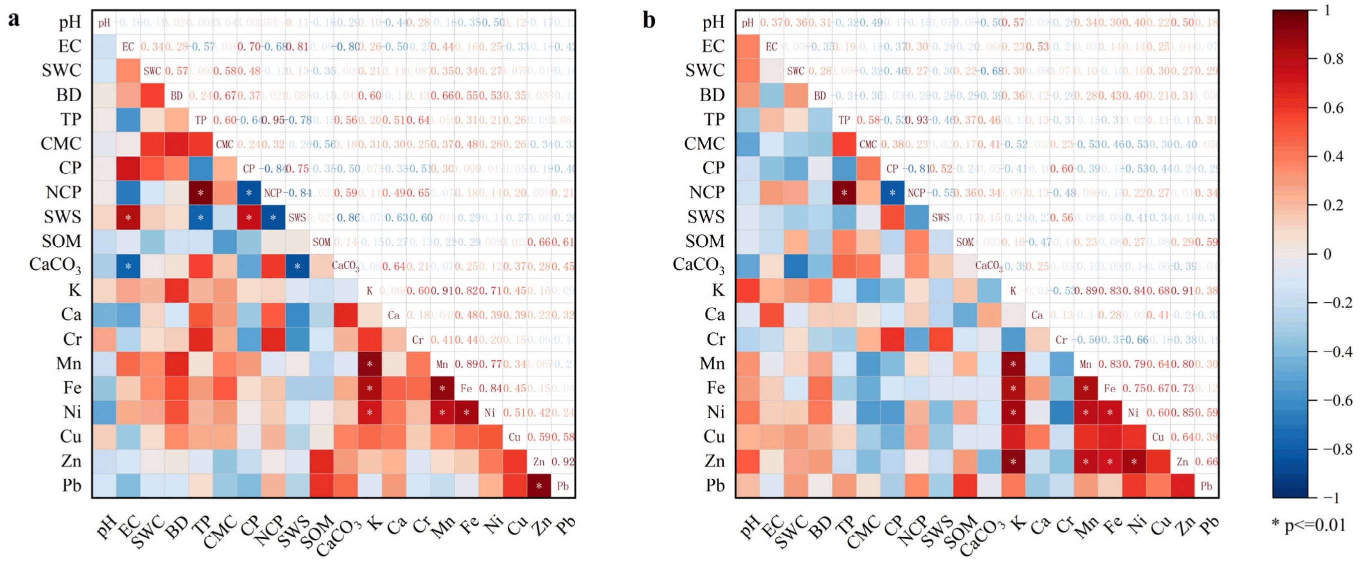


Figure 4. Correlation analysis was performed on soil hydraulic and physicochemical properties, comparing shaded slope (**a**) and sunny slope (**b**). Note: SWC: soil water content, BD: soil bulk density, TP: soil total porosity, CP: soil capillary porosity, NCP: non-capillary porosity, SWS: soil total carbon, SOM: soil organic matter. Significant correlations at $p \leq 0.01$ are indicated by white asterisks.

Soil hydrological properties are substantially affected by the physicochemical attributes of the soil [64]. Changes in soil texture, soil porosity, bulk density (BD), and soil organic matter (SOM) alter soil water retention and hydraulic conductivity, thereby changing the availability of soil moisture [65], which aligns with our findings. Soil pore structure dictates the rate of water ingress and percolation through the soil [66]. The restoration of plants prompts a decrease in BD and a consequential increase in soil porosity, thereby enhancing soil permeability and promoting optimal water retention [67,68]. CP and NCP mainly reflect micropores and macropores, respectively [69]. The distribution of soil pore sizes has a significant impact on the soil hydrological characteristics [70]. Soil moisture content is highly correlated with Fe content [71]. Studies have shown that organic matter content is significantly positively correlated with Fe concentration in gravel soils, which may hinder plants' absorption of water-soluble organic matter due to low organic matter content, thus affecting known plant root growth and germination [72,73].

3.4. Implications for Soil and Water Conservation and Vegetation Restoration in Semi-Arid Regions

The Loess Plateau is an important area for vegetation restoration [74]. The water retention capacity of artificial forests has been vital in addressing water scarcity on the Loess Plateau [75], as forest restoration enhances soil retention properties by physically aggregating soil particles [76,77]. The results indicate that the soil water content (SWC) on shady slopes is significantly higher than on sunny slopes (Figure 2g), suggesting that vegetation on shady slopes may be less susceptible to soil-moisture stress and soil erosion. Higher capillary moisture capacity (CMC) on sunny slopes indicates a greater tolerance of vegetation to drought and high temperatures on these slopes. Studies have shown that implementing soil and water conservation measures can significantly improve most soil physicochemical properties, thereby enhancing soil fertility and vegetation biomass [78]. In addition, soil on different slope aspects exhibits variations in particle size distribution. Within the 0–50 cm soil layer, the clay content on the north-facing (NF) aspect is higher than on the south-facing (SF) aspect, with significant differences, particularly in the 20–30 cm and 30–40 cm layers [40]. The slightly elevated clay content contributes to the greater water retention capacity of the NF soil [79]. However, compared to soil grain size, SOM is the predominant factor influencing water retention in alpine soils [8]. Therefore, this study provides important insights for forestland restoration on the Loess Plateau.

4. Conclusions

This study investigated the relationship between soil hydrological properties and soil physicochemical characteristics on different slope aspects in semi-arid mountainous forestlands of the northwest region. Significant differences were observed between shady and sunny slopes. Soil water storage capacity in the 0–20 cm layer was markedly higher on shady slopes compared to sunny slopes, while soil water retention capacity showed the opposite trend. These findings were consistent with the results for soil capillary porosity (CP) and electrical conductivity (EC). Therefore, it can be concluded that soil water retention and supply capacity are related to CP and EC, indicating that the topsoil on shady slopes may be less susceptible to soil erosion and moisture stress. Additionally, the study demonstrated that slope aspect significantly influences soil hydrological properties, altering soil characteristics such as soil organic matter (SOM), with sunny slopes having significantly higher SOM content than shady slopes. Nutrient elements like Ca, Mn, Cu, and Zn also showed substantial differences between slopes.

In comparison with previous studies, slope is identified as an important factor influencing changes in soil hydrological properties, though it is not the sole factor. As drought intensifies, forests in water-stressed areas will face more severe threats. This study will establish a theoretical basis for predicting the responses, adaptations, and feedback of soil hydrological properties, physical and chemical properties, and nutrient elements to slope changes in this region. Thus, when restoring degraded forests and grasslands in semi-arid ecosystems and formulating soil water conservation strategies, slope aspect should be considered. Moreover, obtaining more accurate and deeper soil data is crucial for conducting soil hydrological studies and managing water resources effectively.

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