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Soil Moisture Responses under Different Vegetation Types to Winter Rainfall Events in a Humid Karst Region

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Abstract: Humid karst ecosystems are fragile, with precipitation being the main source of soil moisture recharge. The process of soil moisture recharge and usage varies by vegetation type. To analyze the dynamics of soil moisture under different vegetation types during rainfall events, we continuously monitored soil moisture in arable land, grassland, shrub, and forest areas at 10-minute intervals from November 6, 2019, to January 6, 2020.The arable land was used as a control group. Soil moisture under the different vegetation types responded to light, moderate, and rainstorm events with large rainfall amounts. However, only the soil moisture in the grassland areas responded to a light rainfall event with a rainfall amount of 0.87 mm. The largest soil moisture recharge (12.63 mm) and decline (2.08%) were observed for the grassland areas, with the smallest observed for the forest areas. While the grassland areas showed the greatest decline in soil moisture following rainfall, they were more easily recharged during the winter rainfall events. Soil moisture in forests and shrubs was less recharged than in grasslands but also declined less. Therefore, forests and shrubs are better at retaining soil moisture in winter, which is informative for the formulation of a regional vegetation recovery model.

Keywords: soil moisture; different vegetation types; winter rainfall events; response characteristics

1. Introduction

Soil moisture plays an important role in the growth of vegetation (Brantley et al. 2017; Laio et al. 2001). Vegetation can affect soil moisture and its response to precipitation via many complex and interacting hydrological processes (Canton et al. 2016; Chen et al. 2007; Daly and Porporato 2005; Rivera et al. 2014). There are differences in the characteristics of the canopy and root distributions of different vegetation types, and these differences affect the response of soil moisture to rainfall (Gehrels et al. 1998). Therefore, it is important to study the responses of soil moisture to rainfall in karst regions with different vegetation types.

The responses of soil moisture under different vegetation types to rainfall have been studied by several researchers. The amount and period of rainfall varies in regions with different humidity conditions. Soil moisture under the same vegetation type has different response characteristics in regions with different humidity conditions. In arid regions, the soil moisture in shrub areas is more sensitive to rainfall than that in grassland or forest areas (Sun et al. 2015; Wang et al. 2008). For example, Sun et al. (2015) studied the soil moisture dynamics in shrub, forest, and grassland areas in arid regions and found that soil moisture in shrub areas is the most sensitive to single rainfall events. Conversely, in semi-arid regions, soil moisture in grassland areas is more sensitive to rainfall than that in shrub or forest areas (Li et al. 2013; Su and Shangguan 2019; Tang et al. 2019; Yu et al. 2018). For example, Li et al. (2013) studied the soil moisture dynamics in shrub and grassland areas in semi-ari d regions and found that grassland soil moisture is more sensitive to summer rainfall than shrub soil moisture. In sub-humid regions, the response of grassland soil moisture to rainfall is more sensitive than that of shrub or forest soil moisture (Lozano-Parra et al. 2015; Mei et al. 2018; Wang et al. 2013). In addition, the results of Wang et al. (2013) showed that grassland soil moisture is more sensitive to rainfall than shrub and forest soil moisture. Meanwhile, in humid regions, Zhu et al. (2014) studied the responses of grassland and forest soil moisture to rainfall and found that their sensitivities to rainfall are similar.

Humid karst regions are a subset of humid regions; however, results obtained in humid regions may not necessarily be representative of humid karst regions. This is because karst environments usually have different characteristics from non-karst environments (Hartmann et al. 2014; Li et al. 2020). Karst environments are usually characterized by a shallow soil layer, high soil permeability, and complex topography (Bonacci et al. 2009; Dai et al. 2017; Fu et al. 2016b; Sohrt et al. 2014).

There has been some research concerning the responses of different vegetation types to rainfall in karst regions. For all the different vegetation types, the response of soil moisture to rainfall under heavy rainfall conditions is more sensitive than that under light and moderate rainfall conditions. The variation in the soil moisture at different soil depths is also known to decrease with increasing soil depth (Jing et al. 2020; Liu et al. 2013; Zhang et al. 2013; Zhang et al. 2016). Jing et al. (2020)

found that the response times of shallow soil moisture under different types of vegetation to rainfall in summer are significantly different and that the response is faster under heavy rainfall conditions than under light and moderate rainfall conditions. Zhang et al. (2013) studied the changes in the soil moisture under different vegetation types throughout the year and found that, when the rainfall is light, the soil moisture does not change significantly, while when the rainfall is heavy, the soil moisture content changes significantly over a short period of time. Even though multiple researchers have studied the responses of soil moisture under different vegetation types to precipitation in karst regions, these results do not represent the situation in winter. Therefore, our understanding of the characteristics of soil moisture responses to winter rainfall events under different vegetation types in karst regions remains incomplete.

In humid karst regions, soil moisture in winter affects both plant growth and hydrological processes. On the one hand, because the winter temperature is not too low, the growth of plants is supported by a certain amount of water and water conditions can threaten plant growth (Ding et al. 2020; Li et al. 2019; Zhang et al. 2012). On the other hand, even though there is less precipitation in humid karst regions in winter, the change in the soil moisture is still an important part of the hydrological process and the ability of the soil to regulate and store water is more important in winter than in summer (Fu et al. 2016a; Yang et al. 2019). Therefore, it is important to study the response processes of the soil moisture under different vegetation types to winter rainfall in humid karst regions.

Accordingly, this study investigates the response processes of soil moisture under different vegetation types to different rainfall intensities in winter. We conducted in-situ observations of soil moist ure under different vegetation types in winter and analyzed the dynamic characteristics of the soil moisture during different rainfall events, which can provide a basis for a vegetation recovery model in karst regions.

2. Materials and Methods

2.1 Overview of the Sample Plots

The study area was located in Guanling County, Guizhou Province, China (25° 34′–26° 05′ N, 105° 15′–105° 49′ E). With complex landform types and an extensive distribution of carbonate rocks, it is one of the most typical areas of karst landform development in Guizhou. The climate in Guanling is primarily based on the humid mid-subtropical monsoon. The annual average temperature is 16.2°C, rainfall is abundant, and the annual precipitation is 1205.1–1656.8 mm (Chen et al. 2018). The rainfall is mostly concentrated from June to August. To eliminate the influence of other environmental factors besides vegetation type and related factors among the sample plots, all sample plots were located on the same slope (Figure 1), with an altitude of approximately 700 m, a slope direction of NE, and an inclination of approximately 30°. The main type of soil in the area is limestone. The main vegetation in the study area is artificially planted corn and plantain, as well as naturally restored secondary grasslands, shrubs, and woodlands. The vegetation information and soil background of the different vegetation types are given in Table 1.

Table 1. Overview of the plots of the various vegetation types.

Plots of different vegetation types	**Vegetation Types**	**Vegetation coverage (%)**	**Vegetation height (m)**	**Soil bulk density（g/cm）**	**Soil organic matter content（g/kg）**

Arable Land	/	/	/	1.22	28.95
Grassland	Blumea balsamifera (Linn.); Ageratum conyzoides Sieber ex Steud; Arthraxon hispidus (Thunb.) Makino et al.	30%	0.6m	1.15	49.23
Shrub	Cipadessa cinerascens (Pellegr.) Hand -Mazz; Albizia kalkora (Roxb.) Prain;Mallotus japonicas var. floccosus (Muell. Arg.) S. M. Hwang et al.	50%	3.4m	1.11	68.15
Forest	Radermachera sinica (Hance) Hemsl; Toona sinensis (A. Juss.) Roem;Broussonetia papyrifera et al.	65%	15m	1.04	70.90

2.2 Experimental Design and Data Collection

Five plots were randomly selected from each vegetation type; the size of each plot was 5 m × 5 m; and the plot spacing was approximately 20 m. The HOBO H21_USB soil moisture monitoring system was used in each plot to monitor the soil moisture content at four soil depths (5 cm, 10 cm, 15 cm, and 20 cm). The data collection frequency was 10 min, and the monitoring time was from November 6, 2019, to January 6, 2020. Because of the shallow soil depth on the karst slope, the sa mple plots selected in this study usually contained a large amount of gravel or reached the bedrock at approximately 30 cm below the surface, even though the soil thickness varied greatly. Therefore, t he maximum depth of the soil profile observations was set to 20 cm. The rainfall observations were measured using a rain gauge (RG3-M) with an accuracy of 0.2 mm. Because of the distance between the different sites, a total of three rain gauges were installed throughout the sample plots. The average value of three rain gauges represents the rainfall in the four types of plots.

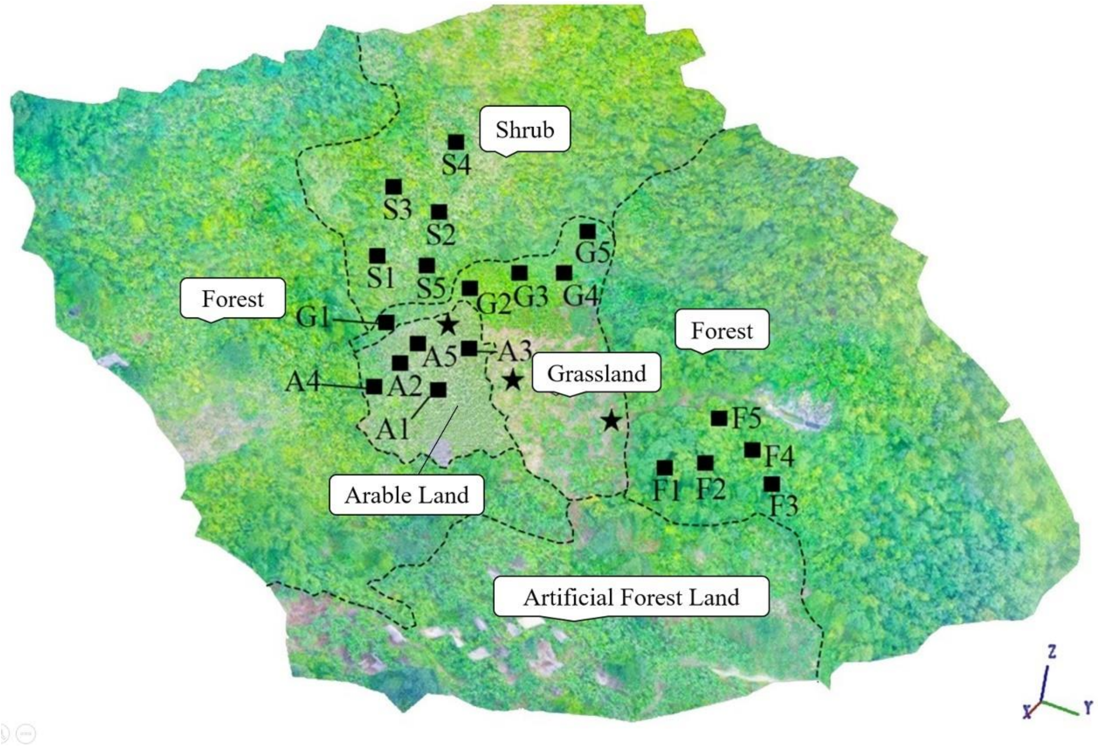


Figure 1. Distribution map of the sample plots. A1–A5 indicate arable land plots; G1–G5 indicate grassland plots; S1–S5 indicate shrub plots; and F1–F5 indicate forest plots. The ★s indicate rain gauges.

2.3 Data Analysis

In this study, the soil moisture responses under the different vegetation types to different rainfall events were analyzed. The soil moisture 10 min prior to the start of a rainfall event was taken as the initial value of the soil moisture. The response characteristics under the different vegetation types were analyzed by observing the changes in the soil moisture 12 h after the end of a rainfall event. The following equations (Yang et al. 2018) are used to calculate the change char acteristics of the soil moisture.

The increase in soil moisture is calculated as

$$\Delta\theta_i = \theta_{max} - \theta_0, \quad (1)$$

where $\Delta\theta_i$ indicates the soil moisture rise rate (%); θ_{max} indicates the peak soil moisture during rainfall; and θ_0 indicates the soil moisture (%) 10 min prior to the start of the rainfall event.

The extent of soil moisture decline is calculated as

$$\Delta\theta_d = \theta_{max} - \theta_e, \quad (2)$$

where $\Delta\theta_d$ indicates the soil moisture drop rate (%) and θ_e indicates the soil moisture (%) 12 h after the end of the rainfall event.

The soil moisture storage is calculated as

$$SW = \sum_{i=1}^{4} \theta_i \, d_i, \quad (3)$$

where SW indicates the soil moisture storage (mm); θ_i indicates the soil moisture content in the i-th layer (%); and d_i indicates the thickness of the soil layer (cm).

The soil moisture recharge is calculated as

$$\Delta SW = SW_{max} - SW_0, \quad (4)$$

where ΔSW indicates the soil moisture recharge (mm); SW_{max} indicates the maximum value of soil moisture storage after the rainfall event (%); and SW_0 indicates the initial value of the soil moisture storage prior to the rainfall event.

Wilcoxon tests were performed on the soil moisture data to test for differences in the soil moisture content at different soil depths under the different vegetation types. Origin 2018 and R (4.0.2) were used to produce the graphs.

3. Results

3.1 Rainfall Characteristics during the Study Period

The rainfall intensity during the experiment was divided and the number of rainfall events of each type was counted according to the standards of the National Meteorological Administration of China, as shown in Table 2. The number of light rainfall events accounted for 80% of the total rainfall events, moderate rainfall events accounted for 13.3% of the total rainfall events, and rainstorm events accounted for 6.7% of the total rainfall events.

Table 2. Classification of the rainfall intensity and the number of each type of rainfall event during the experiment.

