Soil moisture responses under different vegetation types to winter rainfall events in a humid karst region

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Abstract
Soil moisture influences plant growth and hydrological processes. Studying the response characteristics of soil moisture to winter rainfall under different vegetation types in humid karst areas is important for optimizing the restoration patterns in these areas. To this end, we monitored the soil moisture content of arable, grassland, shrub, and forest areas in the karst of Guanling County, Guizhou Province, China, at 10-min intervals. The rainfall threshold for the soil moisture response was the smallest in grassland areas. Under different vegetation types, the soil moisture increase tended to be maximized in light-rainfall events and minimized in medium-rainfall events. Moreover, the increase in soil moisture in the profile under the different vegetation types generally decreased with increasing soil depth during light and rainstorm events, but the opposite variation pattern was observed during moderate-rainfall events. In different rainfall events, the soil moisture recharge and soil moisture decrease were greatest in grassland areas. Among the vegetation types, shrubs maintained the highest mean soil moisture content in winter, with a higher recharge and a smaller decrease in soil moisture. This suggests that shrubs can better maintain their soil moisture content in winter than other vegetation types, which has implications for the selection of regional vegetation restoration patterns.

Keywords Soil moisture · Vegetation types · Winter rainfall events · Response characteristics

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; these differences affect the response of soil moisture to rainfall (Gehrels et al. 1998). Therefore, it is important to study the response of soil moisture to rainfall in karst regions with different vegetation types.

Studies on the response of soil moisture to rainfall in different vegetation types have been conducted by researchers; these studies have mainly been conducted in areas with different wetting conditions. In arid regions, the soil moisture in shrub areas is more sensitive to rainfall compared to that in grassland or forest areas (Sun et al. 2015; Wang et al. 2008). 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). Li et al. (2013) studied the soil moisture dynamics in shrub and grassland areas in semi-arid regions and found that soil moisture in grassland areas is more...
sensitive to summer rainfall compared to that in shrub areas. 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 soil moisture in grassland areas is more sensitive to rainfall compared to that in shrub and forest areas. 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. In summary, the response of soil moisture to rainfall under different vegetation types in areas with different wetting conditions shows varying characteristics. The humid karst region, where this study was conducted, is also a type of humid zone; however, the results obtained from the humid region are not necessarily representative of the humid karst region 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). Elucidating the soil moisture response to rainfall under different vegetation types in humid karst areas will supplement the existing body of knowledge on soil moisture responses to rainfall in humid areas. It will also guide ecological restoration practices in karst areas. Therefore, such a study is pertinent and necessary.

There has been some research concerning the response 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 decreases with increasing soil depth (Jing et al. 2020; Liu et al. 2013; Zhang et al. 2013). Jing et al. (2020) found that the response times of shallow soil moisture under different types of vegetation to rainfall in summer vary widely 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 the soil moisture does not change significantly when the rainfall is light; however, the soil moisture content changes significantly over a short period of time when the rainfall is heavy. Although many researchers have studied the response of soil moisture under different vegetation types to precipitation in karst regions, these results do not represent the situation in winter. 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, although winter precipitation is less in the humid karst region, soil moisture changes are still an important part of the hydrological process. The soil layer in this region is shallow, and the ability of this stored soil moisture in the shallow layer to regulate water under dry winter conditions becomes more important (Fu et al. 2016a; Yang et al. 2019). Therefore, it is important to study the characteristics of soil moisture response to winter rainfall under different vegetation types in humid karst areas.

The purpose of this study is to investigate the characteristics of soil moisture response to winter rainfall under different vegetation types. We performed in situ observations of soil moisture under different vegetation types in winter and analyzed the changes in the increase, decrease, and recharge of soil moisture during different rainfall events. The results of the study can provide a basis for a vegetation recovery model in humid karst regions.

Materials and methods

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 in the months of June–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 (Fig. 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.

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 to monitor the soil moisture content at four soil depths (5, 10, 15, 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 sample 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, the 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, 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.

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 characteristics of the soil moisture.

