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Spatial Variability of Soil Moisture in Relation to Land Use Types and Topographic Features on Hillslopes in the Black Soil (Mollisols) Area of Northeast China

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Abstract: Soil moisture, as a crucial factor in the eco-hydrological process, is of great importance for food production, land management in response to water and soil loss, geomorphic processes, and environmental protection. Understanding the spatial variability of soil moisture induced by different land use types and topographic features is conducive to advancing the adjustment of the land use structure and preventing soil erosion on the hillslopes in the black soil (Mollisols) area of Northeast China. Classical statistical methods and Canonical Correspondence Analysis were used to analyze the spatial heterogeneity of soil moisture at 0–20, 20–40, and 40–60 cm on slopes, to identify the main controlling factors and their relative contributions. The results suggested that: the average soil moisture content followed a decreasing order of grassland > shrubland > soybean land > maize land > adzuki bean (*Vigna angularis*) land > forestland; the profile soil moisture content (SMC) patterns could be divided into four types, related to the comprehensive influence of vegetation types, root system characteristics, and topographic attributes; the spatial variability of soil moisture was strongly influenced by slope gradient, followed by land use types and elevation and slope position, while slope aspect had the least impact; and finally, land use type had a greater impact on the deep layer than the surface layer, while on the contrary, the influence of the topographic attributes on the deep layer was smaller than on the surface layer. Land use types and topographical elements work together on the soil moisture variability and vertical patterns at differing depths. This study provides an insight into policy making of land resource management and can be used in the modeling of hydrological processes.

Keywords: soil moisture; spatial variability; land use types; topography; Canonical Correspondence Analysis

1. Introduction

Soil moisture, as a crucial factor in hydrological processes, influences infiltration, evapotranspiration, runoff, solute transport, and soil erosion [1–7], and furthermore, it is of great importance for food production, land management in response to water and soil loss, geomorphic processes, and environmental protection [2,8–10]. Soil moisture content (SMC) varies spatially, which is affected by the climate [11,12], land use/vegetation [13–15], topography [4,16,17], and soil properties [18–20]. At different scales, the influencing factors of soil moisture differ from each other. For instance, at a large scale, soil moisture is mainly controlled by the climate; at smaller scales, the spatial variability of soil moisture is significantly influenced by topographic elements and land use [10,21,22]. The main reason for this is that, at a large scale, climatic factors mask the effects of land use, topography, and soil properties on soil moisture, while at a small scale, the climatic conditions are relatively uniform, and the influence of other factors is highlighted.

Hillslope scale (or catchment scale) has both the generality of the large scale and the accuracy of the small scale. In addition, variations of SMC on slopes are more complicated due to the synergy and superposition effects of various factors (e.g., land use types, slope gradient, slope aspect, slope position, elevation). Thus, understanding and characterizing the spatial variability of SMC on slopes associated with multiple factors is one of the major challenges within the eco-hydrological sciences, and has become a focus of academic research [23].

Soil moisture variation and its controlling factors at the hillslope scale or even catchment scale have garnered a great deal of interest [6,17,23–26]. For instance, Zucco et al. [6] investigated the influence of land use on soil moisture in a catchment located in central Italy. Famiglietti et al. [17] experimentally found that surface soil moisture content showed significant variability along a hillslope transect in Texas, America. Penna et al. [23] verified that the slope and the topographic wetness index are related to soil moisture variation at the slope scale. In China, studies focused on the Loess Plateau, as well as the red soil region, have revealed soil moisture variability to a great extent [9,27–29]. However, few studies have focused on the black soil (Mollisols) area of China. Because the black soil area of China is completely different from the Loess Plateau/red soil region in terms of topographic features and soil texture, there are many differences in land use/vegetation in this area, and there is little information about the spatial heterogeneity of SMC and its response to the combined influence of land use and topographical factors in the black soil area.

The black soil area of Northeast China is one of the four black soil regions in the world and is also an important commodity grain base in China, playing an important role in safeguarding national food security. However, the black soil area of Northeast China is facing severe challenges of soil erosion and ecological fragility under the combined influences of human activities and natural conditions (e.g., rainfall time concentration). SMC has an important impact on the degree of soil erosion, and also affects crop growth and the implementation of the “Grain for Green Project”. The slope of the black soil area in Northeast China has unique characteristics: (1) The slope is long and gentle. (2) Historically, the slope covered with natural vegetation was reclaimed as cultivated land due to long-term economic development pressure, but later some farmland was converted back to forestlands, shrublands, and grasslands on account of the “Grain for Green project” initiated by the Chinese government. Obviously, this resulted in a plaque mosaic of land use on the slope. (3) There are no irrigation measures and groundwater levels below the surface are deep, thus rainfall is the main source of soil moisture. The unique topographical features and land use characteristics of the black soil area have led to an increase in the degree of soil moisture heterogeneity on the slope. At the same time, the SMC on slopes in the study area is less affected by the climate, due to the relatively small area. Thus, we can focus on the impact of land use and topography on soil moisture, making this area the most suitable area for studying the effects of topographical factors and land use on soil moisture heterogeneity.

In the black soil area of China, several studies have been undertaken to identify the soil moisture variations and their relationship with land use and topographical factors. Su et al. [30] studied the effects of different land use types on SMC and found that the influence of land use on SMC increased with soil depth, and profile features of soil moisture varied under different land use types. In the Guangrong small watershed of Northeast China, Ge et al. [31] observed soil moisture variations in relation to topographic factors, and revealed that SMC was significantly influenced by slope gradient, elevation, and slope position, but slope aspect had no significant effect on SMC. On a cropland-forestland mixed hillslope in China, Guo et al. [22] observed that soil moisture variations along the hillslope, under the impact of four land use structures, differed from each other.

However, the spatial variations of SMC under the combined effect of land use and topographic features have not been given adequate attention, and the relative importance of the two elements remained unclear compared with the research interest on the relationship between soil moisture and soil conservation, management practices, and climatic factors [32–34]. In the literature reporting SMC variability and its relationship with the controlling factors in the black soil area of China, the majority of studies have been conducted in areas where the land use type/topographic condition is relatively uniform, or they have ignored the combined influence of other factors. Thus, it is essential to identify the spatial variations of soil moisture in relation to land use types and topographic features, to assess the relative importance of land use and topographic features, which could be needed by policy-makers for land use planning and environmental protection.

The objectives of this study are: (1) to characterize the spatial variability of the soil moisture content under different land use types; (2) to identify the profile patterns of SMC for six land use types and compare the profile features of soil moisture content at different soil depths; (3) to explore the impacts of topographic properties (e.g., slope aspect and slope position) on soil moisture content; and (4) to reveal the relative influences of land use type and topographic properties on soil moisture content variability using Canonical Correspondence Analysis (CCA) on slopes. This information could be useful for policy-making of land resources management, such as in the "Grain for Green project" and could be used in the modeling of hydrological processes.

2. Materials and Methods

2.1. Study Area

The study area was located in the northern part of Keshan County, Heilongjiang Province (48°14′N, 125°50′E) (Figure 1), which belongs to a hilly area with a long slope length (between 1000 and 1600 m) and gentle slope gradients (<5°), with an elevation ranging from 280 to 350 m. It is a typical black soil area, which is also known as an important commodity grain base and soybean export base in the country. The study area is characterized by a cold temperate continental monsoon climate with dry springs, warm summers and autumns, and cold winters. The average annual temperature is about 2.4 °C, the effective accumulated temperature is 2503.6 °C, and the average annual precipitation is approximately 500 mm, 80% of which falls in summer and autumn. The average annual evaporation is 1222 mm. The soil type is dominated by Mollisols (black soil).

The study area is covered with six land use types: soybean land, adzuki bean (*Vigna angularis*) land, maize land, forestland, shrubland, and grassland, which is an interaction result of nature and human use. Soybean land, adzuki bean land, and maize land belong to slope cropland, with the predominated type of soybean land. Forestlands occur in different slope positions and are dominated by Larix. The breast diameter of Larix is approximately 15–30 cm, and the grasses under the forest are sparse. The shrubland and grassland are mainly positioned at the toe slope, and the grasses under shrubs are frondent. The forestland, shrubland, and grassland are less disturbed by human activities.