Precipitation type	Rainfall in 24 h (mm)	Events
Light rain	<10	12
Moderate rain	10–25	2
Heavy rain	25–50	0
Rainstorm	50–100	1

3.2 Dynamics of the Mean Soil Moisture and Precipitation Distribution

Figure 2 shows the temporal dynamics of the mean soil moisture and precipitation distribution for the three different vegetation types in the karst region. During the study period, the mean soil moisture under the three different vegetation types all responded positively to rainfall. During the period from November 6 to 28, the order of the mean soil moisture content under the different vegetation types was shrub > grassland > arable land > forest. After November 28, the mean soil moisture content in the shrub areas was the highest; this trend continued until December 20. After December 20, the order of the mean soil moisture content under the different vegetation types was arable land > shrub > grassland > forest. During the entire study period, the mean soil moisture content in the forest areas was the lowest, ranging from 23.04% to 32.08%.

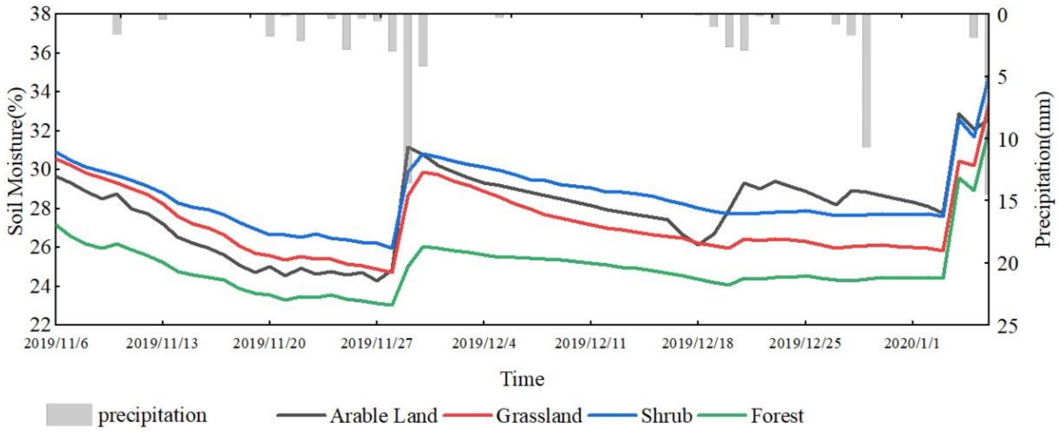


Figure 2. Dynamic changes in the mean soil moisture content and precipitation distribution for the different vegetation types.

3.3 Soil Moisture Characteristics of the Different Soil Layers during the Study Period

Wilcoxon tests were performed on the soil moisture data (Figure 3) and revealed significant differences ($p < 0.001$) in the soil moisture content in all four soil layers under the different vegetation types. A comparison of the median soil moisture in different soil layers revealed that the overall soil moisture content under the different vegetation types showed a tendency to increase with the depth of the soil layer. In arable land areas, the difference in the soil moisture content in the 15-cm and 20-cm soil layers was greater than that in the 5-cm and 10-cm soil layers, while the difference in the soil moisture content in the 15-cm and 20-cm soil layers in the grassland, shrub, and forest areas was smaller than that in the 5-cm and 10-cm soil layers.

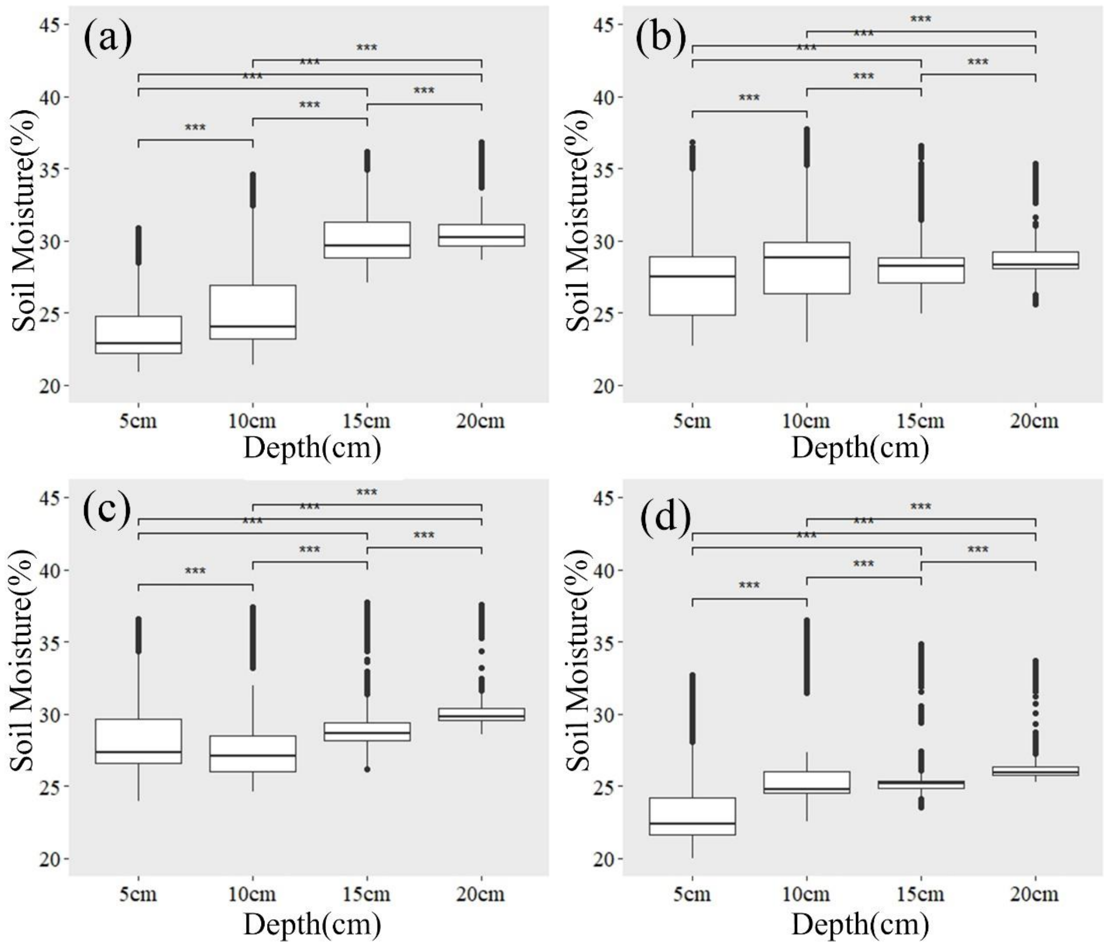
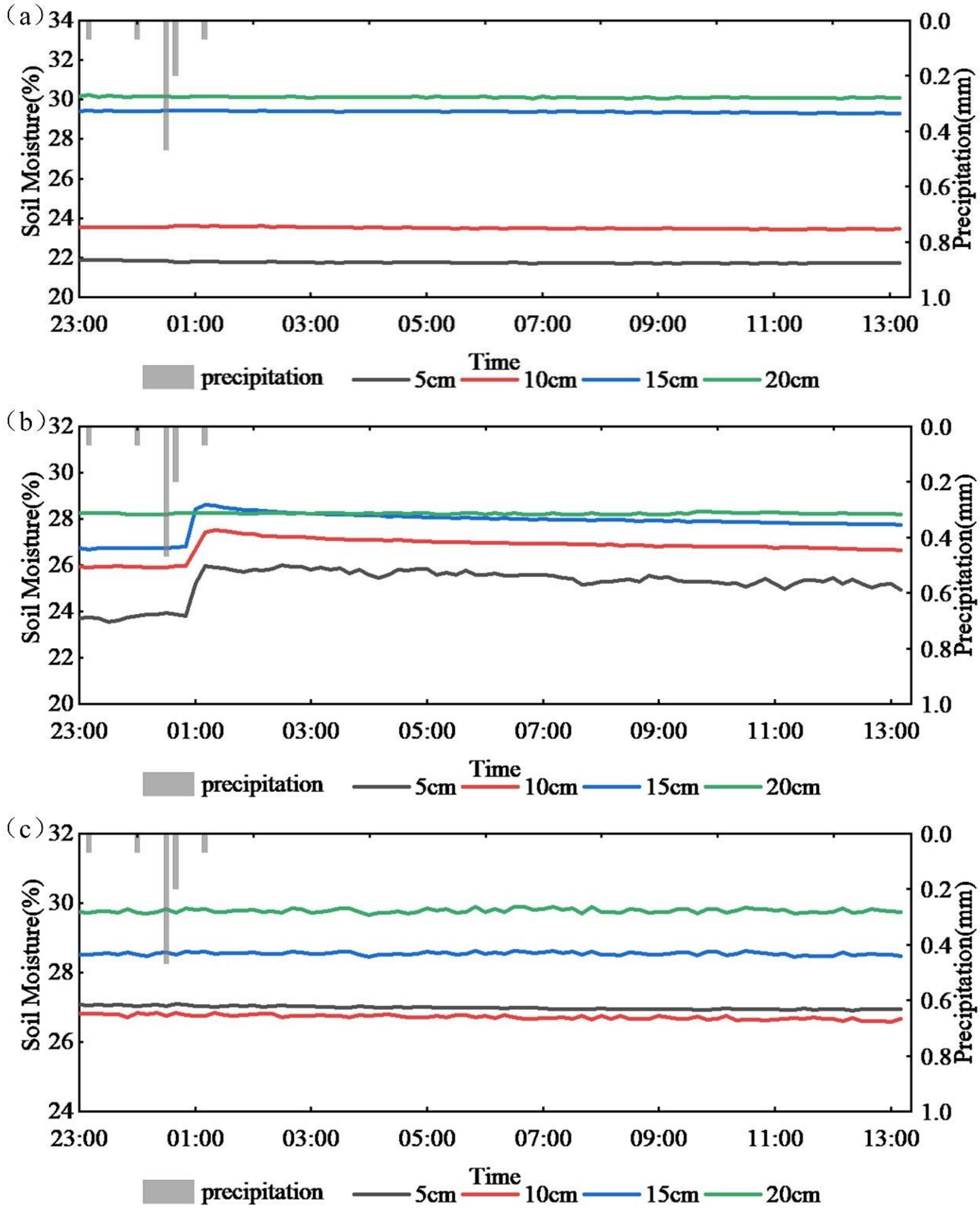


Figure 3. Characteristics of the soil moisture in the different soil layers under the different vegetation types: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

3.4 Responses of Soil Moisture under Different Vegetation Types to Light Winter Rainfall Events

In the analysis of the light rainfall events, two rainfall events with similar average rainfall intensities but different total rainfall amounts were selected for analysis. In the first light rainfall event (Figure 4), the total rainfall was 0.87 mm and the rainfall duration was 2.17 h. During the entire rainfall event, the soil moisture of the different soil layers in the arable land, shrub, and forest areas did not fluctuate significantly. The soil moisture content in the 5-cm, 10-cm, and 15-cm soil layers in the grassland areas had a strong response to the rainfall event, while the soil moisture content in the 20-cm soil layer had a weak response. After the rainfall event, the soil moisture content of the four different soil layers in the grassland areas all began to increase and reached peak values. The order of the peak soil moisture content was 15 cm > 20 cm > 10 cm > 5 cm. In the 5–15-cm soil layers, the time for the soil moisture to reach its peak increased with the soil depth. The greatest rise in the soil moisture content was observed in the 5-cm layer, followed by the 15-cm and 10-cm layers, and the smallest rise in the soil moisture was observed in the 20-cm layer. The decline in the soil moisture content was greatest in the 5-cm soil layer and smallest in the 20-cm soil layer.