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/cm³) | 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%                     | 0.6                   | 1.15                      | 49.23                             |
| Shrub                             | *Cipadesca cinerascens* (Pellegr.) Hand -Mazz; *Albizia kalkora* (Roxb.) Prain; *Mallotus japonicas* var. *flocosus* (Muell. Arg.) S. M. Hwang et al. | 50%                     | 3.4                   | 1.11                      | 68.15                             |
| Forest                            | *Radermachera sinica* (Hance) Hemsl; *Toona sinensis* (A. Juss.) Roem; *Broussonetia papyrifera* et al. | 65%                     | 15                    | 1.04                      | 70.90                             |

/ means not available
The increase in soil moisture content is calculated as

$$\Delta \theta_i = \theta_{\text{max}} - \theta_0,$$

(1)

where $\Delta \theta_i$ indicates the increase in soil moisture content (%); $\theta_{\text{max}}$ indicates the peak soil moisture during rainfall; and $\theta_0$ indicates the soil moisture (%) 10 min prior to the start of the rainfall event.

The decrease in soil moisture content is calculated as

$$\Delta \theta_d = \theta_{\text{max}} - \theta_e,$$

(2)

where $\Delta \theta_d$ indicates the decrease in soil moisture content (%) and $\theta_e$ indicates the soil moisture (%) 12 h after the end of the rainfall event.

The soil moisture storage is calculated as

$$SW = \sum_{i=1}^{4} \theta_id_i,$$

(3)

where $SW$ indicates the soil moisture storage (mm); $\theta_i$ 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

$$\Delta SW = SW_{\text{max}} - SW_0,$$

(4)

where $\Delta SW$ indicates the soil moisture recharge (mm); $SW_{\text{max}}$ 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.

Origin 2018 and R (4.0.2) were used to produce the graphs.

## Results

### Mean soil moisture and rainfall distribution during the study period

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

Figure 2 shows the temporal dynamics of mean soil moisture and rainfall distribution for four vegetation types in the humid karst region. During the study period, the mean soil moisture content of all vegetation types responded positively to rainfall. The mean soil moisture content generally showed the highest in shrub areas, followed by grassland areas. The mean soil moisture content was the lowest in forest areas. Arable areas, in which the mean soil moisture content exceeded that of the other three vegetation types after December 20, showed complex variations in mean soil moisture content. In general, the mean soil moisture under different vegetation types responded positively to rainfall throughout the study period, with the lowest mean soil moisture content noted in forest areas.

### Soil moisture response process to a single winter rainfall

Among all rainfall events in winter, light-rainfall events comprised the largest proportion (Table 2). To study the soil moisture response to winter light-rainfall events under different vegetation types, we selected two light-rainfall events with close average rainfall intensities and different total rainfall amounts. In the first light-rainfall event, the amount of total rainfall was 0.87 mm and the rainfall duration was 2.17 h (Fig. 3). There were no significant fluctuations in soil moisture at different soil depths in arable, shrub, and forest areas throughout the rainfall event, while there were significant fluctuations in the soil moisture at 5-, 10-, and 15-cm soil depths in grassland areas. After the rainfall event, the soil moisture content at different soil depths in the grassland areas started to increase and reached its peak, and the peak soil moisture showed an overall increase with increasing soil depth. The peak soil moisture time at 5-cm soil depth was 3.5 h, while the peak soil moisture time at 20-cm soil depth lagged by 7.17 h. Overall, among the different vegetation types, grassland areas responded to small rainfall events with low amount of total rainfall. The peak of the soil moisture increased with soil layer, and the peak soil moisture time was longest in the 20-cm-deep soil.

In the second light-rainfall event, the amount of total rainfall was 20.75 mm and the rainfall duration was 54.17 h (Fig. 4). Throughout the rainfall event, there were significant fluctuations in soil moisture under all vegetation types, indicating that they responded strongly to the light-rainfall events with higher rainfall amounts. After the rainfall occurred, the soil moisture content at different soil depths of all vegetation types gradually increased and reached its peak and the peak soil moisture generally showed a trend that the shallow layer (5 and 10 cm) was larger than the deep layer (15 and 20 cm).
peak soil moisture time at 5-cm soil depth in arable areas (37.17 h) was the smallest, while grassland, forest, and shrub areas lagged by 0.5, 3.83, and 5.16 h, respectively. In general, all vegetation types responded to light-rainfall events with higher rainfall amounts. The peak soil moisture time at 5-cm soil depth in arable areas for the shortest, while shrub areas reached their peak at 5-cm soil depth for the longest.