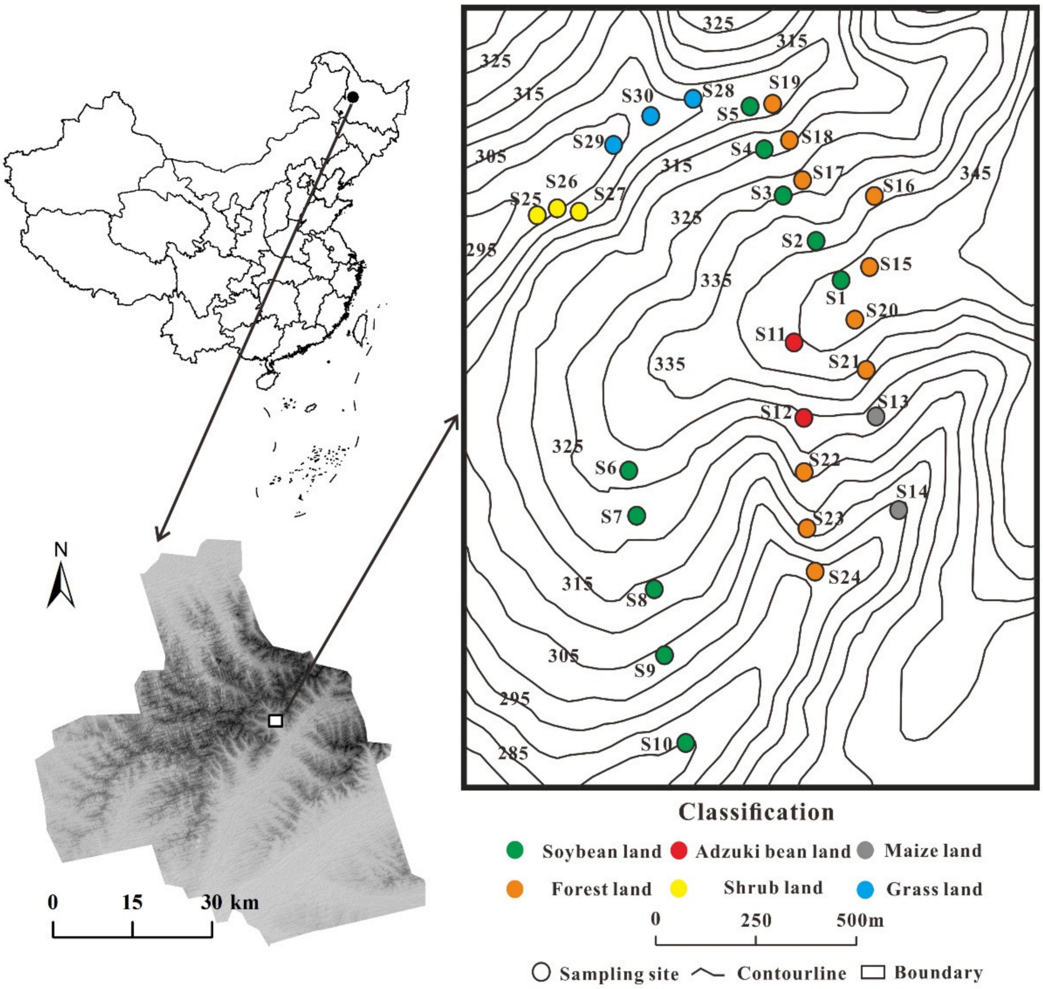

Figure 1. Location of the study area and sampling sites.

2.2. Study Design and Soil Sampling

Two adjacent slopes (sunny slope and shady slope, with slope gradients ranging from 0° to 5°) covered with six land use types (Figure 1) were chosen to investigate the spatial variation in relation to land use types and topographic features in the study area.

There are remarkable variations in land use and topographic properties. Representative sample sites were selected according to different combinations of land use type, slope aspect, and slope position (top slope, upper slope, middle slope, lower slope, and toe slope) on each slope (Figure 1). A total of 30 sampling sites were monitored: 10 in soybean land, 2 in adzuki bean land, 2 in maize land, 10 in forestland, 3 in shrubland, and 3 in grassland. The primary reason for having fewer sampling sites in adzuki bean land and maize land is that the soybean land in the study area is a dominant cropland, while adzuki bean and maize are sporadic on the slopes. Since the shrubland and grassland are mainly distributed at the toe slope and on shady slopes, three samples were randomly selected for each type. The land use type and topographic information of the sampling sites are shown in Table 1.

The experiment was conducted biweekly from 15 August to 12 September 2016, corresponding with a period of abundant rainfall, strong soil evaporation, and large water consumption of vegetation transpiration. To reduce the effect of rainfall and reveal the relationship between land use, topographic factors, and soil moisture variation, no precipitation fell in sampling times. When it rained, the sampling time would be postponed by four days. The rainfall and temperature conditions during the sampling period are shown in Figure 2.

Table 1. Information of sampling points in the study area.

Sampling Site	Land Use Type	Altitude (m a.s.l)	Slope Aspect	Slope Position	Slope Gradient (°)
S1	Soybean land	347	Shady slope	Top slope	2
S2	Soybean land	338	Shady slope	Upper slope	2
S3	Soybean land	329	Shady slope	Middle slope	2
S4	Soybean land	319	Shady slope	Lower slope	4
S5	Soybean land	307	Shady slope	Toe slope	3
S6	Soybean land	328	Sunny slope	Top slope	1
S7	Soybean land	323	Sunny slope	Upper slope	1
S8	Soybean land	314	Sunny slope	Middle slope	2
S9	Soybean land	303	Sunny slope	Lower slope	2
S10	Soybean land	284	Sunny slope	Toe slope	2
S11	Adzuki bean land	344	Sunny slope	Top slope	0
S12	Adzuki bean land	331	Sunny slope	Upper slope	1
S13	Maize land	328	Sunny slope	Middle slope	4
S14	Maize land	302	Sunny slope	Toe slope	3
S15	Forestland	347	Shade slope	Top slope	0
S16	Forestland	338	Shade slope	Upper slope	3
S17	Forestland	327	Shade slope	Middle slope	2
S18	Forestland	319	Shade slope	Lower slope	2
S19	Forestland	309	Shade slope	Toe slope	1
S20	Forestland	349	Sunny slope	Top slope	1
S21	Forestland	339	Sunny slope	Upper slope	3
S22	Forestland	322	Sunny slope	Middle slope	2
S23	Forestland	310	Sunny slope	Lower slope	3
S24	Forestland	297	Sunny slope	Toe slope	1
S25	Shrubland	297	Shade slope	Toe slope	4
S26	Shrubland	300	Shade slope	Toe slope	3
S27	Shrubland	304	Shade slope	Toe slope	3
S28	Grassland	305	Shade slope	Toe slope	0
S29	Grassland	299	Shade slope	Toe slope	0
S30	Grassland	302	Shade slope	Toe slope	0

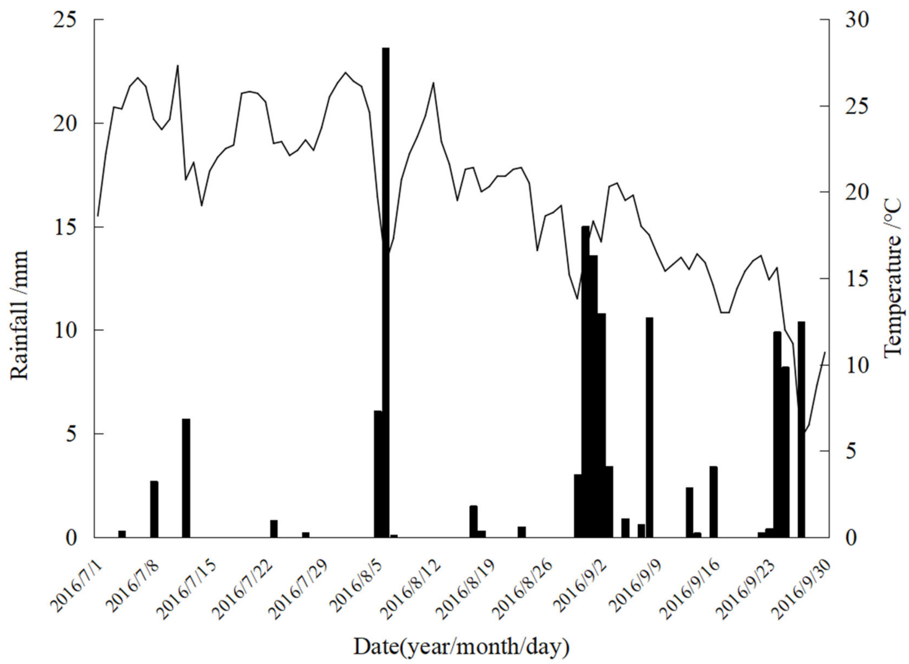

Figure 2. Precipitation (bars) and air temperature (line) of the study area during the period of sampling.