(a)
(b)
(c)
Soil Moisture(%)
Precipitation(mm)
Time
23:00
01:00
03:00
05:00
07:00
09:00
11:00
13:00
precipitation
5cm
10cm
15cm
20cm

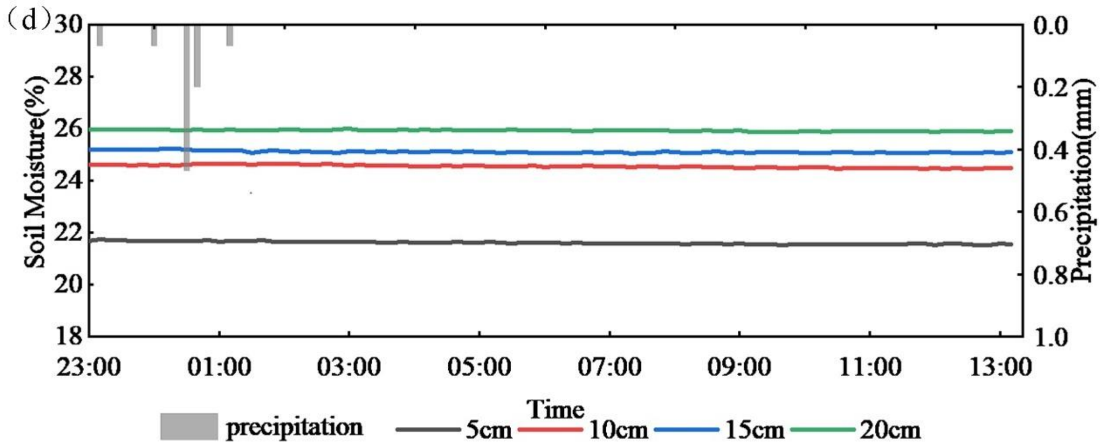
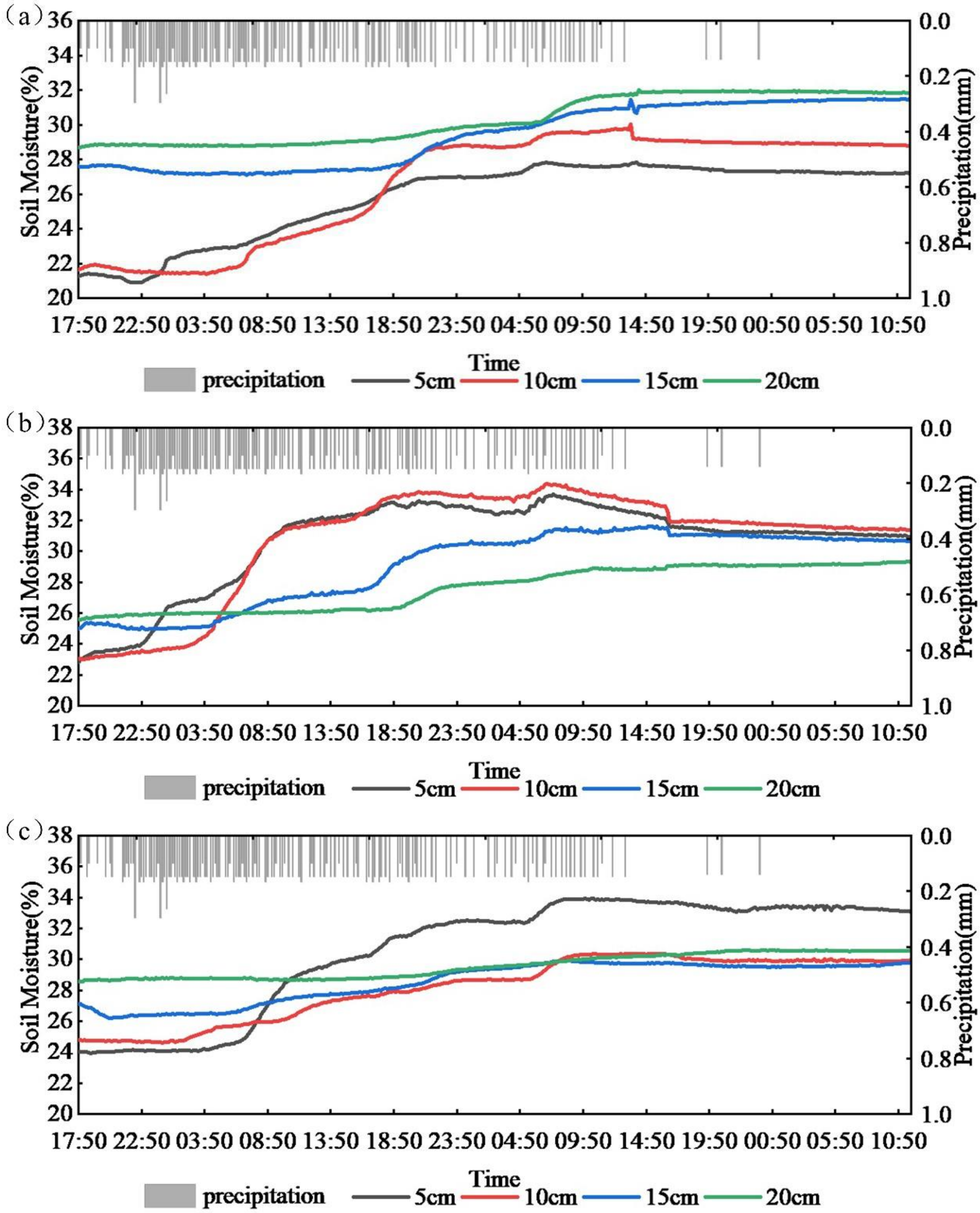


Figure 4. Responses of soil moisture under the different vegetation types to rainfall: (a) arable land; (b) grassland; (c)shrub; and (d) forest.

In the second light rainfall event (Figure 5), the total rainfall was 20.75 mm and the rainfall duration was 54.17 h. There were fluctuations in the soil moisture content at the different soil depths under the three different vegetation types. After the rainfall event occurred, the soil moisture content in the arable land, grassland, shrub, and forest areas gradually increased and reached a peak. In the arable land areas, the peak value of the soil moisture content increased with increasing soil depth, while the grassland, shrub, and forest areas generally had peak values of the soil moisture content in the shallow layers (5 cm and 10 cm) that were larger than those in the deep layers (20 cm and 15 cm). The peak time of the surface soil moisture was the smallest in the arable land areas (37.17 h), and the grassland, forest, and shrub areas lagged by 0.5 h, 3.83 h, and 5.16 h, respectively. The rise in the soil moisture content under the different vegetation types showed a general tendency to be greater in the shallow layers (5 cm and 10 cm) than in the deep layers (15 cm and 20 cm). Both the increase and decrease in the soil moisture content were highest in the grassland areas and lowest in the forest areas.



(a)
(b)
(c)
Soil Moisture(%)
Precipitation(mm)
Time
17:50 22:50 03:50 08:50 13:50 18:50 23:50 04:50 09:50 14:50 19:50 00:50 05:50 10:50
precipitation
5cm
10cm
15cm
20cm

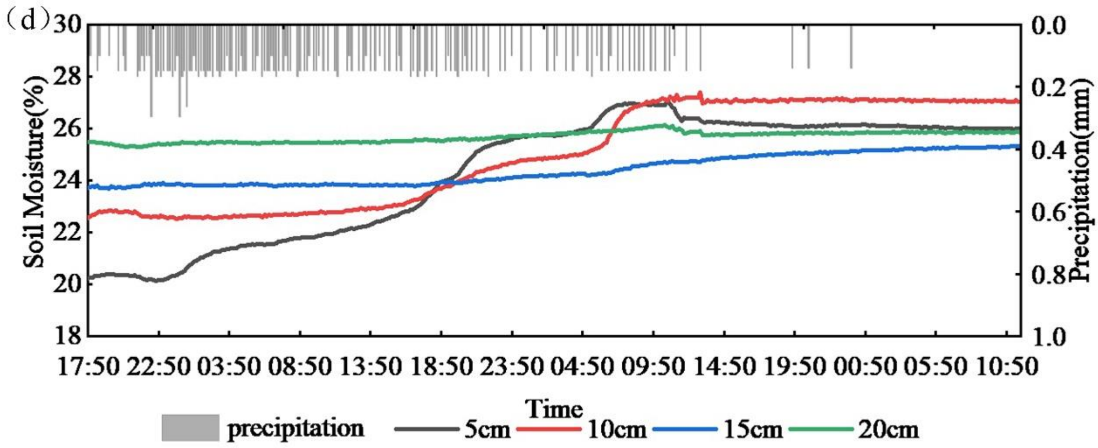
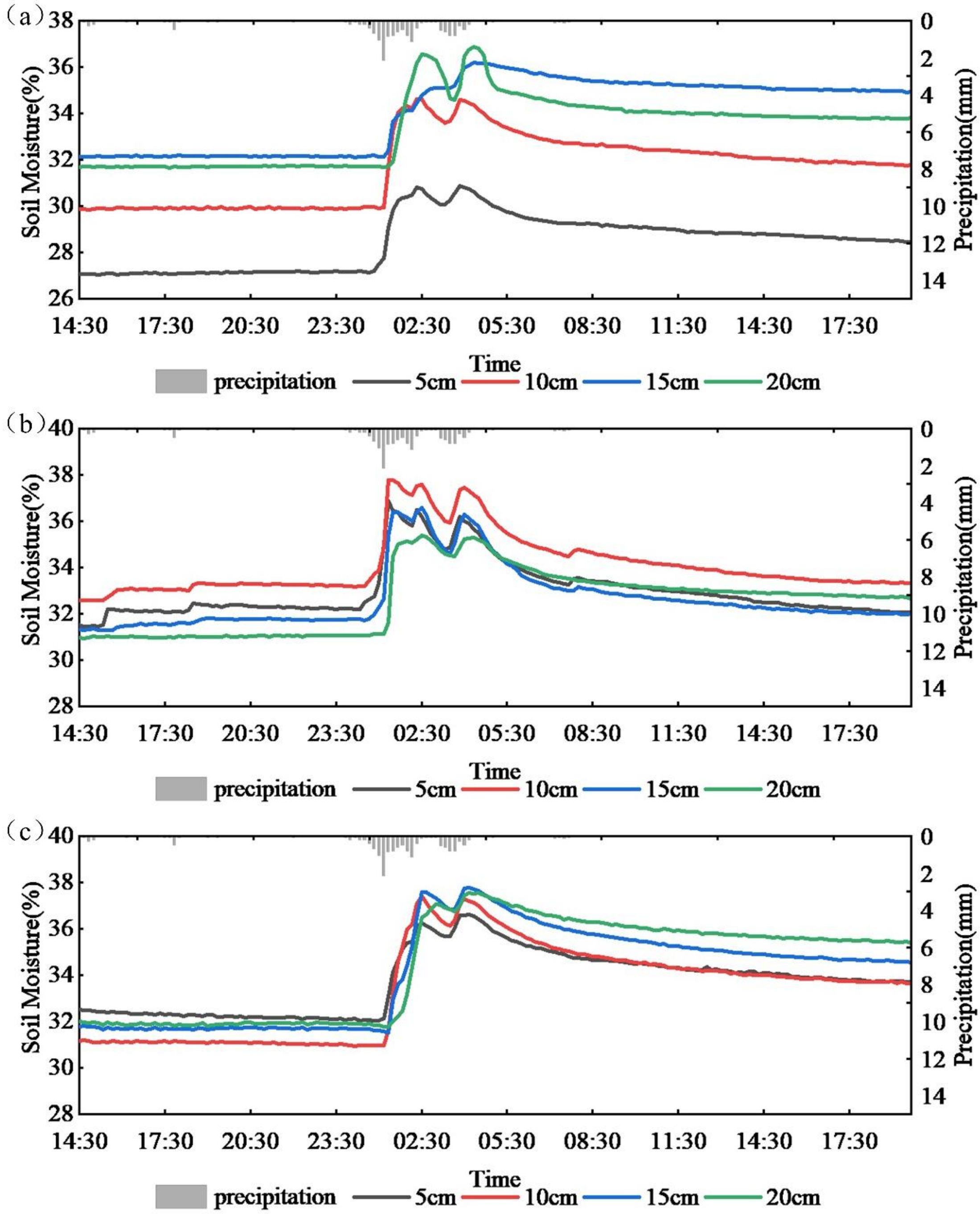


Figure 5. Responses of soil moisture under the different vegetation types to rainfall: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

3.5 Responses of Soil Moisture under Different Vegetation Types to a Moderate Rainfall Event

The analyzed moderate rainfall event lasted 31.67 h and had a total rainfall of 16.33 mm (Figure 6). The surface soil moisture content under the different vegetation types responded strongly to the moderate rainfall event (Figure 6). The order of the peak values of the surface soil moisture content under the different vegetation types was grassland > shrub > forest > arable land. The peak time of the surface soil moisture was 25.5 h in the grassland areas, with a lag of 2.5 h, 2.5 h, and 2.8 h in the forest, arable land, and shrub areas, respectively. The greatest increase in the soil moisture content was found in the shrub areas, and the smallest was found in the grassland areas. The greatest decline in the soil moisture content occurred in the grassland areas, and the smallest occurred in the arable land areas.



（a）
Soil Moisture(%)
Precipitation(mm)
Time
precipitation
5cm
10cm
15cm
20cm
14:30
17:30
20:30
23:30
02:30
05:30
08:30
11:30
14:30
17:30
（b）
（c）