During moderate-rainfall events, soil moisture under all vegetation types responded strongly to rainfall (Fig. 5). During rainfall, the peak soil moisture under different vegetation types was generally greater in shallow layers (5 and 10 cm) than in deep layers (15 and 20 cm). The peak soil moisture time at 5-cm soil depth in grassland areas (25.5 h) was the smallest, while forest, arable land, and shrub areas lagged by 2.5, 2.5, and 2.8 h, respectively. In general, the soil moisture in all soil layers under different vegetation types responded strongly to moderate-rainfall events. Soil moisture reached its peak at 5-cm soil depth in grassland areas for the shortest time, while shrub areas reached their peak at 5-cm soil depth for the longest time.

Soil moisture under different vegetation types responded strongly to the rainfall during rainstorm events (Fig. 6).

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

Fig. 3 Response of soil moisture to rainfall under different vegetation types: a arable, b grassland, c shrub, and d forest areas
Fig. 4 Response of soil moisture to rainfall under different vegetation types: a arable, b grassland, c shrub, and d forest areas.

Fig. 5 Response of soil moisture to rainfall under different vegetation types: a arable, b grassland, c shrub, and d forest areas.
During rainfall, the peak soil moisture under different vegetation types generally showed a trend that the shallow layer (5 and 10 cm) was larger than the deep layer (15 and 20 cm). Among the different vegetation types, the peak soil moisture time at 5-cm soil depth in forest land was 0.67 h. The peak time in grassland, shrub, and arable areas lagged by 0.16, 1, and 1.16 h, respectively. In general, soil moisture in different vegetation types responded strongly to the rainstorm event. Soil moisture at 5-cm soil depth in forests had the shortest time to peak, while soil moisture at 5-cm soil depth in arable areas had the longest time to peak.

**General response characteristics of soil moisture to winter rainfall events**

The increase in soil moisture under each vegetation type in the different winter rainfall events showed an overall trend of maximum during light-rainfall events (total rainfall of 20.75 mm and a duration of 54.17 h) and minimum in the medium-rainfall event (Fig. 7a). In the case of moderate and rainstorm events, the increase in soil moisture under different vegetation types showed an overall increasing trend with increasing rainfall intensity. In the light-rainfall and rainstorm events, the soil moisture in the profiles of different vegetation types tended to decrease with increasing soil depth, whereas in the moderate-rainfall events, the moisture increased with increasing soil depth (Fig. 7b–d).

We calculated the mean soil moisture recharge amount and decrease during three rainfall events (light rain with total rainfall of 20.75 mm; moderate rain; rainstorm) under different vegetation types (Figs. 8 and 9). Among the different vegetation types, the recharge amounts of soil moisture were the largest in grassland areas, followed by shrub and arable areas, while the recharge amounts of soil moisture were the smallest in forest areas. The greatest decrease in soil moisture under different vegetation types was in grassland areas, followed by shrub and arable areas, and the smallest was in arable areas. Overall, the recharge amounts and decrease of soil moisture were the largest in grassland areas, and the smallest in forest areas, but the decrease of soil moisture in forest areas was relatively small.

**Discussion**

**Uniqueness of soil moisture response to winter rainfall in humid karst regions**

Vegetation redistributes the rainfall; in particular, some of the rainfall is retained directly by the vegetation canopy and some enters the soil through the trunk stem or through forest penetration (Llorens and Domingo 2007; Zhang et al. 2015). Seasonal changes in the vegetation canopy structure can affect the vegetation canopy retention capacity (Deguchi et al.
Guo et al. (2016) reported that 6 mm is the threshold precipitation that elicits a soil moisture response on karst slopes. Unlike these earlier findings, the present study found that soil moisture in grasslands responded to winter light-rainfall events (total rainfall of 0.87 mm). This difference is mainly due to seasonal differences between the two studies. The previous study was conducted in autumn, when the vegetation canopy has a complex structure and easily intercepts rainfall events (total rainfall of 0.87 mm).
rainfall. When the total amount of rainfall is small, little moisture can enter the soil. The present study was conducted mainly in winter, when the herbaceous plants of the grassland get withered and their canopy is less able to intercept rainfall; therefore, the soil penetration in winter is lower than that in autumn. Among the different vegetation types, grassland areas exhibited the greatest recharge from different rainfall events, further confirming that grassland areas weakly intercept rainfall (Fig. 8). Therefore, the smaller rainfall threshold of the moisture response of grassland soil in winter than in autumn is reasonable. Shrub and forest areas are unresponsive to winter rainfall events because winter rainfall is intercepted by the canopies of forests and shrubs and litter on the soil surface. In winter, arable areas are fallow and the soil surface is covered with grasses and crop straws, which intercept rainfall. Therefore, the soil moisture in arable areas also responds weakly to rainfall events with total rainfall.