At each soil sampling site of the two slopes, soil samples in the profile were collected to a depth of 60 cm at an interval of 20 cm (divided by three layers: 0–20 cm, 20–40 cm, 40–60 cm) using auger. We had three replicates at each measurement depth. Thus, a total of 810 soil samples were collected from 30 soil sampling sites. The gravimetric SMC was measured by the oven drying method (105 °C, 24 h). The slope gradient and slope aspect were measured with a geological compass. The elevation, longitude, and latitude of each sampling site were determined by GPS (Garmin GPS60). Other properties of each sampling site, such as land use type and slope position, were also recorded.

2.3. Data Analysis

2.3.1. Variable Calculations and Statistical Analysis

In this study, several soil moisture variables were adopted. Following Qiu et al. [35] and Yu et al. [36], the computation equations of the variables were as follows:

1. Averaged SMC on sampling site i (M_i):

$$M_i = \frac{1}{N_l \times N_t} \sum_{j=1}^{N_l} \sum_{k=1}^{N_t} M_{i,j,k} \quad (1)$$

where $M_{i,j,k}$ represents the SMC at sampling site i, layer j, and sampling time k; N_l represents the number of layers N_l = 3, and N_t represents the total number of sampling times N_l = 3

2. Time-averaged SMC on sampling site i and at layer j ($M_{i,j}$):

$$M_{i,j} = \frac{1}{N_t} \sum_{k=1}^{N_t} M_{i,j,k} \quad (2)$$

3. Averaged SMC for each land use type and/or each topographic domain:

$$\overline{M}_i = \frac{1}{N_u} \sum_{i=1}^{N_u} M_i, \quad (3)$$

where N_u represents the number of sampling sites for each land use type and/or each topographic domain.

4. Averaged SMC at layer j for each land use type and/or each topographic domain:

$$\overline{M}_{i,j} = \frac{1}{N_u} \sum_{i=1}^{N_u} M_{i,j}. \quad (4)$$

The statistical parameters (minimum, maximum, mean, standard deviation (SD)), independent sample t-test, and one-way ANOVA were carried out in SPSS software (Version 19.0), and the coefficient of variation (CV) was calculated using Equation (5):

$$CV = \frac{SD}{MN} \times 100\%, \quad (5)$$

where CV is the coefficient of variation, SD is the standard deviation, and MN is the mean.

2.3.2. CCA Method

Canonical Correspondence Analysis (CCA, a direct gradient analysis method) was used to reveal the relative contribution of each environmental variable to soil moisture variation. This kind of method has been widely used in soil-environment research [37–39], for it has the advantage of assessing the relationship between soil properties and environmental factors when species data have non-linear relationships with environmental gradients [39,40]. It also has several advantages when species data and/or environmental variables are nonideal. For example, when environmental variables are intercorrelated or we have not found all of the environmental factors that determine the soil properties, CCA is recommended [41]. Detrended Correspondence Analysis (DCA) was used to estimate the length of the environmental gradient before utilizing CCA; when the length is larger than 4, CCA is the most appropriate method for constrained ordination [42,43]. In our study, the length of ordination axes in DCA was long (larger than 4), and CCA was therefore used.

The environmental data should be coded and two data matrices have to be set up before CCA. In this study, land use type was divided into six types: 1 represented soybean land, 2 adzuki bean land, 3 maize land, 4 forestland, 5 shrubland, and 6 grassland. The slope aspect was coded into two types: 1 represented sunny slope, and 2 shady slope. The slope position was classified into five types: top slope, upper slope, middle slope, lower slope, and toe slope, which were represented by 1, 2, 3, 4 and 5, respectively. Slope gradient and elevation were expressed by actual values measured.

The soil moisture content matrix (profile structure) and environmental variables matrix are also needed for CCA. The matrix of soil moisture content is $P \times N$, where P is the number of sampling layers in the profile, and N represents the number of sampling points. In our paper, P was 3, representing 0–20 cm, 20–40 cm, and 40–60 cm for the sampling layers of the soil profile, and N was equal to 30. The matrix of environmental variables is $P \times N$. P means the number of environmental variables (five in this study, including land use type, slope gradient, slope aspect, slope position, and elevation), and N is the number of sampling points (30 in this study).

The theory of CCA is detailed in the paper by Ter Braak [44] and Bodaghabadi et al. [39]. CCA was performed in the Canoco program for Windows 4.5 and the results of the CCA are shown in the form of a triplot, using Canodraw for Windows program.

3. Results

3.1. Soil Moisture Distribution Under Different Land Use Types

Table 2 shows the statistical variables of SMC under six different land use types (soybean land, adzuki bean land, maize land, forestland, shrubland, and grassland, Figure 3). The ranges of SMC in the six land use types were 14.02%–45.90% in soybean land, 12.32%–21.69% in adzuki bean land, 15.01%–25.14% in maize land, 10.29%–22.73% in forestland, 25.03%–33.90% in shrubland, and 47.67%–55.06% in grassland. The average SMC of grassland was 50.94%, which was significantly higher than the other land use types ($p < 0.05$); it was found that grassland on the toe slope was in a state of long-term water accumulation at the sampling time, during the rainfall season. The average SMC was lowest in forestland, which was lower than that of soybean land, shrubland, and grassland, with significant differences ($p < 0.05$). The average SMC followed a decreasing order of grassland > shrubland > soybean land > maize land > adzuki bean land > forestland. The difference among the slope arable lands (soybean land, adzuki bean land, and maize land) was not significant ($p > 0.05$). A significant difference was found among forestland, shrubland, and grassland ($p < 0.05$).

Table 2. Descriptive statistical variables of soil moisture content under different land use types.

Item	Soybean Land	Adzuki Bean Land	Maize Land	Forestland	Shrubland	Grassland
Min (%)	14.02	12.32	15.01	10.29	25.03	47.67
Max (%)	45.90	21.69	25.14	22.73	33.90	55.06
Mean (%)	25.65b	17.01bc	20.08bc	16.95c	28.29b	50.94a
Standard deviation	8.80	6.63	7.17	4.27	4.88	3.77
CV (%)	37.2	39.0	35.7	25.2	17.2	7.4

Means with the same lowercase letters (a, b, c) are not significantly different between soil moisture contents under different land use types at $p < 0.05$.

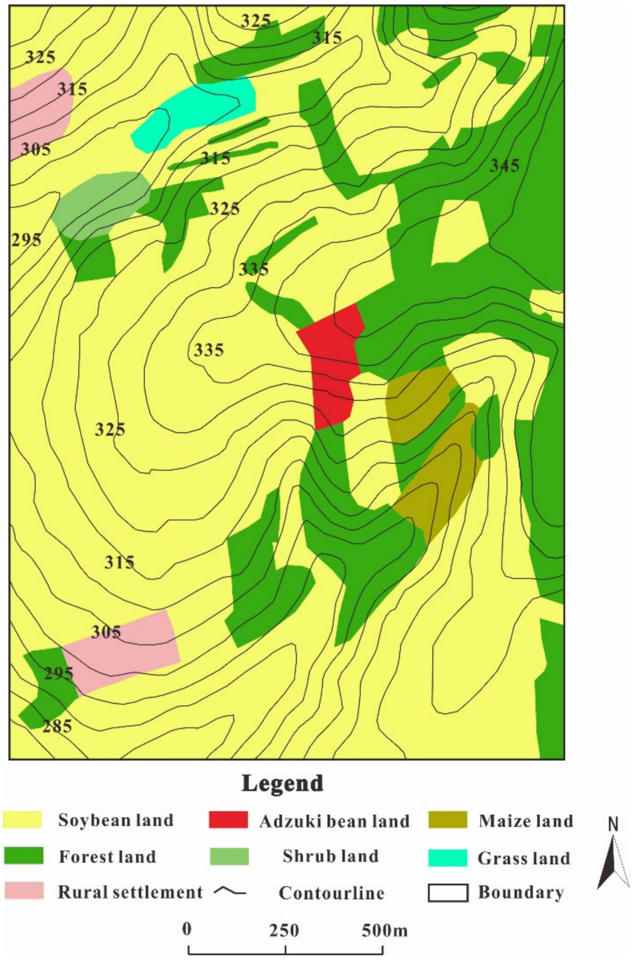

Figure 3. Spatial land use map of the study area.