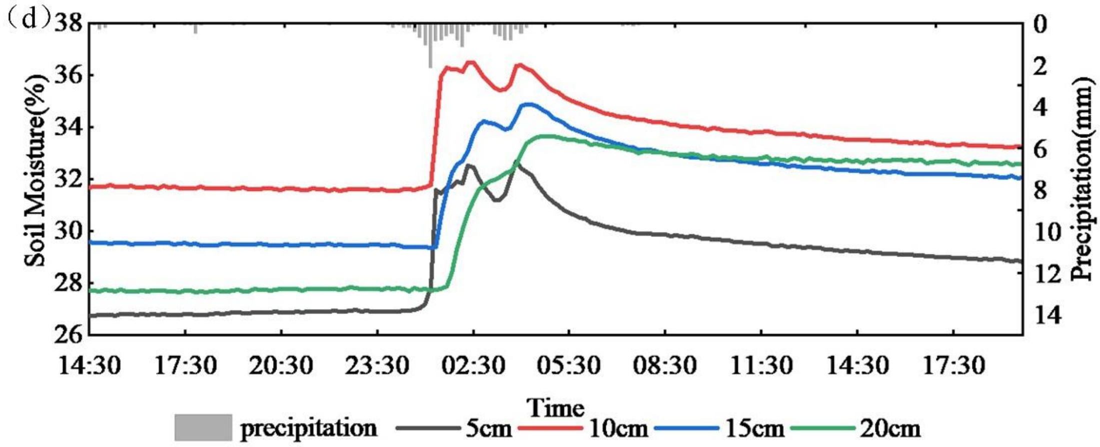
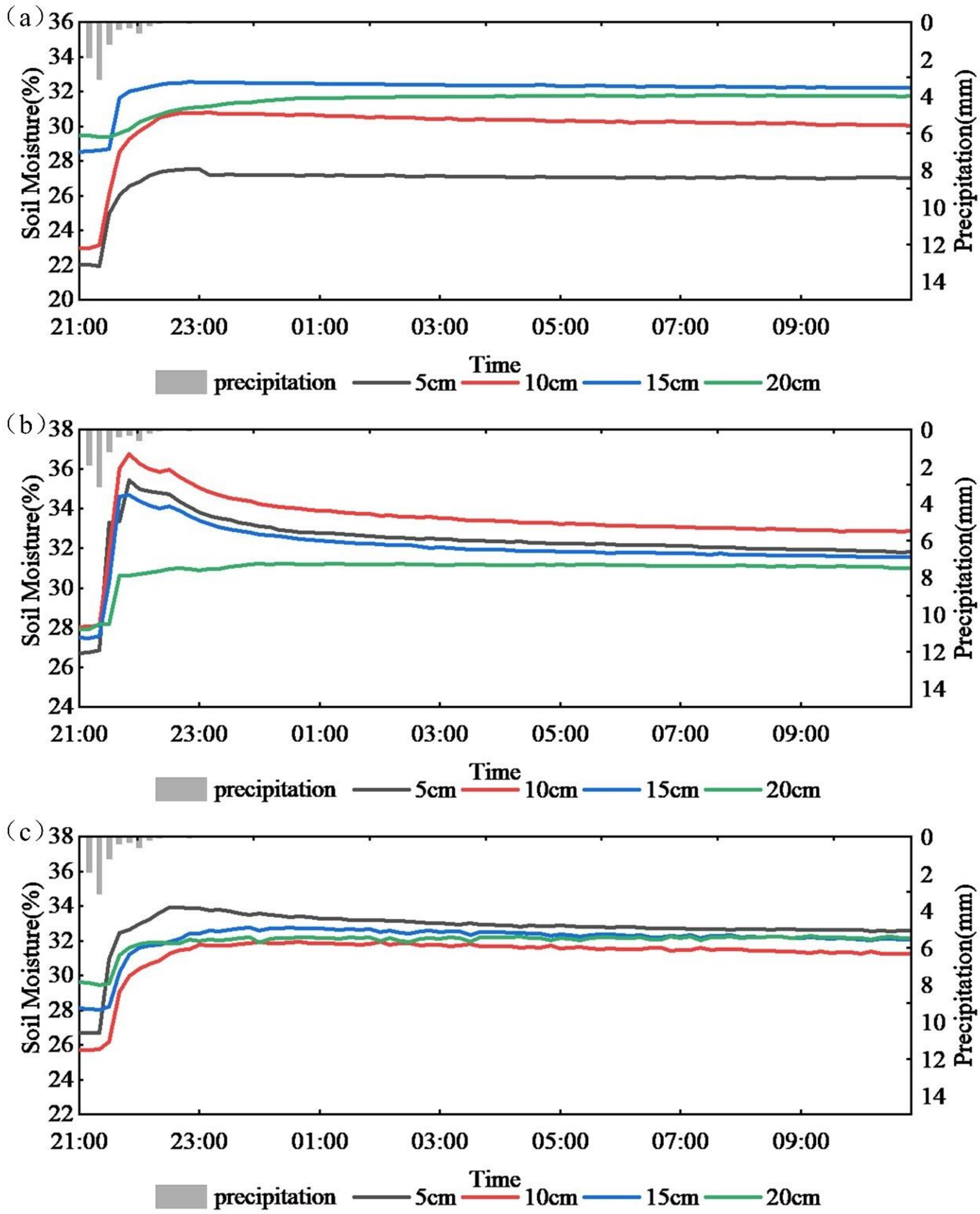


Figure 6. Responses of soil moisture under the different vegetation types to rainfall: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

3.6 Responses of Soil Moisture under Different Vegetation Types to a Winter Rainstorm Event

The rainstorm event lasted 1.83 h and had a total rainfall of 7.9 mm (Figure 7). During the entire rainfall event, the surface soil moisture content under the different vegetation types responded strongly to the rainfall. The order of the peak values of the surface soil moisture content under the different vegetation types was grassland > shrub > forest > arable land. The peak time for the surface soil moisture content was 0.67 h in the forest areas and lagged by 0.16 h, 1 h, and 1.16 h in the grassland, shrub, and arable land areas, respectively. The greatest increase in the soil moisture content was in the grassland areas, and the smallest was in the arable land areas. The greatest decline in the soil moisture content was in the grassland areas, and the smallest was in the arable land areas.



(a)
Soil Moisture(%)
Precipitation(mm)
36
34
32
30
28
26
24
22
20
0
2
4
6
8
10
12
14
21:00
23:00
01:00
03:00
05:00
07:00
09:00
Time
precipitation
5cm
10cm
15cm
20cm
(b)
Soil Moisture(%)
Precipitation(mm)
38
36
34
32
30
28
26
24
0
2
4
6
8
10
12
14
21:00
23:00
01:00
03:00
05:00
07:00
09:00
Time
precipitation
5cm
10cm
15cm
20cm
(c)
Soil Moisture(%)
Precipitation(mm)
38
36
34
32
30
28
26
24
22
0
2
4
6
8
10
12
14
21:00
23:00
01:00
03:00
05:00
07:00
09:00
Time
precipitation
5cm
10cm
15cm
20cm

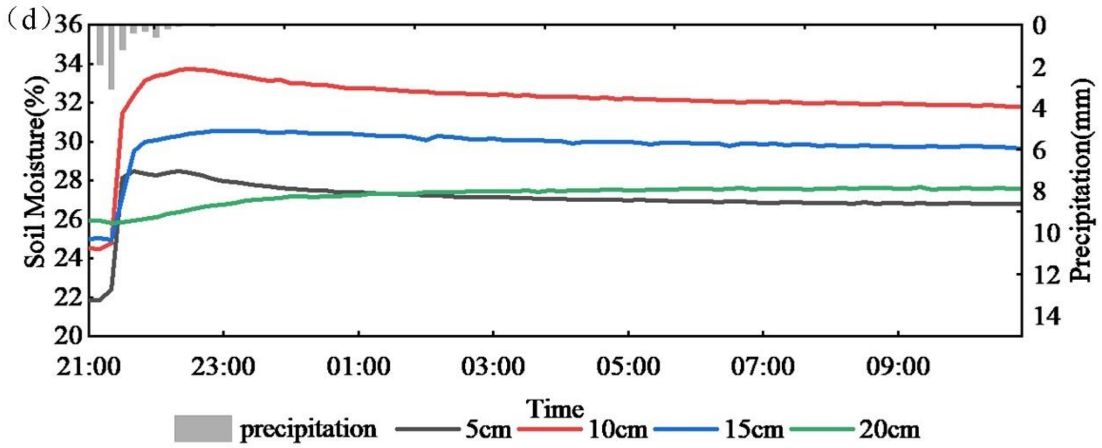


Figure 7. Responses of soil moisture of different vegetation types to rainfall: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

4. Discussion

4.1 Responses of the soil moisture under different vegetation types to different winter rainfall events

Vegetation redistributes rainfall, some of which is intercepted directly by vegetation and some of which reaches the soil via stem flow or penetrating rain (Llorens and Domingo 2007; Zhang et al. 2015). Guo et al. (2016), who studied the process of soil moisture responses to rainfall on karst slopes in autumn, showed that 6 mm of rainfall is the threshold for a soil moisture response, which is different from the results of our study. In our study, the soil moisture in the different soil layers (0–20 cm) of the grassland areas responded to a winter rainfall event with a total rainfall of only 0.87 mm likely because grassland areas have a smaller ability to trap rainfall, allowing the smaller total rainfall to pass through the grassland vegetation and reach the soil. In the studied humid karst region, the soil moisture in the 0–20-cm soil layers under the different vegetation types responded to light (20.75 mm total rainfall), moderate (16.33 mm total rainfall), and rainstorm (7.9 mm total rainfall) winter rainfall events.

Rainfall intensity is an important influence on soil moisture variability (Zhang et al. 2016). Han et al. (2016) studied changes in the soil moisture under artificial rainfall conditions in karst regions and found that the magnitude of the soil moisture changes increased with increasing rainfall intensity. In our study, the magnitude of the increase in the soil moisture under the different vegetation types during moderate and rainstorm events also increased with increasing rainfall intensity (Figure 8a), which is similar to the results of previous studies. We found that the variation in the soil moisture content of the arable land, grassland, and shrub areas was the largest for a light rainfall event (with a total rainfall amount of 20.75 mm). The variation range of the soil moisture content in the forest areas increased with increasing rain intensity. In the light rainfall event, the soil moisture content of the arable land, grassland, and shrub areas experienced the largest changes, mainly because the total amount of rainfall during the light rainfall event was relatively large and the rainfall had a continuous impact on the soil water. Soil water in different vegetation types affects the soil response to rainfall. The response to the light rainfall event with a large total rainfall amount was strong. Forest areas have large vegetative covers and a surface cover of dead debris, which intercepts rainfall. Therefore, rainfall of shorter duration and greater intensity is more likely to enter forested soil.

In the light and rainstorm events, the variation range of the soil moisture content of the soil profile under the different vegetation types showed a decreasing trend as the depth increased (Figures 8b–8d). This is similar to the results of previous studies (Liu et al. 2013) in the spring and summer in karst regions. This shows that the response of the soil moisture content in the soil profile to different rainfall events in winter is similar to those in spring and summer and that th e response degree decreases with increasing soil depth. The variation in the soil moisture content at depths of 15 cm and 20 cm was greater than that at depths of 5 cm and 10 cm under the different vegetation types during the moderate rainfall event. This indicates that the moderate rainfall event had a greater effect on the soil moisture at deeper soil layers (15 cm and 20 cm).

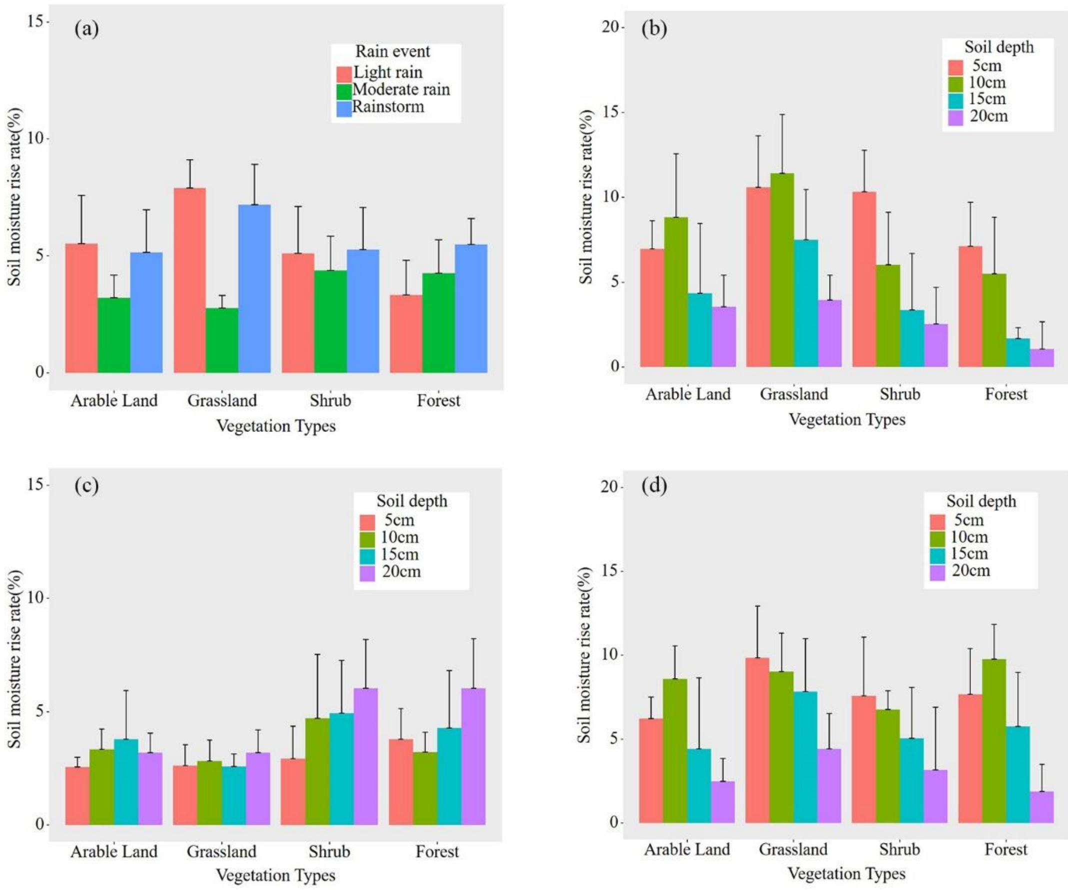


Figure 8. Statistical graphs of the increase in the soil moisture under the different vegetation types (a) during three different rainfall events; (b) at different depths during a light rainfall event; (c) at different depths during a moderate rainfall event; and (d) at different depths during a rainstorm event.

4.2 Winter Soil Moisture Characteristics under the Different Vegetation Types

Soil moisture varies with the season, and vegetation communities have different soil moisture content in different seasons (Gao et al. 2018). Considering the changes in the mean soil moisture content under the four different vegetation types (Figure 2), we see that the shrub areas maintained a high mean soil moisture content while the forest areas had the lowest average soil moisture content. This is consistent with previous studies (Chen et al. 2006) in summer in karst regions. The shrub areas maintained a high soil moisture content during the entire study period, which may be due to the large vegetative coverage of the shrubs and the poor light transmittance, which can effectively prevent soil water from evaporating. Therefore, the mean shrub soil moisture content was relatively high. Soil moisture is a limiting factor for vegetation growth. In winter, among the different vegetation types, the mean soil moisture content of the shrub areas was higher, which is beneficial to the growth of shrub communities. The mean soil moisture content in the forest areas was low, and this low mean soil moisture content may limit the growth of forest communities.