Zhang et al. (2013) analyzed the dynamic pattern of the soil moisture content in the depression profile of a karst region over a period of one year. They found that moderately intense, prolonged, and heavy rainfall facilitated the compensation and recovery of soil moisture. In the present study, the soil moisture under each vegetation type tended to be maximally increased in light-rainfall events with large rainfall amount and long durations (Fig. 7a). Long-duration and large rainfall amount light-rainfall events that deposit a large rainfall have a continuous effect on soil moisture, allowing soil moisture to accumulate. In contrast, moderate and rainstorm rainfall events produce a smaller rainfall total and shorter duration than the light-rainfall events; consequently, their impact on soil moisture is diminished and the increase in soil moisture is small. The soil moisture generally increased with increasing soil depth in the case of moderate-rainfall events, but the opposite pattern was noted during light and storm rainfall events (Fig. 7b-d). Excessively low or high rainfall intensity is detrimental to rainfall infiltration because the infiltration capacity of soil is limited. In rainfall events with low rainfall intensity, the soil moisture deficit in each soil layer is barely met and infiltration is low; thus, these events have little effect on the soil moisture in deeper soil layers. Higher-intensity rainfall produces surface runoff, which also acts against rainfall infiltration. In conclusion, the increase in soil moisture was greatest in the light-rainfall events with higher rainfall amount and longer duration, which was beneficial for soil moisture recovery. The increase in soil moisture at deeper soil depths was greater in medium-rainfall events, which was beneficial to the recovery of soil moisture at deeper soil depths. Overall, the present results are similar to those of previous studies. In humid karst regions, the situation is similar in winter and throughout the year, i.e., rainfall events with moderate rain intensity, longer duration, and higher rainfall amount have a positive impact on soil moisture. Soil properties such as infiltration capacity are relatively consistent throughout the year, indicating no seasonal differences among the degree of influence of rainfall with moderate rain intensity, longer duration, and higher rainfall on soil moisture.

Yang et al. (2007) investigated the changes in soil moisture in karst areas after rainfall in summer. They showed that the decrease in soil moisture content was greater in shrub areas than in grassland areas. In our study, the decrease in soil moisture content was greater in grassland areas (2.08%) than in shrub areas (1.03%) (Fig. 9). The difference between ours and previous studies can be explained by the high biomass and plant transpiration rates in shrub communities during summer, whereas grass has a relatively small biomass and low plant transpiration rate; accordingly, the soil moisture was greater in shrub areas than in grassland areas. In the present study area, the winter season is windy and relatively dry, plant transpiration is weak, and the soil moisture continues to evaporate (Lao and Wu 2008). Under such dry conditions, soil moisture gets depleted mainly via evaporation. In the present study, grassland areas exhibited the greatest decrease in moisture content for two main reasons. First, the plants in the grassland sample sites were mostly annual herbaceous plants. In winter, such herbaceous plants wilt and expose a large area of bare soil from which the moisture evaporates under dry conditions. Second, the amount of litters on the soil surface of grassland areas is low, which also leads to bare soil and fast evaporation of soil moisture. In contrast, shrub areas have perennial plants that retain some vegetation cover and a thick layer of surface litter during winter. Therefore, the soil moisture of shrubs is less disturbed by the outside world and evaporates more slowly than that of grasslands. Accordingly, the decrease in soil moisture in shrubs is less than in shrubland areas during winter. Forest areas also have a certain amount of vegetation cover and a thick layer of surface litter in winter; thus, the decrease in soil moisture in forested areas is less than in shrubland. Moreover, in winter, the weeds and straw on the soil surface of arable areas slow the evaporation from soil, leading to a low decrease in soil moisture in arable areas.