In terms of the coefficient of variation (CV) (Table 2), the CV of SMC in soybean land, adzuki bean land, maize land, forestland, and shrubland ranged from 17.2 to 39.0%. All of them showed medium variation (10% ≤ CV ≤ 100%), while the CV of SMC in grassland (7.4%) showed weak variation (CV < 10%), indicating that the spatial pattern of grassland soil moisture was more stable. The CVs of slope croplands such as soybean land, adzuki bean land, and maize land were higher than those of forestland, shrubland, and grassland, indicating that human disturbance can increase the spatial heterogeneity of soil moisture.

3.2. Profile Distribution of SMC Variations Across Various Land Use Types

The profile features of SMC among the six land use types are presented in Figure 4a. According to the changing trends of SMC in the profile, it could be divided into four types. The first type included soybean land and adzuki bean land, in which no significant differences of SMC at different depths were found ($p > 0.05$). The second type included maize land and forestland, in which the surface layer (0–20 cm) SMC was significantly higher than that at 40–60 cm ($p < 0.05$). The third type was shrubland, for which the SMC of the subsurface layer (21.91%) was lower than that at 0–20 cm (35.99%), with significant difference ($p < 0.05$). The fourth type was grassland; a considerable increasing trend of SMC was shown in the profile distribution of SMC, and the SMC increased from 39.78% at the depth of 0–20 cm to 54.70% at the depth of 20–40 cm, and then reached 58.33% at the depth of 40–60 cm; the SMC in the surface layer was significantly lower than that of the 40–60 cm soil layer ($p < 0.05$).

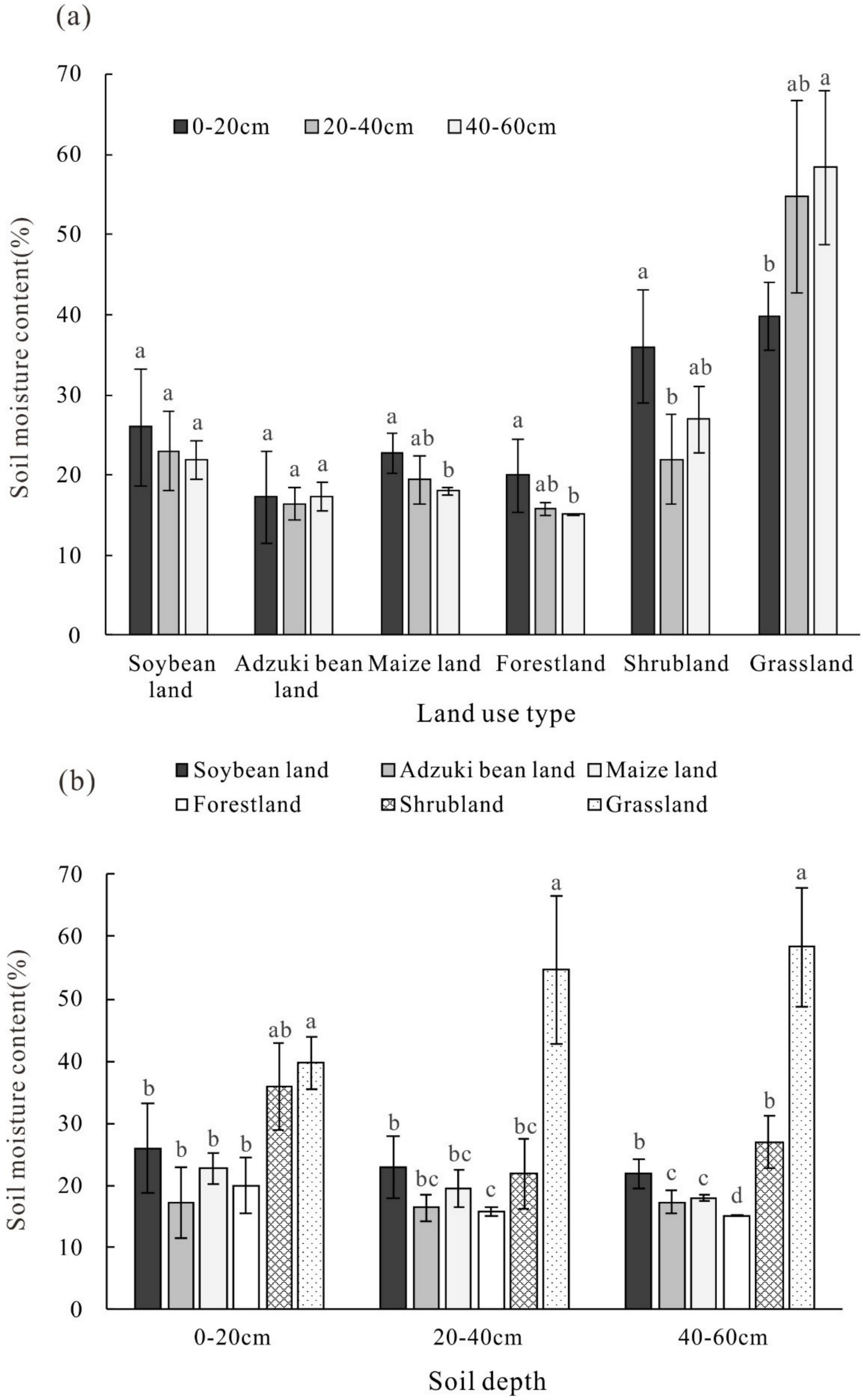

Figure 4. Profile variations of soil moisture under six land use types. (**a**) Vertical patterns of soil moisture under different land use types; (**b**) comparisons of profile soil moisture at the depth of 0–20 cm, 20–40 cm, and 40–60 cm for different land use types. The error line represents the standard deviation. Lowercase letters a, b, c, d at the top of error line indicate significant differences. The significance level is 0.05.

Figure 4b shows the SMC distribution at the depths of 0–20, 20–40, and 40–60 cm under the six land use types. The SMCs of the surface layer (0–20 cm) in soybean land, adzuki bean land, maize land, forestland, shrubland, and grassland were 26.00%, 17.23%, 22.78%, 19.96%, 35.99%, and 39.78%, respectively. The SMC of grassland was significantly higher than that of soybean land, adzuki bean land, maize land and forestland ($p < 0.05$). One possible explanation is that the grassland located on the toe slope could widely accept slope water inflow, and the vegetation transpiration was relatively weak. However, the difference of SMC between shrubland and grassland was not significant ($p > 0.05$), which was due to the fact that they are located in the same slope position; thus, the higher SMC resulting from slope water inflow and rainfall supplement reduced the soil water heterogeneity caused by different plant types.

At the depth of 20–40 cm, the SMCs of the six land use types were 22.99%, 16.43%, 19.42%, 15.76%, 21.91%, and 54.70%, respectively. Among them, the SMC of grassland was significantly higher than that of the other land use types ($p < 0.05$), and the SMC of soybean land was significantly higher than that of forestland ($p < 0.05$). Compared with the surface layer (0–20 cm), the difference of SMC at the depth of 20–40 cm between grassland and shrubland was significant ($p < 0.05$). The most likely reason for this is that the water absorption of shrub roots in this layer is larger than that of grassland, and moreover the rainfall supplement in this layer is weaker than that in the surface layer, leading to the remarkable heterogeneity of SMC under these two land use types. The reason the SMC of soybean land was significantly higher than that of forestland lies in the strong water consumption capacity of forest roots.