There are significant differences in the soil moisture profiles under the different vegetation types, and the change in the soil moisture generally increases with increasing soil depth (Figure 3). This is consistent with the results of previous studies (Liu et al. 2005) in summer. The influence of external factors on the soil moisture weakens with increasing soil depth (Guber et al. 2008; Zhao et al. 2020). Surface soil moisture is most affected by external factors, and the soil moisture content is the smallest in the surface soil layer. External factors have less of an influence on the soil moisture in deeper soil layers. The deep soil layer maintains a high soil moisture co ntent, which reflects the weak water holding capacity of the shallow and thin soil layers in karst regions.

4.3 Characteristics of Soil Moisture Replenishment under Different Vegetation Types in Winter

Different vegetation types tend to exhibit different recharge characteristics during the recharge of soil moisture by rainfall (Yang et al. 2018). Zhang et al. (2013) analyzed the dynamic pattern of the soil moisture content in the depression profile of a karst region over a year and found that moderately intense, prolonged, and heavy rainfall is conducive to the compensation and recovery of soil moisture. In our study, three rainfall events (light, moderate, and rainstorm events with large total rainfall amounts and long durations) were analyzed to investigate the soil moisture recharge characteristics of the rainfall for the different vegetation types. The results showed that the soil moisture recharge was greatest in the grassland areas (12.63 mm) and smallest in the forest areas (9.40 mm) (Figure 9). Different vegetation types have different interception techniques. The smallest amount of soil moisture was recharged to the forest areas, likely because the rainfall was intercepted in part by the canopy as well as by the layer of dead branches and leaves that covers the forest floor. As a result, the amount of rainfall recharging the forest floor is low. Grasslands have less vegetative cover and intercept less rain. As a result, more rain replenishes the soil in grassland areas.

In karst regions, the canopy retention is greater than the shrub retention (Zhou et al. 2016). During rainfall events, forest areas intercept more rainfall and replenish the soil moisture less, which explains why the soil moisture replenishment in the shrub areas in this study was greater than that in the forest areas. Among the different vegetation types, grasslands had the smallest abil ity to retain rainfall and were more likely to have their soil moisture recharged, while forests had the greatest ability to retain rainfall and had the least recharged soil moisture.

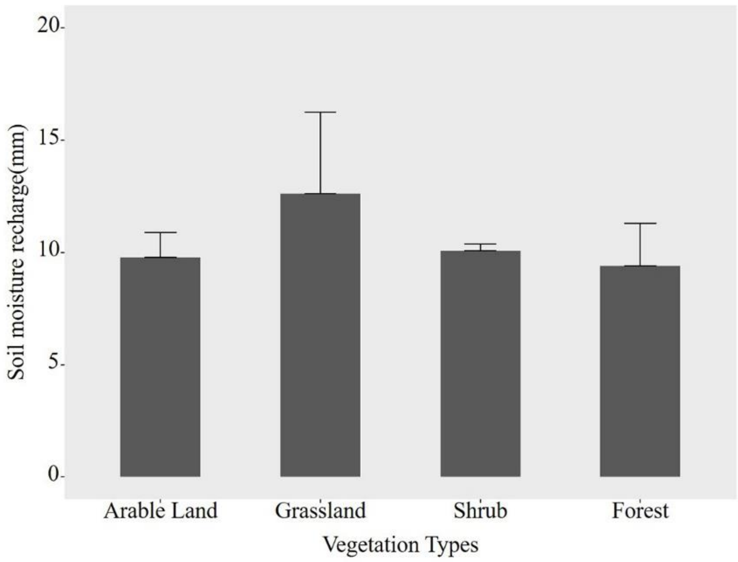


Figure 9. Soil moisture replenishment under the different vegetation types.

4.4 Characteristics of the Soil Moisture Decline under the Different Vegetation Types after Winter Rain

Yang et al. (2007) studied soil moisture changes after rainfall in summer karst regions, and their results showed that the decline in the soil moisture in shrub areas was greater than that in grassland areas. In our study, the decline in soil moisture was greater in the grassland areas (2.08%) than in the shrub areas (1.03%), which differed from these previous findings (Figure 10). This may be because the study of Yang et al. (2007) was primarily conducted in summer. There are many types of vegetation in shrub communities, and the amount of plant transpiration is greater in shrub areas than in grassland areas. In karst regions, there is little rain or wind in winter and soil moisture evaporates continuously under dry conditions. Plant transpiration in winter is weak; therefore, the soil moisture is primarily consumed by soil evaporation. In our study, the gras sland soil moisture decreased the most. This may be because the vegetative coverage of the grassland areas was low, the exposed soil area was large, and the soil moisture of the grassland areas continued to evaporate under the dry winter conditions. The vegetative coverages of the forest (0.88%) and shrub (1.03%) areas were larger, and their surfaces were covered by a layer of litter, which was less disturbed by the outside world. This also explains why grassland soil moisture decreases more than forest and shrub in winter. In winter, the arable land (0.76%) is in a state of fallow, and its water consumption is the least, which can better maintain soil moisture in winter.

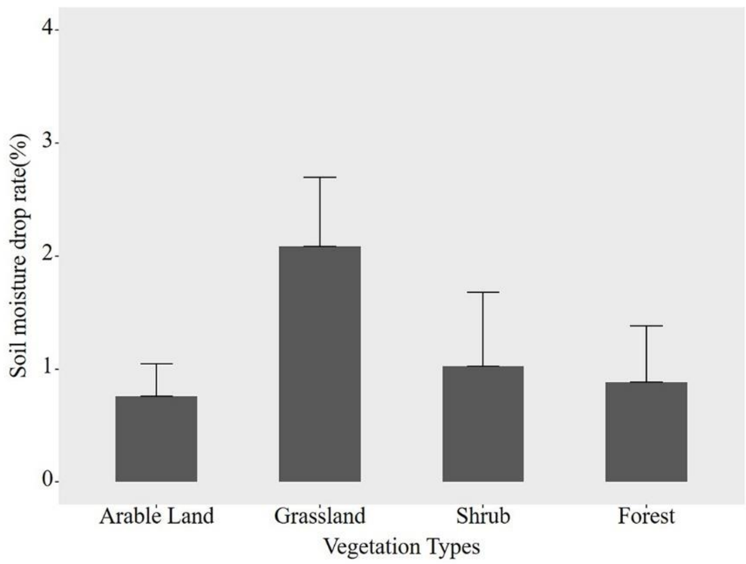


Figure 10 Statistical graph of the decline in soil moisture of different vegetation types

5. Conclusions

In our study, the response of soil moisture under different vegetation types to different rainfall events in winter in humid karst areas was observed at ten-minute intervals. Among different vegetation types, only the soil moisture in different soil layers of grassland can respond to light rain events (the total rainfall is 0.87mm). The soil moisture under different vegetation types responds to light rain events, moderate rain events and rainstorm events with a large total rainfall. In the event of moderate rain and rainstorm rain, the variation range of soil moisture in the soil profile under different vegetation types increases with the increase of rainfall intensity. There are significant differences in soil moisture in the soil profile of different vegetation types, and the changes in soil moisture generally show a trend of increasing with the increase of soil depth. Shrub maintain a high mean soil moisture content, while forests have the lowest mean soil moisture content. The replenishment and decline of soil moisture in grassland are both the largest, and the results of forest land research are opposite to grassland.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

References

Bonacci O, Pipan T, Culver DC (2009) A framework for karst ecohydrology Environmental Geology 56:891-900 doi:https://10.1007/s00254-008-1189-0

Brantley SL et al. (2017) Reviews and syntheses: on the roles trees play in building and plumbing the critical zone Biogeosciences 14 doi:https://10.5194/bg-14-5115-2017

Canton Y et al. (2016) Vertical and lateral soil moisture patterns on a Mediterranean karst hillslope Journal of Hydrology 64:209-217 doi:https://10.1515/johh-2016-0030

Chen H-S, Fu W, Wang K-L, Zhang J-G, Zhang W (2006) Dynamic Change of Soil Water in Peak-Cluster Depression Areas of Karst Mountainous Region in Northwest Guangxi Journal of Soil and Water Conservation 20:136-139 doi:https://10.13870/j.cnki.stbcxb.2006.0

4.033 (In Chinese)

Chen L, Huang Z, Gong J, Fu B, Huang Y (2007) The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China Catena 70:200-208 doi:https://10.1016/j.catena.2006.08.007

Chen Q, Xiong K, Zhou M, Xu F (2018) Characteristics of soil and water loss in different rocky desertification areas in Guanling county Research of Soil and Water Conservation 25 doi:https://10.13869/j.cnki.rswc.2018.05.003 (In Chinese)

Dai Q, Peng X, Yang Z, Zhao L (2017) Runoff and erosion processes on bare slopes in the Karst Rocky Desertification Area CATENA 152:218-226 doi:https://doi.org/10.1016/j.catena.2017.01.013

Daly E, Porporato A (2005) A review of soil moisture dynamics: from rainfall infiltration to ecosystem response Environmental engineering science 22:9-24 doi:https://10.1089/ees.2005.22.9

Ding Y, Nie Y, Chen H, Wang K, Querejeta JI (2020) Water uptake depth is coordinated with leaf water potential, water-use efficiency and drought vulnerability in karst vegetation New Phytologist doi:https://doi.org/10.1111/nph.16971

Fu T, Chen H, Fu Z, Wang K (2016a) Surface soil water content and its controlling factors in a small karst catchment Environmental Earth Sciences 75:1406 doi:https://10.1007/s12665-016-6222-0

Fu T, Chen H, Wang K (2016b) Structure and water storage capacity of a small karst aquifer based on stream discharge in southwest China Journal of Hydrology 534:50-62 doi:https://doi.org/10.1016/j.jhydrol.2015.12.042

Gao Y, Liu H, Wu H, Alamus (2018) Seasonal changes in soil water repellency of different land use types in Inner Mongolia grassland Soil and Tillage Research 177:37-44 doi:https://doi.org/10.1016/j.still.2017.11.011

Gehrels J, Peeters J, De Vries J, Dekkers M (1998) The mechanism of soil water movement as inferred from 18O stable isotope studies Hydrological sciences journal 43:579-594 doi:https://10.1080/02626669809492154

Guber A, Gish T, Pachepsky Y, van Genuchten MT, Daughtry C, Nicholson T, Cady R (2008) Temporal stability in soil water content patterns across agricultural fields Catena 73:125-133 doi:https://10.1016/j.catena.2007.09.010

Guo X, Gong X, Tang Q, Chen C, Jiang G, Li X, Zou Y (2016) The response processes of moisture at soil profile to precipitation in typical karst hillslopes Carsologica Sinica 35:629-638 doi:https://10.11932/karst20160604 (In Chinese)

Han W-J, Pan Y-J, Du B (2016) Effects of different rainfall intensity on limestone soil water transport of huaxi area in Guiyang city Modern Agricultural Science and Technology 6:189-191+202 (In Chinese)

Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Karst water resources in a changing world: Review of hydrological modeling approaches Reviews of Geophysics 52:218-242 doi:https://10.1002/2013RG000443

Jing J, Liu Z, Li Y, Wang J, Luo D, Cai L (2020) Vegetation Types Affect Responsive Change in Soil Moisture to Rainfall in under Karst Rocky Desertification Control Areas Journal of Irrigation and Drainage 39:100-109 doi:https://10.13522/j.cnki.ggps.2019137

Laio F, Porporato A, Ridolfi L, Rodriguez-Iturbe I (2001) Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics Advances in water resources 24:707-723 doi:https://10.1016/s0309-1708(01)00005-7

Li X-Y, Zhang S-Y, Peng H-Y, Hu X, Ma Y-J (2013) Soil water and temperature dynamics in shrub-encroached grasslands and climatic implications: Results from Inner Mongolia steppe ecosystem of north China Agricultural and Forest Meteorology 171-172:20-30 doi:https://doi.org/10.1016/j.agrformet.2012.11.001

Li X, Li Y, Chen A, Gao M, Slette IJ, Piao S (2019) The impact of the 2009/2010 drought on vegetation growth and terrestrial carbon balance in Southwest China Agricultural and Forest Meteorology 269:239-248 doi:https://10.1016/j.agrformet.2019.01.036

Li Z, Xu X, Zhang Y, Wang K (2020) Fingerprinting sediment sources in a typical karst catchment of southwest China International Soil and Water Conservation Research 8:277-285 doi:https://doi.org/10.1016/j.iswcr.2020.06.005

Liu B, Mu B, Gu X-P (2013) Vertical variability of soil moisture under different precipitation conditions in Guizhou karst areas Guangdong Agricultural Sciences 40:46-49 doi:https://10.16768/j.issn.1004-874x.2013.02.031 (In Chinese)

Liu H, Jiang T, Liu H, Xiao H, Xia J (2005) Impact of land use on spatio-temporal variation of soil moisture of sloping upland in karst mountainous area Acta Pedologica Sinica 42 (In Chinese)

Llorens P, Domingo F (2007) Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe Journal of hydrology 335:37-54 doi:https://10.1016/j.jhydrol.2006.10.032

Lozano-Parra J, Schnabel S, Ceballos-Barbancho A (2015) The role of vegetation covers on soil wetting processes at rainfall event scale in scattered tree woodland of Mediterranean climate Journal of Hydrology 529:951-961 doi:https://doi.org/10.1016/j.jhydrol.2015.09.018

Mei X-m, Ma L, Zhu Q-k, Wang S, Zhang D, Wang Y (2018) Responses of soil moisture to vegetation restoration type and slope length on the loess hillslope Journal of Mountain Science 15:548-562 doi:https://10.1007/s11629-017-4415-y