**Variability of soil moisture under different vegetation types in humid karst areas in winter**

In winter, the vegetation coverage of grassland areas is low; in addition, grassland areas have the greatest recharge among the vegetation types but also experience the greatest decrease in soil moisture after rain, indicating that grassland areas have poor water-retention capacity. In winter, vegetation also needs a certain amount of soil moisture to maintain its life activities. Under the dry winter conditions, the vegetation growth in grassland areas with poor water-retention capacity may be stressed due to low soil moisture. Therefore, grassland areas are not the best choice when selecting a vegetation restoration mode. Although the soil moisture is better retained in forest...
areas with greater vegetation coverage than in grassland areas with low coverage, most of the rainfall is intercepted by the forest canopy during rainfall events and some is intercepted by the litter covering its soil surface. Most of the winter rainfall events are small events with small rainfall totals, which cannot easily recharge the soil moisture in forest areas. The mean soil moisture changes during the study period indicate that the forest areas maintain low soil moisture. Therefore, when deciding a vegetation restoration pattern, restorers should not blindly pursue high vegetation coverage but should also consider the interactions among vegetation, soil moisture, and rainfall. Shrub areas maintained a high average soil water content in winter, with a higher recharge and smaller decrease in post-rainfall soil moisture than other vegetation types. Therefore, shrub areas seem to be the best choice for vegetation restoration patterns in karst areas.

**Representation of the study period and specificity of the subsurface conditions**

The sample site of this study is located in a humid subtropical karst region dominated by a subtropical mountainous monsoon climate. During the distinct 4–6-month-long dry season in winter/spring, plants typically receive only 20–30% of the annual rainfall (Nie et al. 2011). The present study was conducted from November 6, 2019, to January 6, 2020, which covers the dry winter months. This study period is representative of other winter months as the subtropical mountainous monsoon climate brings low precipitation and mild temperatures throughout the winter, which are similar in different years. Therefore, the present study period well represents the winter conditions in the humid karst region.

The geological background of the karst region is complex, and the lithological conditions vary greatly. When selecting the sample sites for observation, we intended to control the influence of factors other than vegetation type and to reflect (as far as possible) the variations in the soil moisture response to rainfall caused by vegetation type alone. For this purpose, several sample sites with different vegetation types on the same slope were selected. The karst slopes are mainly limestone and dolomite-dominated substrata. Slopes distributed with dolomite and limestone conditions differ greatly in soil formation and soil characteristics as they have different mineral compositions and weathering rates (Liu et al. 2020). For example, limestone soils have higher porosity and saturated hydraulic conductivity than dolomite soils. Soil properties also affect the response characteristics of soil moisture to rainfall; for example, saturated hydraulic conductivity influences the infiltration process of rainfall. The sample site was located on a relatively pure limestone slope with mainly limestone soil. Therefore, the study results illustrate the response of soil moisture to rainfall on limestone-dominated slopes in wet karst areas during winter. However, as the karst environment is very heterogeneous, the soil properties and the response characteristics of soil moisture to rainfall may differ on karst slopes of other lithologies.

**Conclusions**

In this study, the dynamics of soil moisture under different vegetation types in the humid karst region during winter rainfall events were observed in real time at 10-min intervals; in addition, the response characteristics of the soil moisture under different vegetation types during winter rainfall events were analyzed. Among the different vegetation types, grassland areas with a low vegetation coverage had the smallest rainfall threshold for the soil moisture response, and their recharge was largest and most decreased. Forest areas with the highest vegetation cover exhibited the lowest recharge and the lowest mean moisture content. Compared with other types of vegetation, shrub areas with moderate vegetation cover maintained a higher mean soil moisture content in winter, with a higher recharge and smaller decrease in soil moisture. To better guide vegetation restoration practices, we suggest that the differences in soil moisture recharge and consumption under different vegetation types should be fully considered when selecting a vegetation restoration pattern in humid karst areas. We emphasize that this study was conducted in winter, when the vegetation cover, soil moisture recharge, and consumption of different vegetation types have special characteristics, and the response characteristics of soil moisture to winter rainfall events are also an important research topic.

**Authors’ contribution** 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. were involved in the experimental assays.