In the deep layer (40–60 cm), the SMCs of soybean land, adzuki bean land, maize land, forestland, shrubland, and grassland were 21.95%, 17.36%, 18.02%, 15.12%, 26.98%, and 58.33%, respectively. The differences of SMC in the six land use types at this depth were considerable. The results of a multiple comparison showed that the average SMC of grassland was the highest, followed by soybean land and shrubland, then adzuki bean land and maize land, while forestland was the lowest. At the depth of 40–60 cm, the strong water consumption of forest roots caused the SMC of forestland to be significantly lower than the other land use types ($p < 0.05$). On the contrary, grass has no root distribution in this layer, and furthermore the grassland may receive more slope water (i.e., rainfall and/or lateral runoff) due to the location of the toe slope, and these factors may result in significantly higher SMC in the grassland than the other land use types ($p < 0.05$).

3.3. Variations of SMC Influenced by Slope Aspect

The soybean land and forestland were selected to analyze the variation of SMC induced by slope aspect and slope position (Table 3), as soybean land and forestland are distributed on both of the two slopes (sunny slope, shady slope) and at all the slope positions. Thus, a total of 20 samples were chosen, including 10 on the sunny slope and 10 on the shady slope. The average SMC of the sunny slope (18.90%) was lower that of the shady slope (21.69%), but no significant difference was found ($p > 0.05$). The average SMC of the soybean land on the sunny slope was 22.31%, and that on the shady slope was 24.99%, with no significant difference ($p > 0.05$). The average SMC of forestland on the sunny slope and shady slope were 15.50% and 18.40%, respectively. Although the SMC on the sunny slope was lower than that on shady slope, the difference was not significant ($p > 0.05$). As a whole, the CV of the shady slope was higher than that of the sunny slope, and so was the CV of soybean land. However, the CV of forestland on the shady slope was lower than that on the sunny slope.

Table 3. Impact of slope aspect on soil moisture content (SMC) in the analyzed area, for soybean land and forestland.

Item	Analyzed Area		Soybean Land		Forestland	
	Sunny Slope	Shady Slope	Sunny Slope	Shady Slope	Sunny Slope	Shady Slope
Mean	18.90a	21.69a	22.31a	24.99a	15.50a	18.40a
coefficient of variation (CV, %)	28.57	43.02	14.79	50.42	32.77	17.12

The lowercase letter indicates no significant difference ($p < 0.05$) in SMC under different slope aspects.

3.4. Spatial Variability of SMC Influenced by Various Slope Positions

In general, the slope position had no obvious effect on SMC at each depth (Figure 5a–d), but various patterns can be seen for the relationships between SMC and slope position at the depths of 0–20, 20–40, 40–60, and 0–60 cm in L1, L2, L3, and L4 (Figure 6, Table 4). Figure 6a and c suggest that a linear relationship exists between SMC and slope position at the four depths for the shady slope (L1, L3). The SMC in L1 (soybean land and shady slope) was positively linearly related with slope position, whereas the SMC in L3 (forestland and shady slope) showed a linear and negative correlation with slope position. The relationships at depths of 20–40, 40–60, and 0–60 cm in L3 (with R^2 ranging from 0.64–0.70) were better than those at the depth of 0–20 cm in L3, and all the depths in L1 (Table 4). Moreover, quadratic curve relationships between SMC and slope position were found in L2 and L4 (Figure 5b,d). The correlations were found to be relatively larger in L2 (with R^2 ranging from 0.78 to 0.91) than in L4 (with R^2 ranging from 0.49 to 0.66) (Table 4). In L2, the SMC generally decreased from the top slope to the middle slope, and increased from the middle slope to the toe slope, with the lowest SMC being found on the middle slope at each measured depth. In L4, the SMCs of the middle slope and lower slope were lower than the other slope positions. Different patterns of soil moisture among slope positions in L1, L2, L3, and L4 revealed soil moistures on hillslopes were influenced by land use types and topography together.

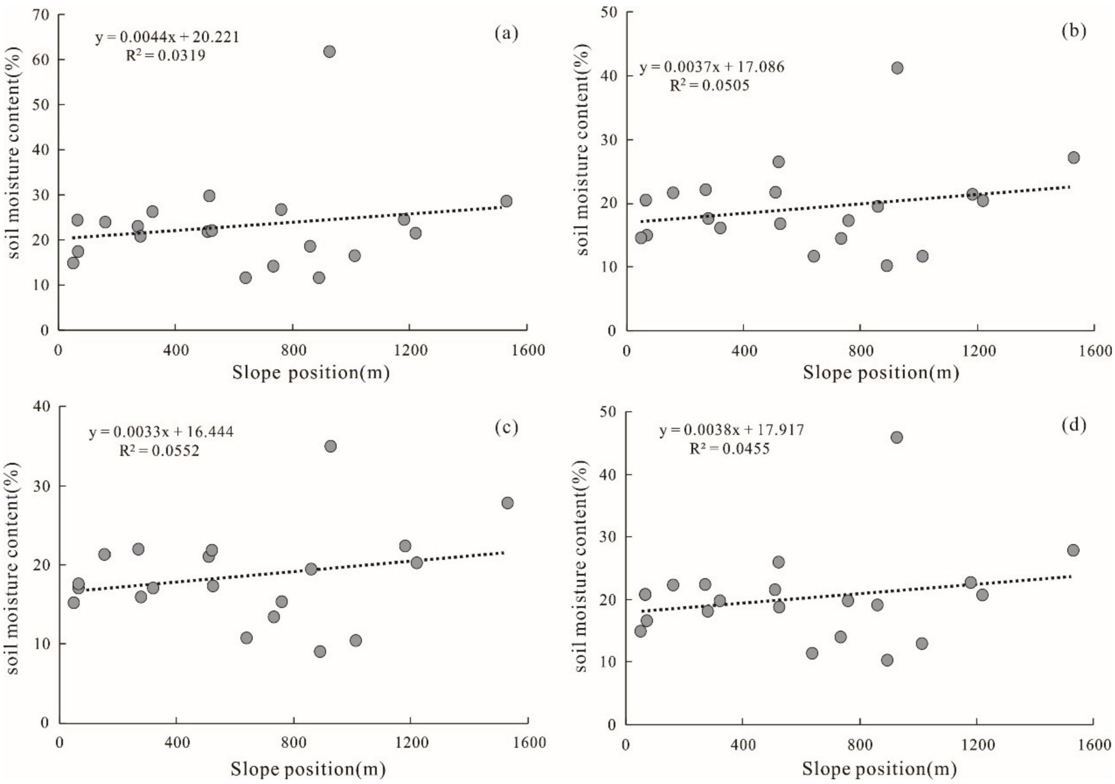

Figure 5. Relationships between the SMC and slope position at various depths. (**a**) At the depth of 0–20 cm; (**b**) at the depth of 20–40 cm; (**c**) at the depth of 40–60 cm; (**d**) at the depth of 0–60cm.