Rivera D, Lillo M, Granda S, assessment (2014) Representative locations from time series of soil water content using time stability and wavelet analysis Environmental Monitoring 186:9075-9087 doi:https://10.1007/s10661-014-4067-0

Sohrt J, Ries F, Sauter M, Lange J (2014) Significance of preferential flow at the rock soil interface in a semi-arid karst environment CATENA 123:1-10 doi:https://doi.org/10.1016/j.catena.2014.07.003

Su B, Shangguan Z (2019) Decline in soil moisture due to vegetation restoration on the Loess Plateau of China Land Degradation Development 30:290-299 doi:https://10.1002/ldr.3223

Sun F, Lü Y, Wang J, Hu J, Fu B (2015) Soil moisture dynamics of typical ecosystems in response to precipitation: A monitoring-based analysis of hydrological service in the Qilian Mountains CATENA 129:63-75 doi:https://doi.org/10.1016/j.catena.2015.03.001

Tang M, Zhao X, Gao X, Zhang C, Wu P (2019) Land Use Affects Soil Moisture Response to Dramatic Short-term Rainfall Events in a Hillslope Catchment of the Chinese Loess Plateau Agronomy Journal 111:1506-1515 doi:https://10.2134/agronj2018.06.0405

Wang S, Fu B, Gao G, Liu Y, Zhou J (2013) Responses of soil moisture in different land cover types to rainfall events in a re-vegetation catchment area of the Loess Plateau, China CATENA 101:122-128 doi:https://doi.org/10.1016/j.catena.2012.10.006

Wang X-P, Cui Y, Pan Y-X, Li X-R, Yu Z, Young MH (2008) Effects of rainfall characteristics on infiltration and redistribution patterns in revegetation-stabilized desert ecosystems Journal of Hydrology 358:134-143 doi:https://doi.org/10.1016/j.jhydrol.2008.06.002

Yang J, Chen H, Nie Y, Wang K (2019) Dynamic variations in profile soil water on karst hillslopes in Southwest China CATENA 172:655-663 doi:https://doi.org/10.1016/j.catena.2018.09.032

Yang L, Zhang HD, Chen LD (2018) Identification on threshold and efficiency of rainfall replenishment to soil water in semi-arid loess hilly areas Science China Earth Sciences 61:292–301 doi:https://10.1007/s11430-017-9140-0 (In Chinese)

Yang S-T, Wang Y-J, Wen Z-Q, Lu T (2007) Research on Soil Moisture in the Typical Shrub-grass Zone in Karst Regions Bulletin of Soil and Water Conservation 27 doi:https://10.13961/j.cnki.stbctb.2007.04.030 (In Chinese)

Yu X, Huang Y, Li E, Li X, Guo W (2018) Effects of rainfall and vegetation to soil water input and output processes in the Mu Us Sandy Land, northwest China CATENA 161:9

6-103 doi:https://doi.org/10.1016/j.catena.2017.10.023

Zhang C, Chen H-S, Nie Y-P, Zhang W, Feng T, Wang K-L (2013) Dynamics of soil profile water content in peak-cluster depression areas in karst region Chinese Journal of Eco-Agriculture 21:1225-1232 doi:https://10.3724/SP.J.1011.2013.01225 (In Chinese)

Zhang D-H, Li X-R, Zhang F, Zhang Z-S, Chen Y-L (2016) Effects of rainfall intensity and intermittency on woody vegetation cover and deep soil moisture in dryland ecosystems Journal of Hydrology 543:270-282 doi:https:// 10.1016/j.jhydrol.2016.10.003

Zhang L, Xiao J, Li J, Wang K, Lei L, Guo H (2012) The 2010 spring drought reduced primary productivity in southwestern China Environmental Research Letters 7:045706 doi: https://10.1088/1748-9326/7/4/045706

Zhang Y-f, Wang X-p, Hu R, Pan Y-x, Paradeloc M (2015) Rainfall partitioning into throughfall, stemflow and interception loss by two xerophytic shrubs within a rain-fed re-vegetated desert ecosystem, northwestern China Journal of Hydrology 527:1084-1095 doi:https://10.1016/j.jhydrol.2015.05.060

Zhao Z, Shen Y, Wang Q, Jiang R (2020) The temporal stability of soil moisture spatial pattern and its influencing factors in rocky environments Catena 187:104418 doi:https://10.1016/j.catena.2019.104418

Zhou Q, Yan H, Ma L, Cai M, Dai L (2016) Distribution characteristics of rainfall interception of coniferous forest in Karst area Ecological Science 35:140-145 doi:https://10.14108/j.cnki.1008-8873.2016.06.019 (In Chinese)

Zhu Q, Nie X, Zhou X, Liao K, Li H (2014) Soil moisture response to rainfall at different topographic positions along a mixed land-use hillslope CATENA 119:61-70 doi:https://doi.org/10.1016/j.catena.2014.03.010

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Contributions

W.Y. and Q.Z. conceived and wrote the manuscript; D.P. and X.W. polished the language of the manuscript; X.T., E.Y., Y.W. and C.S. was involved in the experimental assays.

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Ethics declarations

Competing Interest

The authors declare no conflict of interest.

Ethical approval

Not applicable.

Consent to Participate

Not applicable.

Consent to publish

Not applicable.

Figures

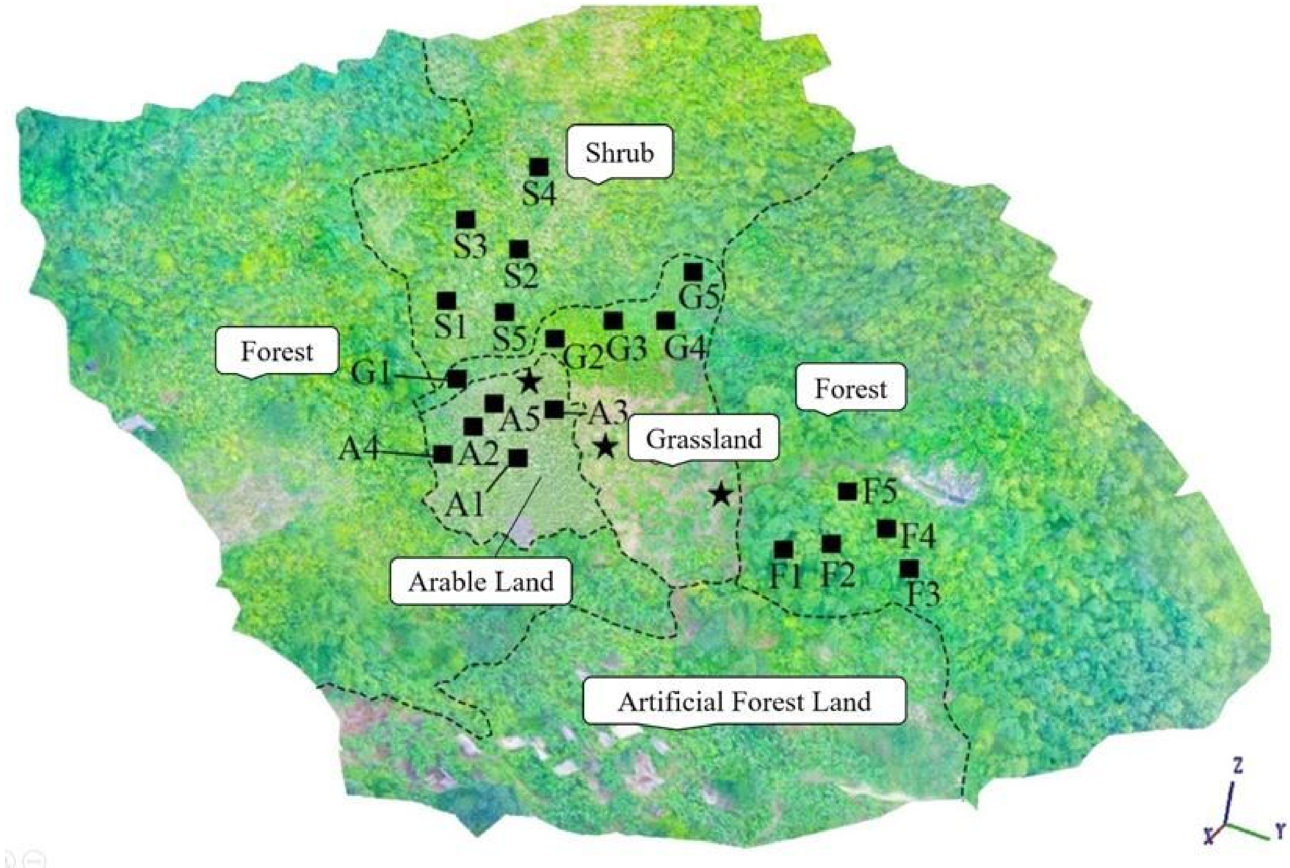

Figure 1

Distribution map of the sample plots. A1–A5 indicate arable land plots; G1–G5 indicate grassland plots; S1–S5 indicate shrub plots; and F1–F5 indicate forest plots. The s indicate rain gauges. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

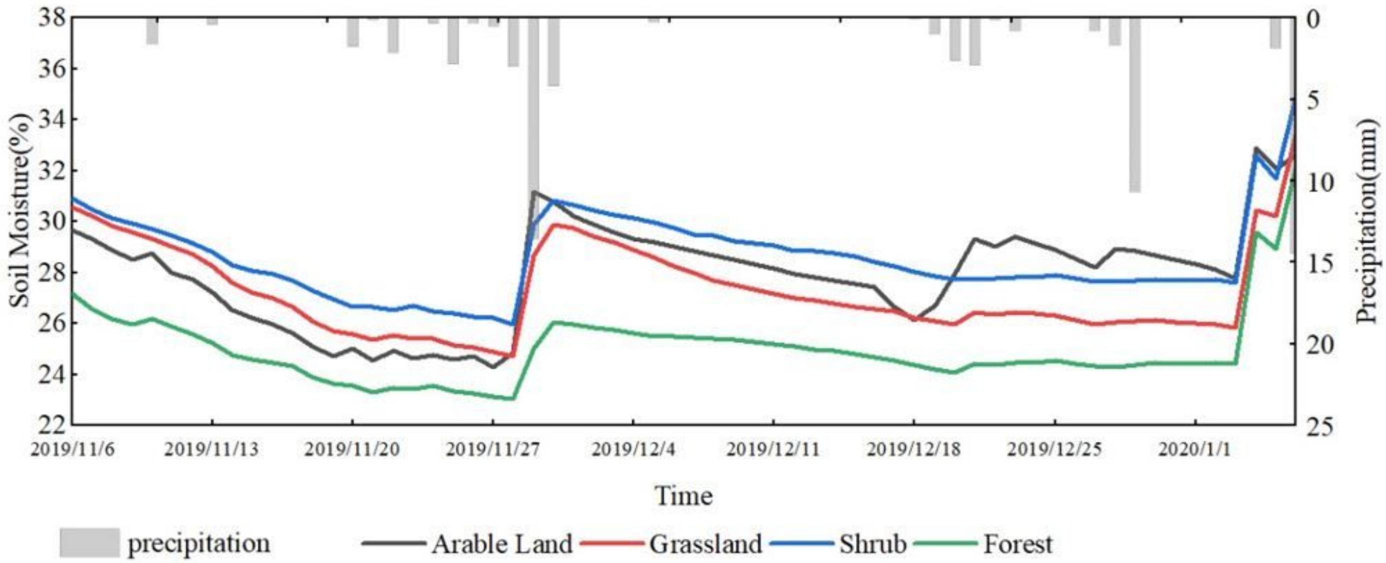

Figure 2

Dynamic changes in the mean soil moisture content and precipitation distribution for the different vegetation types.