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.
References

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

Brantley SL, Eisenstat DM, Marshall JA, Godsey SE, Balogh-Brunstad Z, Karwan DL, Papuga SA, Roering J, Dawson TE, Evaristo J, Chadwick O, McDonnell JJ, Weathers KC (2017) Reviews and syntheses: on the roles trees play in building and plumbing the critical zone. Biogeosciences 14:5115–5142. https://doi.org/10.5194/bg-14-5115-2017

Canton Y, Rodríguez-Caballero E, Contreras S, Villagarcia L, Li XY, 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. https://doi.org/10.1016/j.catena.2006.08.007

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. https://doi.org/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. Res Soil Water Conserv 25. https://doi.org/10.13609/j.cnki.zswc.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. 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. Environ Eng Sci 22:9–24. https://doi.org/10.1089/ees.2005.22.9

Deguchi A, Hattori S, Park HT (2006) The influence of seasonal changes in canopy structure on interception loss: application of the revised Gash model. J Hydrol 318:80–102. https://doi.org/10.1016/j.jhydrol.2005.06.005

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 Phytol. 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. Environ Earth Sci 75:1406. https://doi.org/10.1007/s12665-016-5222-0

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

Gehrels J, Peeters J, De Vries J, Dekkers M (1998) The mechanism of soil water movement as inferred from 18O stable isotope studies. Hydrol Sci J 43:579–594. https://doi.org/10.1080/02626669809492154

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. Carsol Sin 35:629–638. https://doi.org/10.11932/karst20160604 (In Chinese)

Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Rainfall characteristics on infiltration and redistribution patterns in a typical karst catchment of southwest China. Agric For Meteorol 269:239–248. https://doi.org/10.1016/j.agrformet.2019.01.036

Li X, Xu X, Zhang Y, Wang K (2020) Fingerprinting sediment sources in a critical karst catchment in southwest China. Int Soil Water Conserv Res 8:277–285. 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 Agric Sci 40:46–49. https://doi.org/10.16768/j.issn.1004-874x.2013.02.031 (In Chinese)

Liu H, Dai J, Xu C, Peng J, Wang H (2020) Bedrock-associated belowground- and aboveground interactions and their implications for vegetation restoration in the karst critical zone of subtropical Southwest China. Prog Phys Geogr 45:45–19. https://doi.org/10.1177/030913320948965 (In Chinese)

Lorens P, Domingo F (2007) Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. J Hydrol 335:37–54. https://doi.org/10.1016/j.jhydrol.2006.10.032

Lozano-Parras 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. J Hydrol 529:951–961. 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. J Mt Sci 15:548–562. https://doi.org/10.1111/s11629-017-4415-y

Nie YP, Chen HS, Wang KL, Tan W, Deng PY, Yang J (2011) Seasonal water use patterns of woody species growing on the continuous dolostone outcrops and nearby thin soils in subtropical China. Plant Soil 341:399–412. https://doi.org/10.1007/s11104-010-0653-2

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

Sohr J, Ries F, Sauter M, Lange J (2014) Significance of preferential flow at the rock soil interface in a semi-arid karst environment. Catena 124:1–10. 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 Degrad Dev 30:290–299. https://doi.org/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 services in the Qilian Mountains. Catena 128:63–75. 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. Agron J 111:1506–1515. https://doi.org/10.2134/agronj2018.06.0405

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. J Hydrol 358:134–143. https://doi.org/10.1016/j.jhydrol.2008.06.002

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. https://doi.org/10.1016/j.catena.2012.10.006
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. Bull Soil Water Conserv 27. https://doi.org/10.13961/j.cnki.stbctb.2007.04.030 (In Chinese)

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

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. https://doi.org/10.1016/j.catena.2018.09.032

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 161:96–103. https://doi.org/10.1016/j.catena.2017.10.023

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

Zhang C, Chen HS, Nie YP, Zhang W, Feng T, Wang KL (2013) Dynamics of soil profile water content in peak-cluster depression areas in karst region Chinese. J Eco-Agric 21:1225–1232. https://doi.org/10.3724/SP.J.1011.2013.01225 (In Chinese)

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. J Hydrol 527:1084–1095. https://doi.org/10.1016/j.jhydrol.2015.05.060

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. https://doi.org/10.1016/j.catena.2014.03.010

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