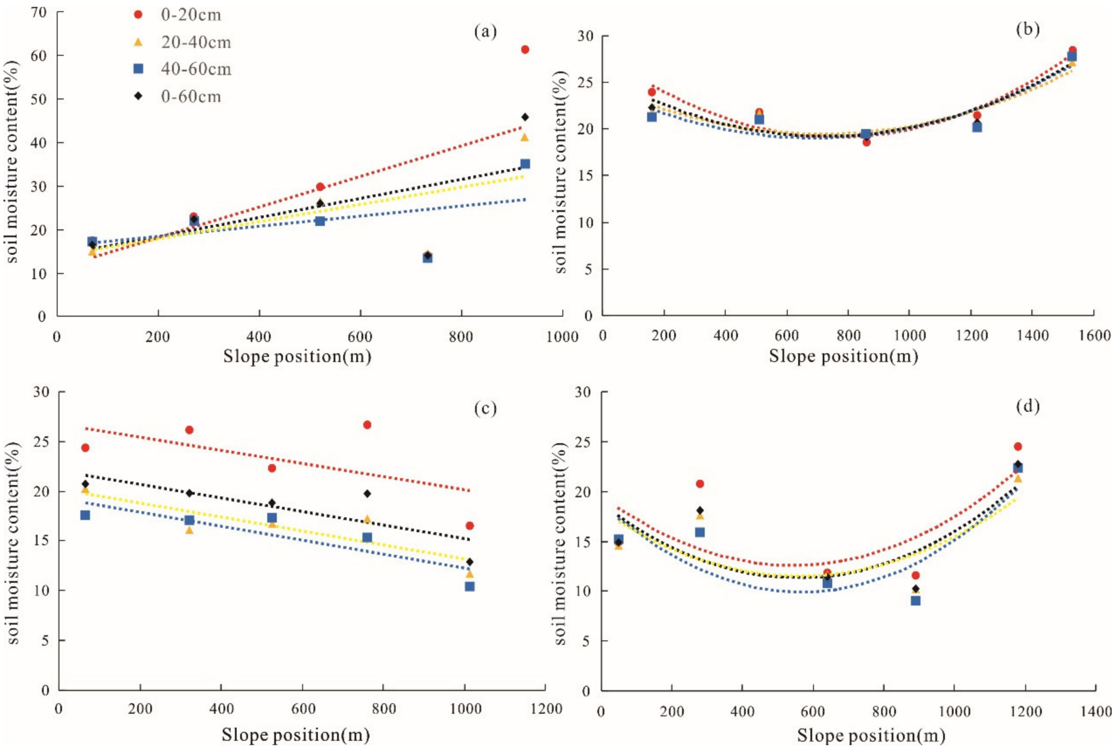

Figure 6. Relationships between the SMC and slope position under different land use type and slope aspect combinations. (**a**) Soybean land and shady slope (L1); (**b**) soybean land and sunny slope (L2); (**c**) forestland and shady slope (L3); (**d**) forestland and sunny slope (L4)

Table 4. The correlation of soil moisture (y) with the slope position (x).

Depth (cm)	L1 Equation	R^2	L2 Equation	R^2
0–20	$y = 0.0351x + 11.412$	0.41	$y = 0.00002x^2 - 0.0232x + 28.033$	0.91
20–40	$y = 0.02x + 13.809$	0.40	$y = 0.00001x^2 - 0.0144x + 24.607$	0.78
40–60	$y = 0.0117x + 15.997$	0.25	$y = 0.00001x^2 -0.0151x + 24.27$	0.83
0–60	$y = 0.0223x + 13.739$	0.37	$y = 0.00001x^2 - 0.0176x + 25.637$	0.85
Depth (cm)	**L3 Equation**	**R^2**	**L4 Equation**	**R^2**
0–20	$y = -0.0066x + 26.734$	0.35	$y = 0.00002x^2 - 0.0255x + 19.653$	0.42
20–40	$y = -0.007x + 20.167$	0.70	$y = 0.00002x^2 - 0.0233x + 18.198$	0.49
40–60	$y = -0.007x + 19.312$	0.74	$y = 0.00003x^2 - 0.0316x + 18.936$	0.66
0–60	$y = -0.0068x + 22.071$	0.64	$y = 0.00002x^2 - 0.0268x + 18.929$	0.52

L1 = soybean land and shady slope; L2 = soybean land and sunny slope; L3 = forestland and shady slope; L4 = forestland and sunny slope.

3.5. Dominating Factors of SMC Variability by Canonical Correspondence Analysis (CCA)

Canonical Correspondence Analysis (CCA) was conducted to analyze the relationship between soil moisture variation and the environmental variables which were measured in this research. By means of Monte Carlo permutation test, we tested the significance of constrained ordination (CCA) and assessed the effect of the obtained environmental variables (land use type, slope gradient, elevation, slope aspect, and slope position) on the heterogeneity of soil moisture. The tests (499 permutations were performed) of the first ordination axis and the second ordination axis were significant ($p = 0.010$ and $p = 0.004$, respectively). Additionally, the first two ordination axes explained most of relationship between soil moisture and the environmental variables (99.0%). Thus, a triplot involving the first two axes was drawn to present the CCA results. The CCA results also suggest that the explanatory power of the first canonical axis (91.5%) was stronger than the other axes together, which indicates that the first ordination axis is of great importance in interpreting the relationship between soil moisture content variation and influencing factors.

The CCA ordination diagram (Figure 7) displays the sampling point scores and soil depth scores and ranks the importance of environmental variables in contributing to soil moisture variation. The interpretations of the CCA ordination diagram are as follows: each arrow represents an environmental variable, and the length of an arrow tends to explain the relative importance for determining soil moisture variation; the longer arrows represent more important variables. The angle between an arrow and axis 1/axis 2 is equal to the correlation of the environmental variable and axis 1/axis 2; the closer the angles, the greater the correlation. The quadrant in which an arrow is located represents the positive/negative correlation between an environmental variable and an ordination axis; the first quadrant and third quadrant represent positive correlations, while the second quadrant and fourth quadrant represent negative correlations. The projection of the species points (soil depths) onto an environmental variable arrow provides the ordering of the effects of environmental variable on species.

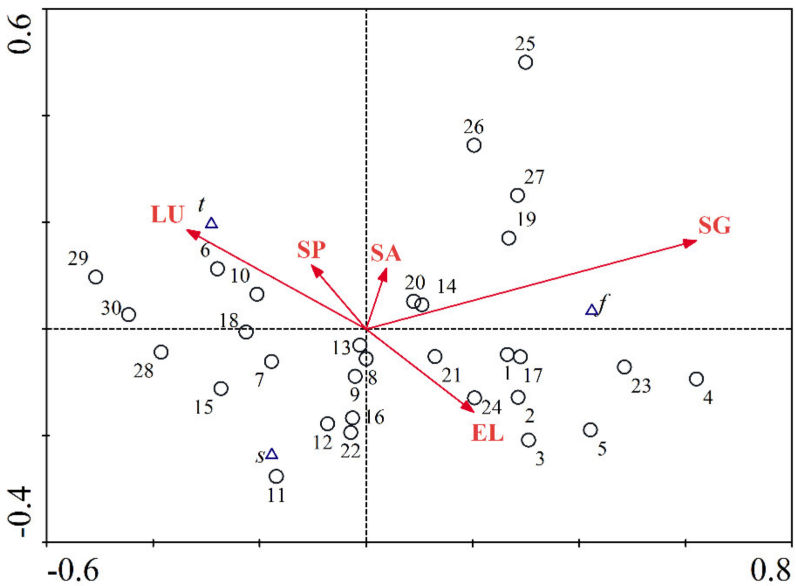

Figure 7. Canonical Correspondence Analysis (CCA) ordination diagram with sampling points (circles), soil depths (triangles), and environmental variables (arrows). Sampling points: 1–30; environmental variables: LU = land use type, SP = slope position, SA = slope aspect, SG = slope gradient, EL = elevation. Soil depths: f = 0–20 cm; s = 20–40 cm; t = 40–60 cm.

The first ordination axis (Axis 1) was significantly positively correlated with the slope gradient ($p < 0.001$), and was significantly negatively correlated with land use type ($p < 0.05$), and the correlation coefficients were 0.87 and −0.47, respectively (Table 5). Therefore, the first ordination axis was mainly interpreted as a gradient of the slope gradient and land use type. The second ordination axis (Axis 2) was significantly negatively correlated with elevation ($p < 0.05$), and was significantly positively correlated with both the slope gradient, and land use type ($p < 0.05$); the correlation coefficients were −0.40, 0.42, and 0.47, respectively (Table 5). The second ordination axis reflected the comprehensive gradient of elevation, slope gradient, and land use type. In addition, in terms of the length of the arrows, the slope gradient arrow was the longest, the land use type arrow and that of elevation were second, and the slope position and the slope aspect were the shortest (Figure 7), indicating that the slope gradient has the greatest influence on the heterogeneity of soil moisture, while the slope position and slope aspect have the least impact.

Table 5. Correlation coefficients of environmental factors and the first two axes of CCA.

Environmental Variables	Axis1	Axis2
Elevation	0.28	−0.40*
Slope gradient	0.87***	0.42*
Slope position	−0.14	0.31
Land use	−0.47*	0.47*
Slope aspect	0.05	0.29

*Significant at the 0.05 level; *** Significant at the 0.001 level.