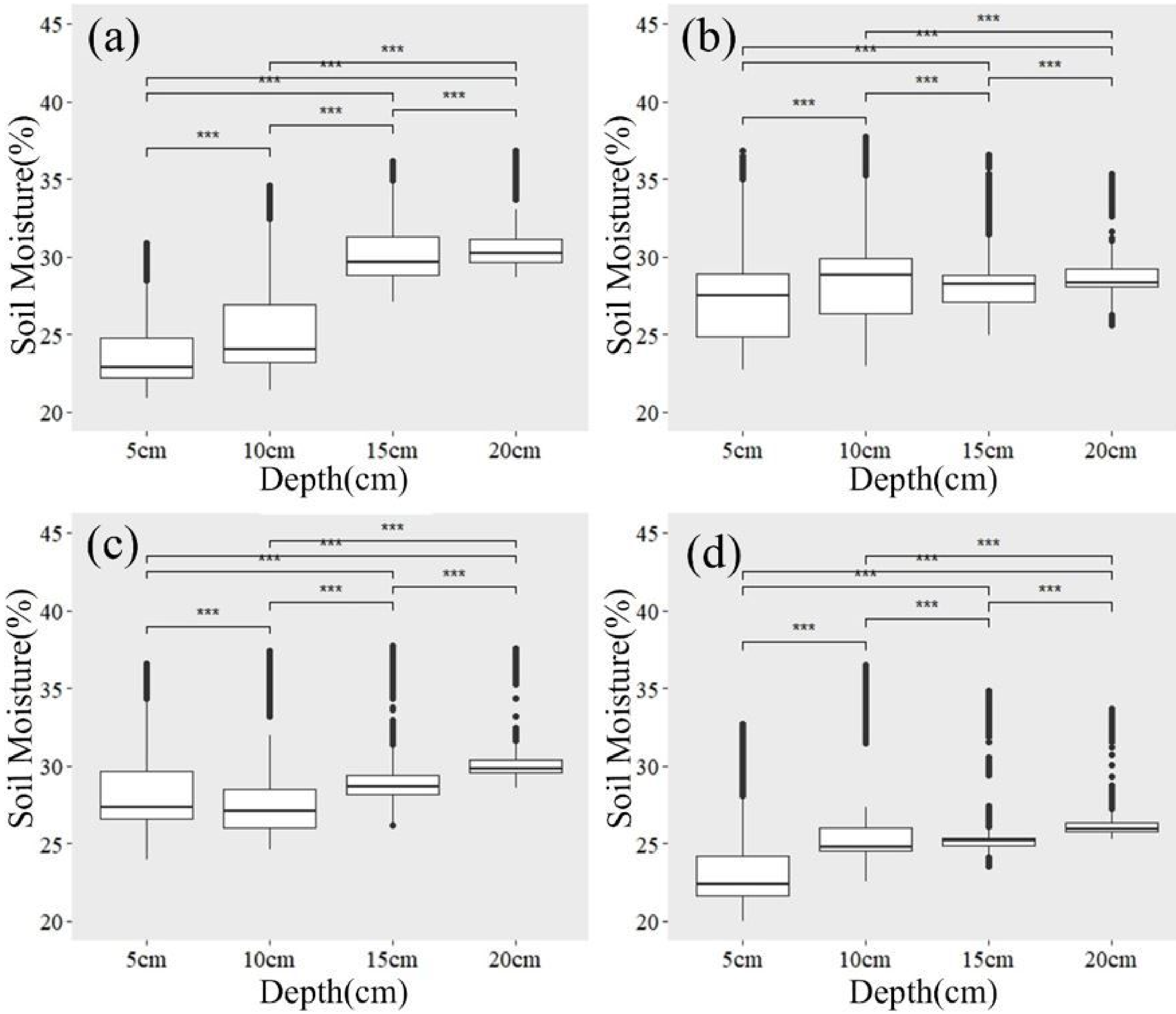

Figure 3

Characteristics of the soil moisture in the different soil layers under the different vegetation types: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

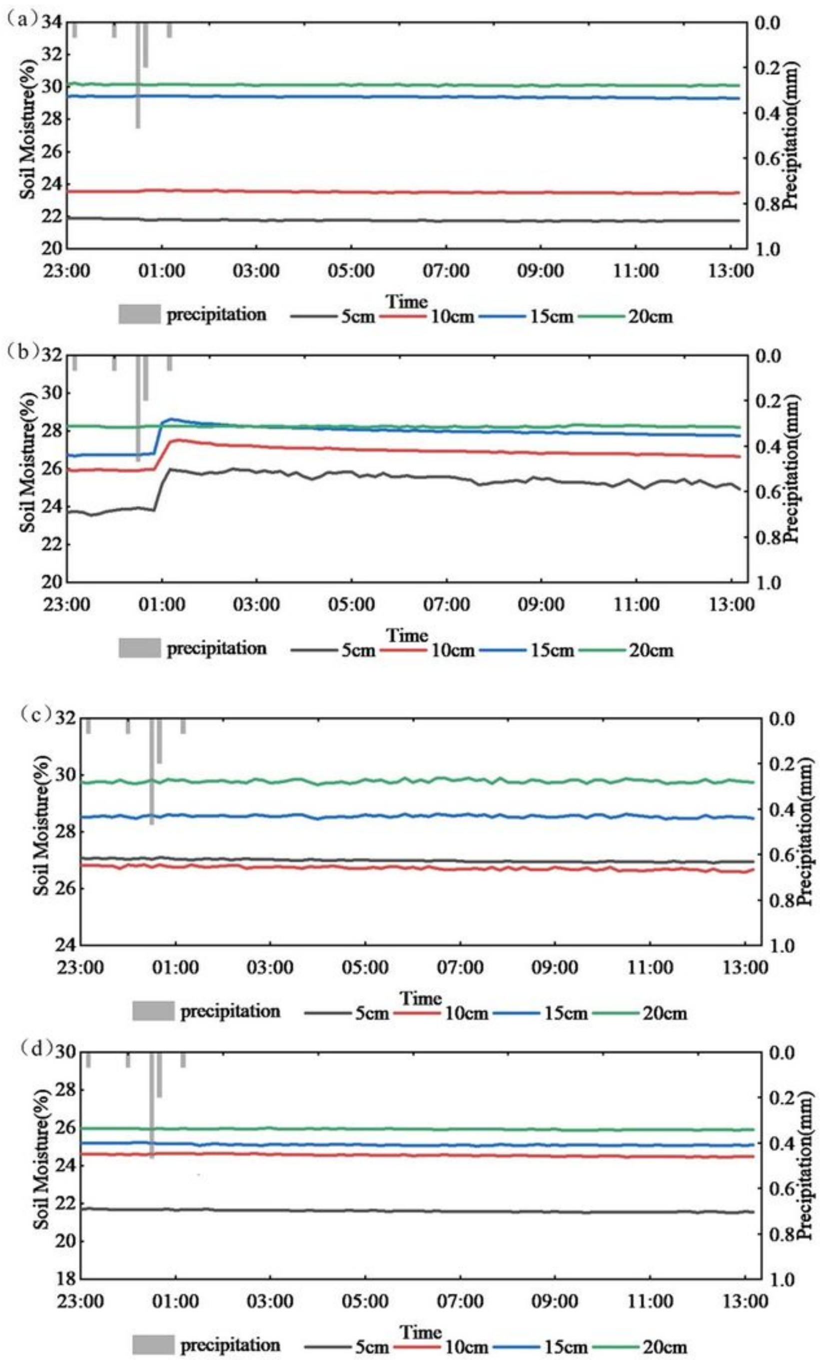

Figure 4

Responses of soil moisture under the different vegetation types to rainfall: (a) arable land; (b) grassland; (c)shrub; and (d) forest.

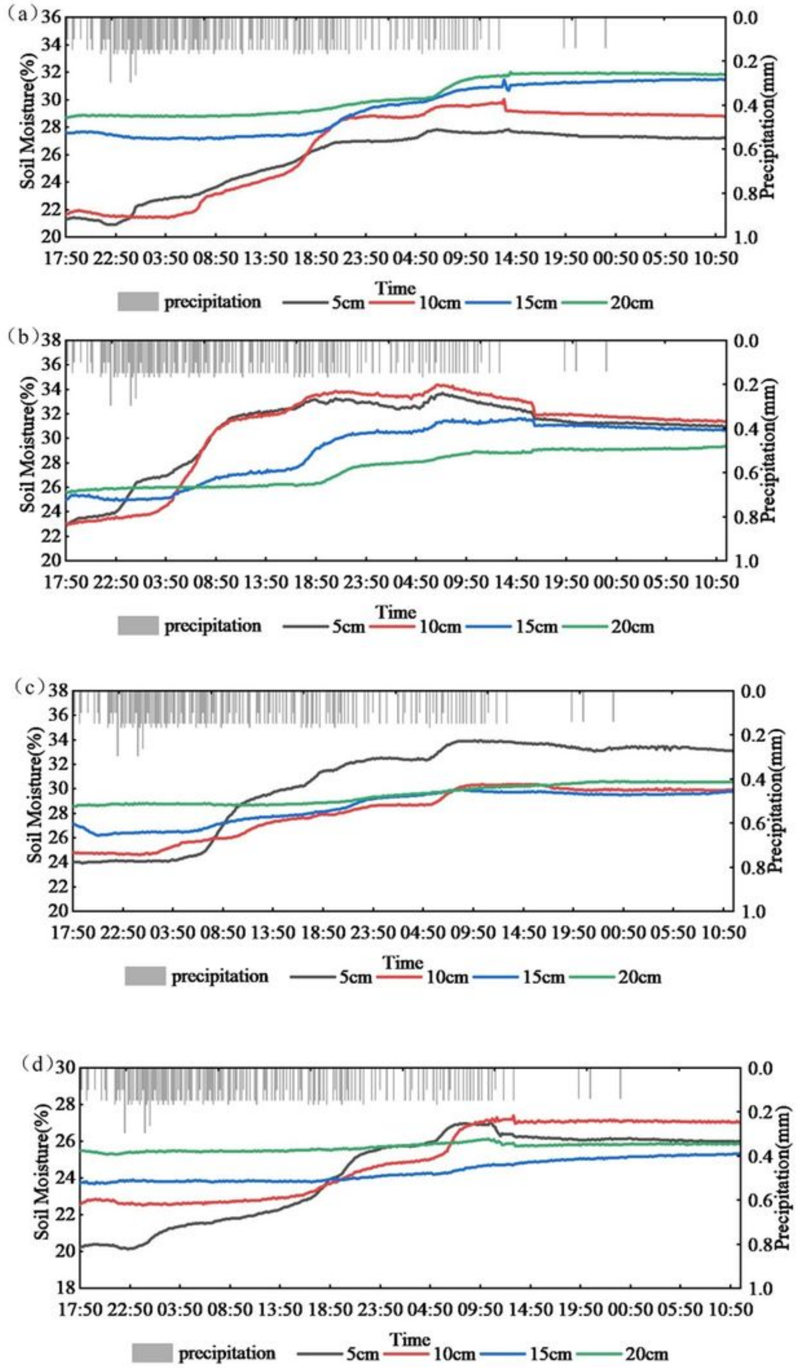

Figure 5

Responses of soil moisture under the different vegetation types to rainfall: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

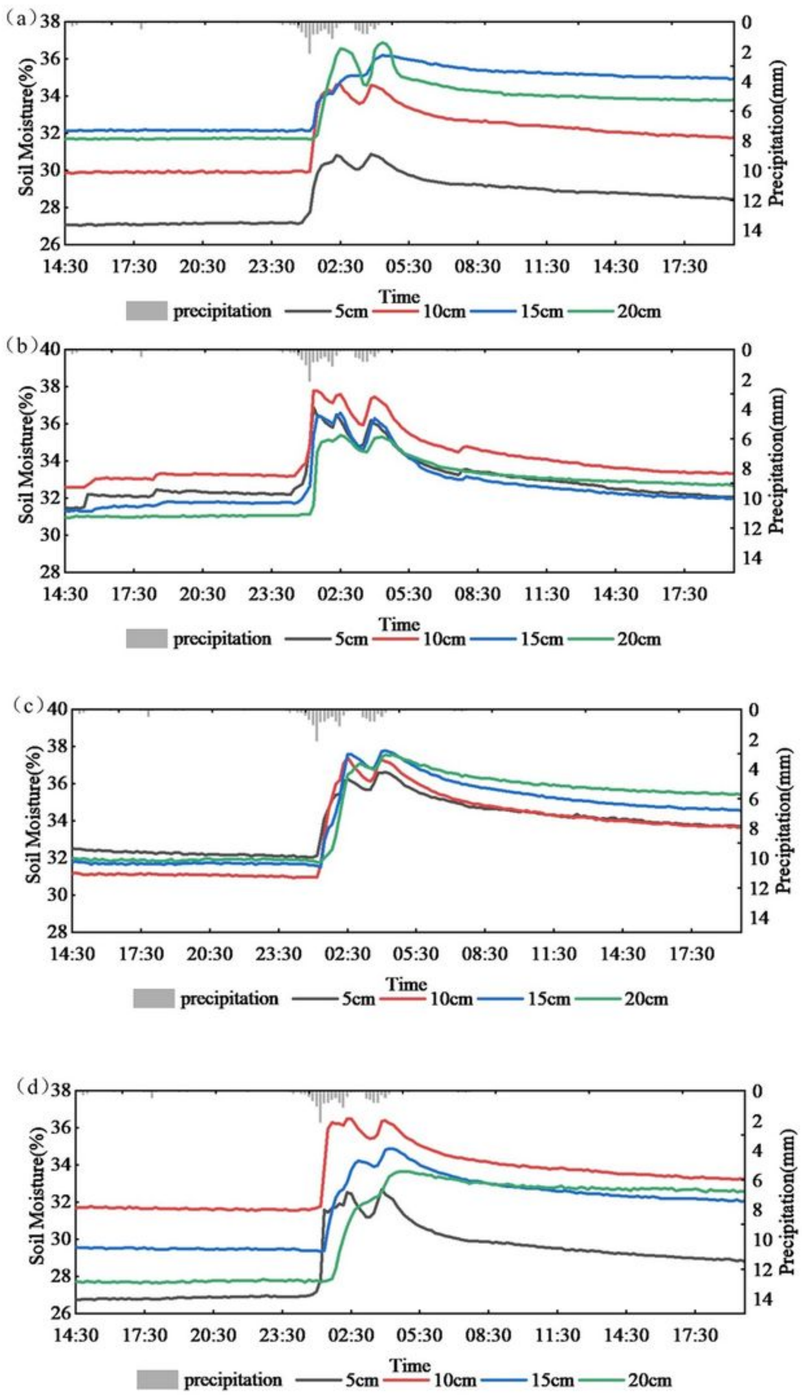

Figure 6

Responses of soil moisture under the different vegetation types to rainfall: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

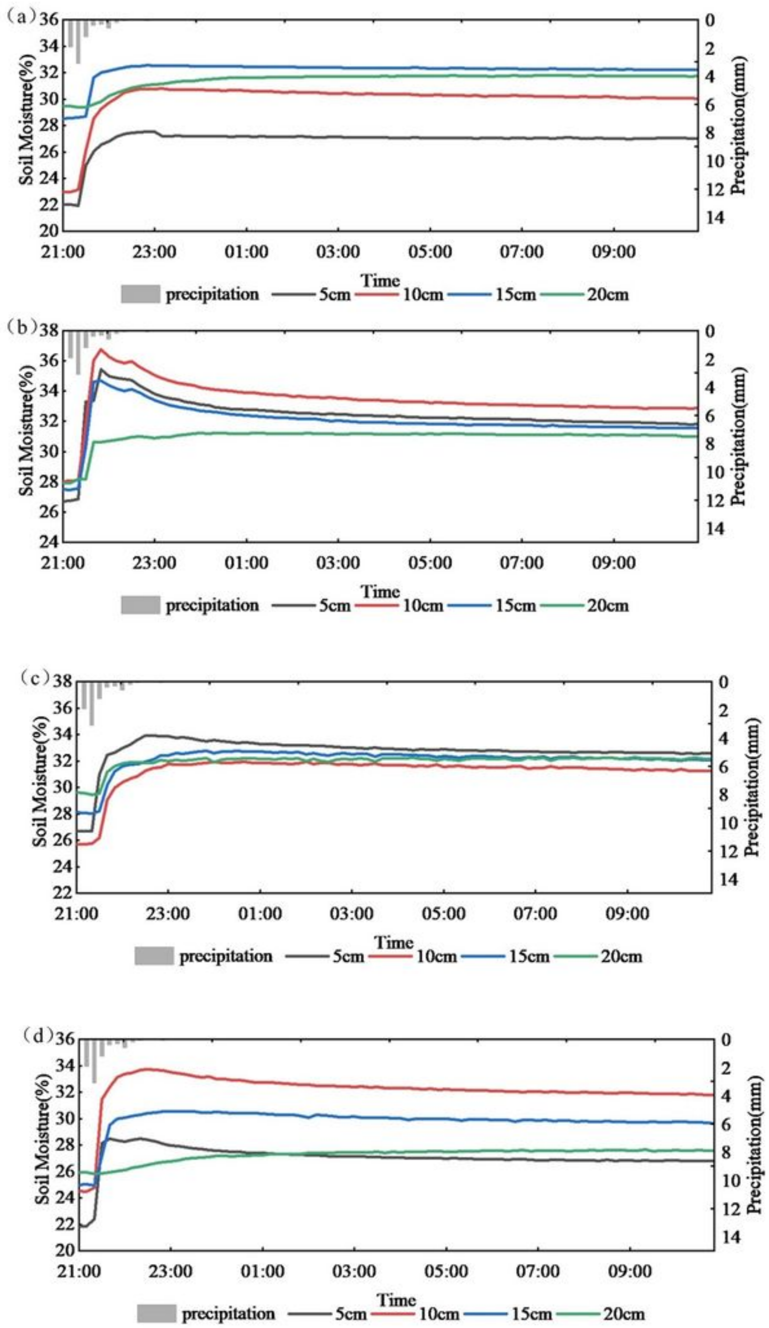

Figure 7

Responses of soil moisture of different vegetation types to rainfall: (a) arable land; (b) grassland; (c) shrub; and (d) forest.

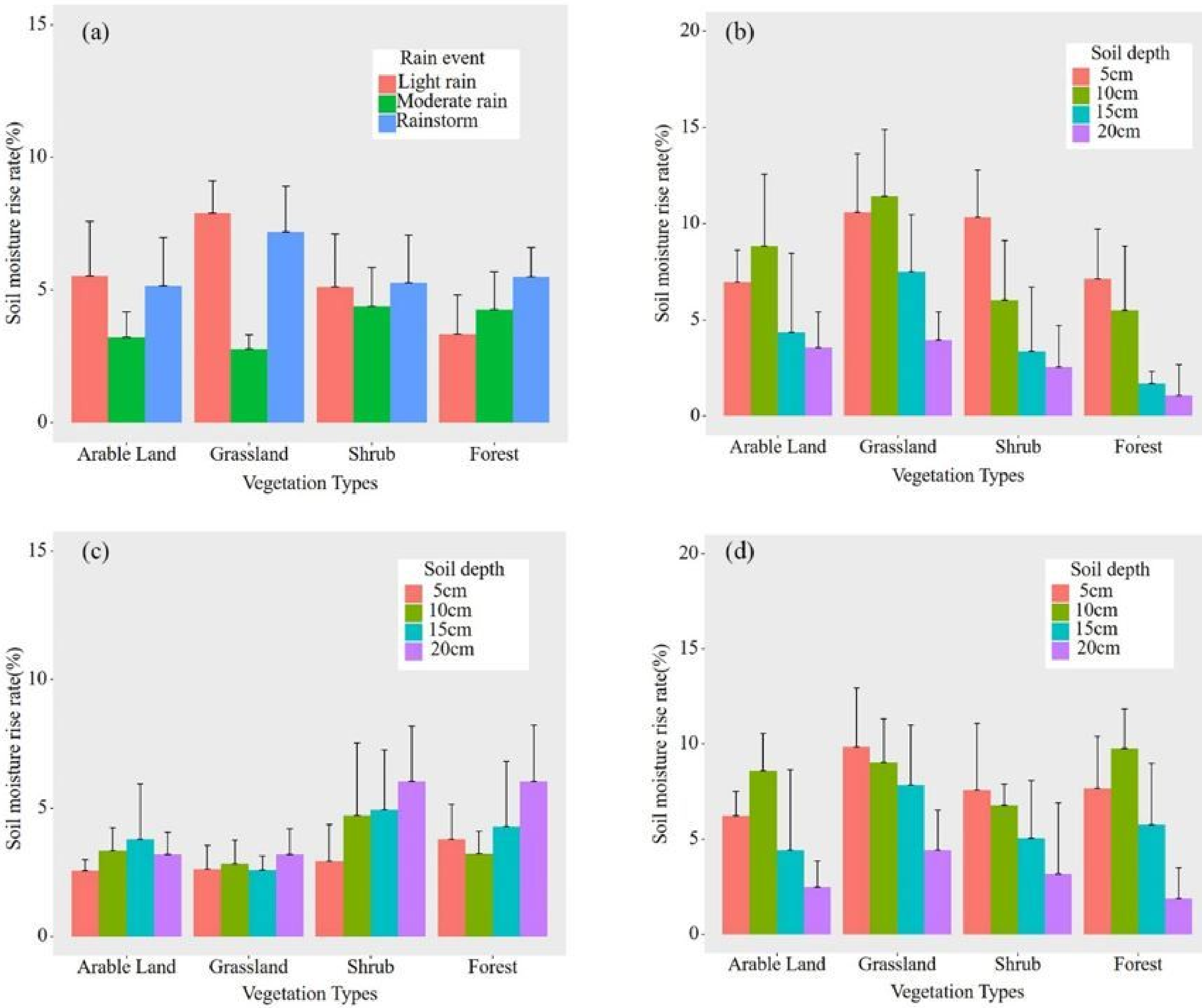

Figure 8

Statistical graphs of the increase in the soil moisture under the different vegetation types (a) during three different rainfall events; (b) at different depths during a light rainfall event; (c) at different depths during a moderate rainfall event; and (d) at different depths during a rainstorm event.

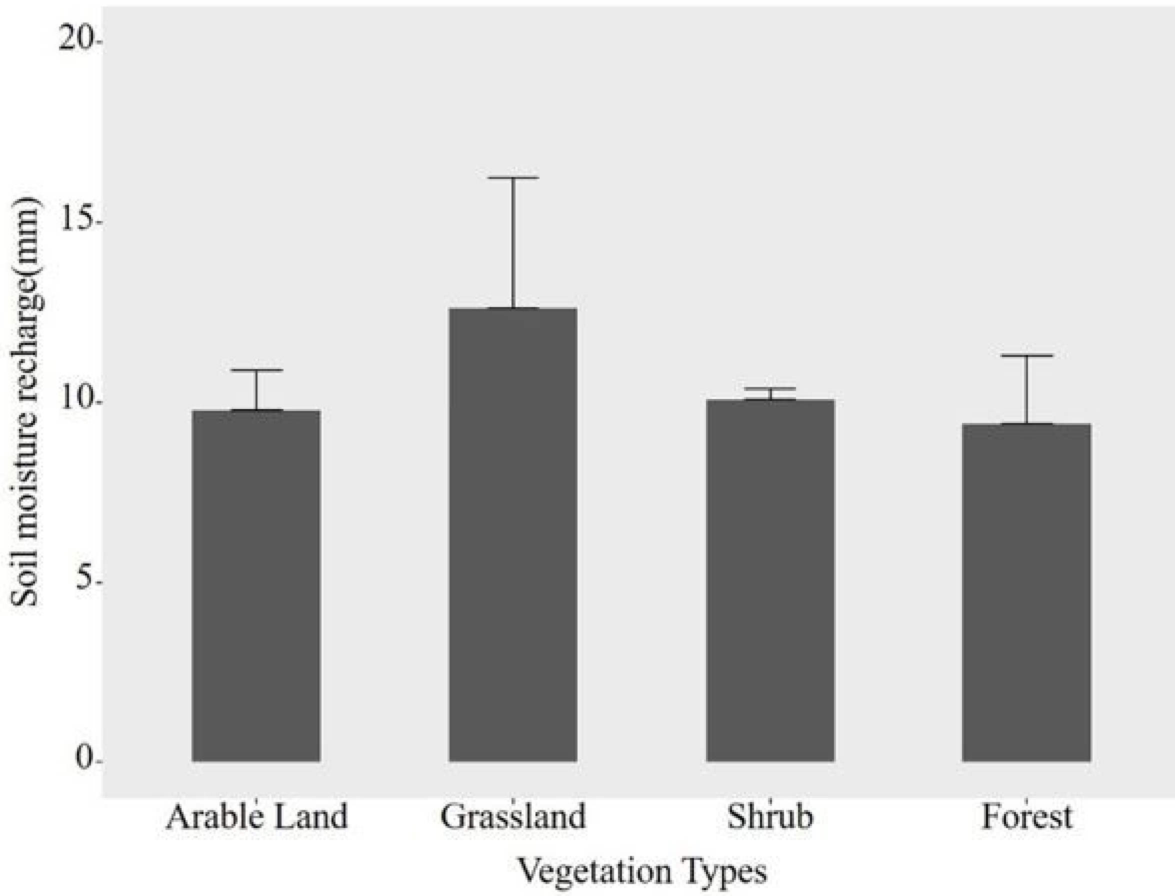

Figure 9

Soil moisture replenishment under the different vegetation types.

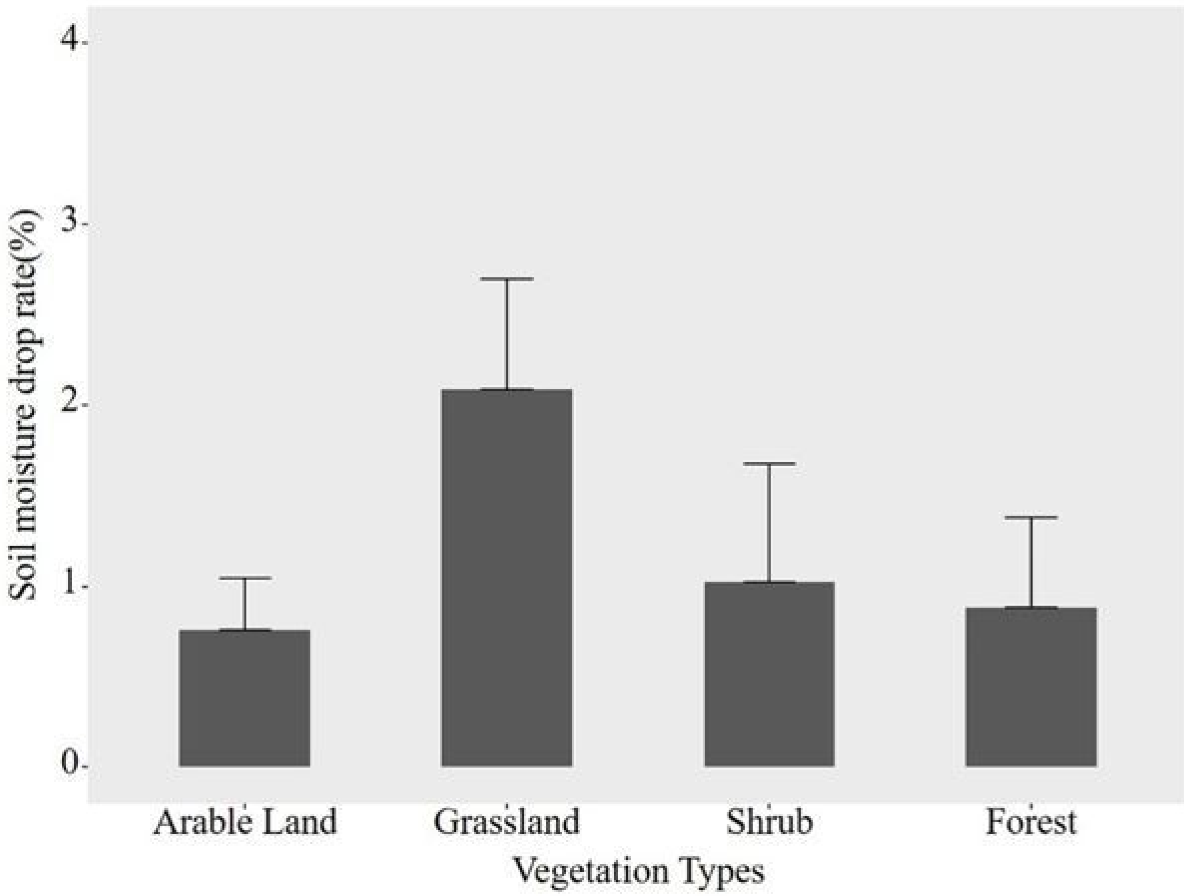

Figure 10

Statistical graph of the decline in soil moisture of different vegetation types