The surface layer (0–20 cm) point is located at the right side of the diagram, which indicates that it is greatly affected by slope gradient and elevation; the 20–40 cm soil layer, located in the third quadrant, is far away from the environmental variable arrows but relatively close to the center of the diagram, compared with the surface layer (0–20 cm) and the deep layer (40–60 cm); this means the 20–40 cm soil layer was influenced by many environmental factors, but all of the factors had relatively less effect on the 20–40 cm soil layer. The 40–60 cm soil layer (in the second quadrant) was mainly affected by land use type. By projecting the 0–20 cm, 20–40 cm, and 40–60 cm soil layer points onto the arrows of the three main environmental variables (slope gradient, land use type, elevation), it can be seen that land use type had the greatest impact on the 40–60 cm soil layer, followed by the 20–40 cm soil layer, and land use type had the least impact on the 0–20 cm soil layer. That is, for land use type, as the depth of the soil layer increases, the degree of influence increases. Slope gradient and elevation had opposite effects to land use type; as the depth of the soil layer increases, the degree of influence becomes smaller.

4. Discussion

4.1. Spatial Patterns of Vertical SMC Variations for Different Land Use Types in the Black Soil Area of China

The soybean land and adzuki bean land exhibited the same changing trend for the profile SMC. This is likely due to the fact that soybeans and adzuki beans are both legumes. Compared with other land use types, the similar leaf coverage, plant height, and root depth may lead to the same soil moisture infiltration and consumption patterns. In addition, because of long-term farming, soil texture in cropland (soybean land and adzuki land) is loose, and the soil vertical infiltration efficiency is high; thus, no significant difference of SMC was found between the depth of 20–40 cm and the depth of 0–20 cm, accompanied by timely precipitation weak consumption ($p < 0.05$). Further, most of the roots of these plants are distributed at the depths of 0–40 cm [45], and thus in the deep layer (40–60 cm) the consumption of soil moisture is weak. This is why the differences in SMC between the depth of 40–60 cm and the other layer were not significant ($p > 0.05$).

The SMCs of maize land and forest land showed a decreasing trend with the increase in depth, and the SMC of the surface layer (0–20 cm) was significantly higher than that of the deep layer (40–60 cm) (Figure 4a). The main reason for this is that both of these plants are relatively tall and require strong transpiration to ensure water and nutrient supply to their top leaves, compared with soybean land and adzuki bean land; moreover, transpiration is one of the main motives for absorption by roots. As a result, due to a large amount of water consumption by root absorption and insufficient water supply at the depth of 40–60 cm, the moisture content in that layer was significantly lower than in the surface layer ($p < 0.05$).

The SMC in the surface layer of shrubland was high. This is due to three main reasons. Firstly, shrubland receives more water from the slope because it is located on the toe slope; secondly, the evaporation of the surface soil layer is relatively weak for the coverage of the canopy and litter layer; thirdly, the infiltration of soil moisture into the surface layer is large. The reasons for the large amount of soil moisture infiltration into the surface soil include: (1) the canopy is close to the surface and the shrubland is covered by a deep litter layer (this is also the reason for weakening of the surface evaporation), which can effectively prevent rainfall splashing and increase vertical infiltration; (2) at the same time, the coverage of surface vegetation and litter will cause the soil to form an anaerobic environment, accelerating the decay of the litter and dead roots, thereby increase soil organic matter content and forming a good agglomerate structure, which ultimately improves the soil's physical and chemical properties, increasing soil porosity and connectivity between pores [46,47]. In addition, the roots of shrubs are usually shallower than the roots in forestland. The shrubs in the study area were shallow root types, which are mainly distributed within 40 cm. Therefore, due to the interweaving of the shrub roots, there were many cracks around the roots at the depth of 20–40 cm, producing preferential flow [48,49]. The SMC in the subsurface layer was significantly lower than that of the surface layer, which can be attributed to soil moisture consumption by the roots and soil moisture seepage. In conclusion, the profile variation pattern of soil moisture in shrubland is mainly related to coverage and root distribution.

The SMC of grassland increased with the increase of soil depth, and the SMC in the 40–60 cm soil layer was significantly higher than that of the surface layer (0–20 cm). Possible explanations are: (1) grassland is located on the toe slope and the slope gradient is gentle (Table 1), resulting in more reception of moisture from the slope; (2) the SMC of the deep soil layer (40–60 cm) is more abundant in a state of water accumulation during the rainy period, and the roots of grass are situated in the shallow soil layer, thus they consume less water in the deep soil layer [50].

4.2. The Effect of Land Use Type on Soil Moisture

To some extent, various land use types (i.e., different vegetation types) have vital impacts on soil moisture heterogeneity by affecting the infiltration rate, surface runoff intensity, soil evaporation intensity, and soil physical and chemical properties, combined with vegetation transpiration, root distribution, and hydraulic redistribution [51–54].

The results of CCA showed that land use type had a significant effect on soil moisture variability in the study area ($p < 0.05$) (Table 5), and the influence degree in the profile followed a decreasing order of deep layer (40–60 cm) < subsurface layer (20–40 cm) < surface layer (0–20 cm) (Figure 7). That is, as the depth of the soil increased, the impact of land use type on soil moisture increased (Figure 8). This was consistent with the results of Su et al. [30] in the black soil area. Yu et al. [36] have also reported similar results in the study of the Loess Plateau, and pointed out that the effect of land use type on soil moisture in the deep layer is greater than that of the surface layer, which was mainly related to the root distribution characteristics of vegetation. As a common view, the 0–20 cm soil layer is an active interface between the atmosphere, soil, vegetation, and human activities, and is the most affected by precipitation, infiltration, soil evaporation, and canopy cover [12,55]. During the sampling period, abundant precipitation recharge and the redistribution of rainfall by topographical elements will mask the impact of different land use types on the soil moisture variation in the surface layer. On the contrary, root distribution, water consumption of roots [9,56], and soil physical and chemical properties (e.g., organic matter content and soil porosity) caused by roots change differently in the deeper layers, which makes land use type show a greater impact on the deep layer and less impact on the surface layer.

4.3. The Influence of Topographic Features on Soil Moisture

At the small scale, topographical factors have an important influence on the spatial differentiation of soil moisture [5,16,36]. Compared with the slope aspect, elevation, and slope position, the influence of slope gradient on soil moisture variation has been confirmed by many scholars [17,21,24,27]. The slope gradient of the study area had the greatest impact on soil moisture (Figure 7), and it was significantly correlated with the first sorting axis (Axis 1) ($p < 0.001$, Table 5). This is in agreement with the findings of previous studies. Further, the surface layer was more affected by slope gradient than the deep layer (Figure 7). A possible reason for is that rainfall is the only source of soil moisture in the black soil area, and the slope gradient is highly prone to the effect of precipitation redistribution, which determines the amount of infiltration and runoff; as the slope gradient increases, the slope runoff intensity will increase, and the soil moisture infiltration rate in the surface layer will decrease accordingly [57,58]. On the profile, the SMC at the surface layer is most affected by precipitation supplements, so it is more susceptible to slope gradient than the deeper layers.

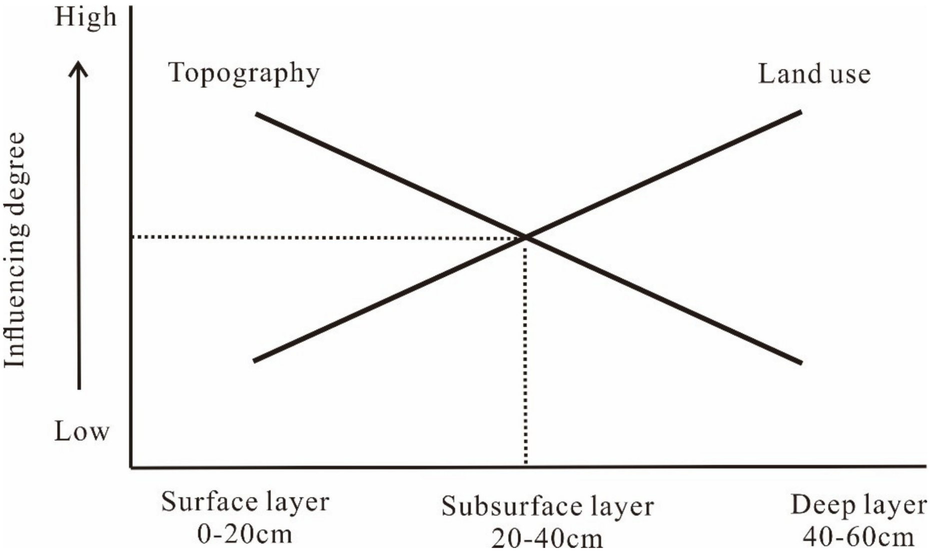

Figure 8. Conceptual model of the impact of land use and topography on profile soil moisture (topography mainly concerns the slope gradient and elevation).

In addition, the elevation of the study area also impacts on soil moisture to some extent. The CCA study results (Figure 7, Table 5) show that the elevation was significantly negatively correlated with the second axis ($p < 0.05$), and among the topographical elements, its influencing degree on soil moisture heterogeneity was only less than slope gradient. However, contradictory conclusions have been found in other research. Some scholars have revealed that elevation is an important factor affecting the spatial variety of soil moisture. For example, Yang et al. [10] observed a spatial distribution pattern and heterogeneity of soil moisture in the small watershed of the Loess Plateau, and found that the elevation and SMC showed a significantly negative correlation in various land use types such as cropland, garden land, grassland, and forestland, but not shrubland ($p < 0.01$); on the contrary, some scholars believe that the effect of elevation on the spatial distribution of soil moisture is weak [36]. This discrepancy could be attributed to the elevation difference. Elevation may have an important effect on soil moisture only when the elevation difference exceeds a critical value.

No significant difference ($p > 0.05$) was found between the average SMC of the sunny slope (18.90%) and that of the shady slope (21.69%); the same conclusions were observed in soybean land and forestland. Generally, the temperature of the surface layer varies due to differing amounts of solar radiation received by different slope aspects, resulting in various soil evaporation and vegetation transpiration intensities, which ultimately affect SMC [17,21]. The black soil area is characterized by a long and gentle slope, so the difference in solar radiation received by the shady slope and the sunny slope is not significantly obvious. In addition, the sampling period was during abundant precipitation, thus the sufficient supplement of soil moisture could reduce soil moisture variation caused by different solar radiation on the two slopes.

The results of CCA show the slope position had no significant effect on the heterogeneity of soil moisture in the whole study area (Figure 7), and the same results are presented in Figure 5. The main reasons for this are that slope position is not a single variable—slope gradient, land use type, and elevation are superimposed on different slope positions; at the same time, differing slope positions are also affected by the comprehensive and cumulative effects of slope ecological and hydrological processes [9,22]. However, within the combination of slope aspect and land use type, the relationships between SMC and slope position showed various trends at the depths of 0–20, 20–40, 40–60, and 0–60 cm in L1, L2, L3, and L4 (Figure 6, Table 4). For example, the SMC in L1 (soybean land, shady slope) and L3 (forestland, shady slope) showed a linear correlation with slope position (Figure 6a,c), and quadratic curve relationships between SMC and slope position were found in L2 (soybean land, sunny slope) and L4 (forestland, sunny slope) (Figure 6b, d), with the lowest SMC on the middle slope. Scholars [22,30] have discovered that the SMCs under a single land use type on the slope of the northeast black soil area generally decrease from the top slope to the middle slope, and increase from the middle slope to the toe slope. This is driven by the character of a long slope and more solar radiation near the middle slope, which leads to strong evaporation and transpiration, thus the SMC near the middle slope is relatively lower. The trend found in L2 and L4 is in agreement with previous studies in the black soil area of China. The SMC of soybean land on the shady slope increased from the top slope to the toe slope, which can be attributed to relatively weak solar radiation and the low water consumption intensity of soybean. As a result, the greater the distance from the top slope, the higher the accumulation of slope water. Because of the water consumption capacity and water retention capacity of forest, more water is intercepted at a position far from the top slope, so the SMC was relatively lower here.

4.4. Comprehensive Impact Mechanism of Soil Moisture Variation

The difference in SMC is controlled by the amount of soil moisture supplement and consumption. In rain-fed agricultural areas, the soil moisture balance equation can describe the difference in SMCs and soil hydrological processes [59].

$$\frac{d\theta}{dt} = P - ET - L - R - Q, \tag{6}$$

where θ represents the soil moisture content, P represents precipitation, ET represents actual evapotranspiration, L represents drainage, R represents the runoff of surface, and Q represents lateral subsurface flow.

The depth of groundwater in the black soil area is deep, and there is no irrigation in the study area. Therefore, the soil moisture replenishment mainly depends on precipitation. Meanwhile, soil moisture consumption is related to surface runoff, subsurface flow, soil evaporation, vegetation transpiration, and so forth. These direct factors that affect SMC are driven by factors such as the climate, soil, land use type, and topographic elements. The scale-dependent properties of influence factors mean soil moisture is controlled by different factors at small scales and at large scales [9,60,61]. At a small scale, land use and topographic features jointly affect the replenishment and consumption of soil moisture through soil hydrological processes, resulting in variability of soil moisture [22].

In short, the potential mechanisms/hydrological processes (Table 6) that may control the soil moisture variability on the slopes in the black soil area (assuming relatively uniform rainfall supplementary conditions due to the small scale of the study area) are as follows: (1) land use type mainly affects rainfall infiltration, soil evaporation, vegetation transpiration, and root absorption through differing leaf cover, litter cover, root systems, and the changing of soil physical and chemical properties; and (2) topographical factors affect the distribution of precipitation and soil moisture evaporation to a certain degree on the surface and subsurface layers. Further, land use type has a greater impact on the deep layer (40–60 cm) than the surface layer, while on the contrary, the influence of the topographical elements on the deep layer is smaller than on the surface layer (Figure 7). Figure 8 also shows the conceptual model. Therefore, land use type and topographical elements work together on the vertical soil moisture at different depths, resulting in various profile patterns of soil moisture heterogeneity.

Table 6. Main influence mechanisms of land use type and topography features on soil moisture.

Factors	Parts/Features	Mechanisms	Influencing Result
Land use type	Leaf cover	Transpiration	Consumption of soil moisture
		Rainfall distribution	Interception of precipitation, reducing surface runoff, increasing infiltration
		Reducing surface evaporation	Reducing surface soil moisture consumption
	Litter cover	Reducing evaporation of soil moisture	Reducing the consumption of Soil moisture
		Reducing runoff, improving the physical and chemical properties of soil	Increasing soil moisture infiltration
	Roots	Uptake water	Consumption of soil moisture
		Formation of priority flow through the interspersed roots	Loss of soil moisture
Topography	Slope gradient	Partitioning the rainfall into runoff and infiltration	Determining the amount of runoff and infiltration; generally, the gentler the slope, the more the infiltration
	Slope aspect	Determining the amount of solar radiation received	Resulting in different soil evaporation intensities and vegetation transpiration intensities
	Slope position	Cooperating with land use type, slope aspect, slope gradient	Comprehensive mechanism with land use types and topographical elements
	Elevation	Impacting on the distribution of soil moisture and heat	The influencing degree on soil moisture is related to the elevation differences. The smaller the differences, the less the effect

5. Conclusions

The spatial heterogeneity of soil moisture under six land uses types and different topographic attributes was investigated on the slopes in the black soil area of China, and the dominant factors controlling SMC variability and their relative contributions were evaluated. SMCs of different land use types exhibited remarkable spatial variability, and the average soil moisture content followed a decreasing order of grassland > shrubland > soybean land > maize land > adzuki bean land > forestland. Four types of profile SMC patterns were found. The first type included soybean land and adzuki bean land, for which there were no significant differences ($p < 0.05$) of SMC at different depths. The second type included maize land and forestland, for which the surface layer (0–20 cm) SMC was significantly higher than that at 40–60 cm ($p < 0.05$). The third type was shrubland, for which the SMC of the surface layer was lower than that at 40–60 cm with significant difference ($p < 0.05$). The fourth type was grassland, for which the SMC in the surface layer was significantly lower than that of the 40-60 cm soil layer ($p < 0.05$). Further, spatial variability of soil moisture was strongly influenced by slope gradient, followed by land use type and elevation, while slope position and aspect had the least impact. The impact degree of land use type on soil moisture increased with increasing depth, but on the contrary, topographic elements (mainly slope gradient and elevation) had the opposite changing trend. Under the relatively uniform rainfall supplementary conditions, soil moisture heterogeneity and vertical patterns of the black soil area of China were controlled by the comprehensive mechanisms of land use type (leaf cover, litter cover, root system, and the changing of soil physical and chemical properties) and topographic elements (mainly the slope gradient and elevation). These results might be helpful in optimizing land use structures, preventing soil erosion, and in the modeling of hydrological processes.

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