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Effects of conventional soil and water conservation measures on soil moisture of sloping land in the loess region

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ABSTRACT

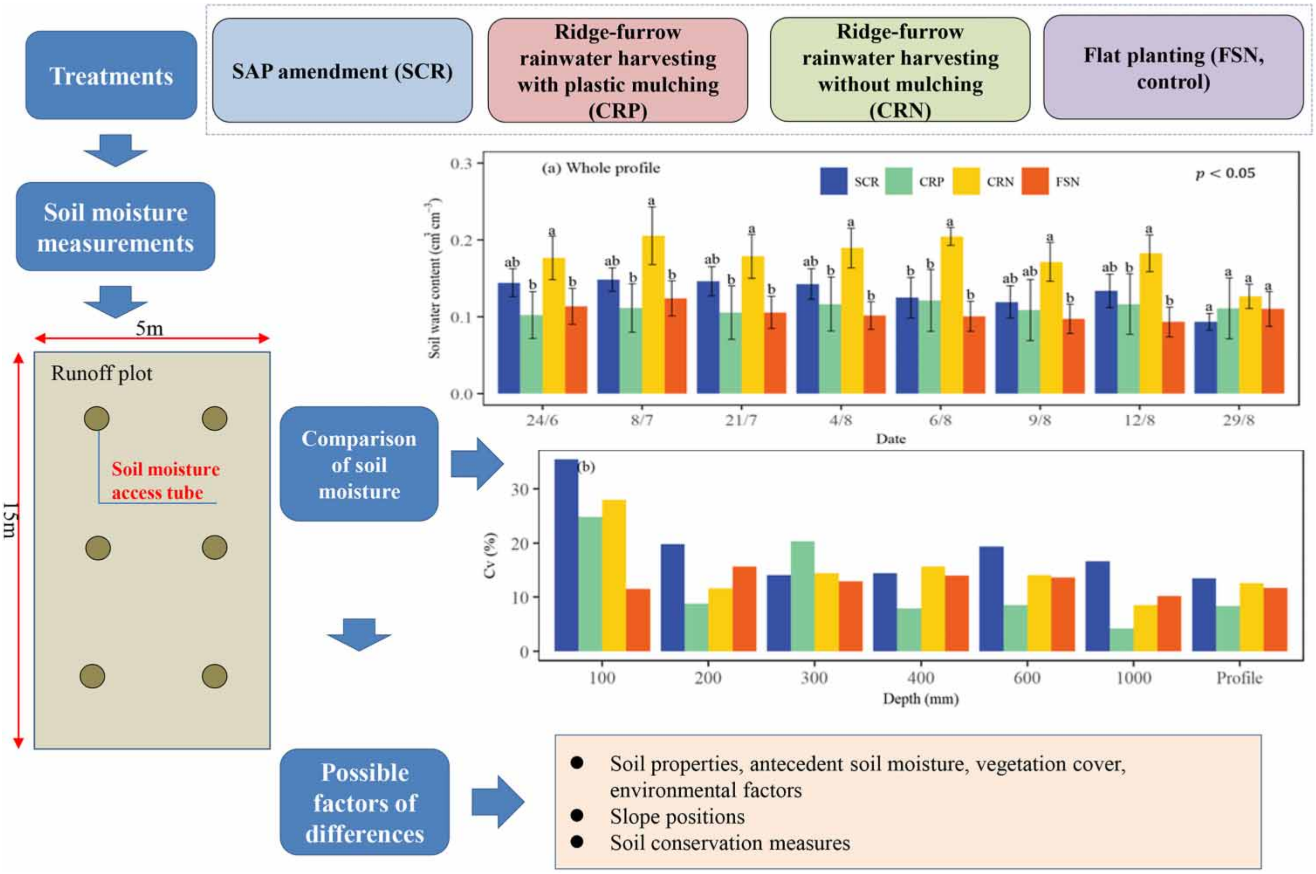
Traditional soil conservation measures were widely recognized for their excellent ability to promote rainwater infiltration in the loess region. However, little is known about how these measures affect the soil moisture variations under natural rainfall conditions. To compare their effects on soil water content, four different treatments were conducted at runoff plots, i.e., super absorbent polymer amendment (SCR), ridge–furrow rainwater harvesting with plastic mulching (CRP), the same measure with CRP but without mulching (CRN), and flat planting (FSN, control), soil moisture at multiple slope positions and depths were periodically measured. The results showed that in the top 0- to 30-cm soil, SCR and CRN relatively greatly varied with time, yet CRP and FSN changed less. The mean soil water content of these treatments generally followed the pattern of CRN > SCR > CRP > FSN. Responding to a heavy rainfall event, the recharge and depletion rates of soil water storage generally showed similar patterns of SCR > CRN > CRP > FSN in the topsoil, yet in the deeper soil they followed the patterns of CRP > CRN > FSN > SCR. It suggested that SCR and CRN could improve the water accumulation and infiltration performances in the topsoil, and thus may be more suitable for rain-fed crop planting on sloping farmlands of the loess region.

Key words: loess region, plastic mulching, ridge–furrow rainwater harvesting, soil amendment, soil moisture

HIGHLIGHTS

- The variations of soil water content under different treatments were assessed.
- The differences in soil water content among different treatments were compared.
- The variations of soil water storage responding to a heavy rainfall event were evaluated.

GRAPHICAL ABSTRACT



INTRODUCTION

Soil moisture is a key hydrologic state variable which impacts the water transport and energy exchange in the soil–plant–atmosphere continuum, and is also the most important factor to affect vegetation growth and hydrological process, especially in water-limited ecosystems (Vereecken *et al.* 2022). Detailed knowledge related to soil moisture dynamics is considered to be important to improve the understanding of the relevant eco-hydrological processes (Zhou *et al.* 2021), and provide valuable insights for selecting the appropriate measures of soil and water conservation in the area suffering from severe soil erosion and drought (Zhang *et al.* 2019).

The loess region in northwestern China has a fragile arid and semi-arid ecosystem and is characterized by severe soil erosion, sparse vegetation, and poor soil structure with high silt content but low organic matter content. This region annually generated approximately 90% of the sediment and nutrients entered into the Yellow River (Li *et al.* 2023), thus was considered as one of the most severely affected areas by soil erosion in the world. Sloping farmlands are the basic and important farmland resource in this region, and soil erosion is very pronounced due to the lack of water absorption and plant blockage, especially for bare slopes. Therefore, over the decades, to control soil erosion and improve rainfall infiltration, the Chinese government has implemented various conventional measures, such as building terraces (Feng *et al.* 2020), reshaping micro-topographies (Gou *et al.* 2021), soil mulching (Fan *et al.* 2014), vegetation restoration (Deng *et al.* 2016), and so on. Meanwhile, many field studies have been conducted to study their effects on soil erosion and demonstrated that they could effectively conserve soil moisture in shallow soil, increase rainfall infiltration, reduce soil and water loss, and increase crop yields (Jun *et al.* 2015; Li *et al.* 2023). Among them, the tillage technique of ridge–furrow rainwater harvesting (with or without plastic mulching), as a commonly applied technique in this region, can effectively gather rainfall and increase soil water content, through effectively regulating and redistributing the unevenly distributed rainfall in time and space. And many studies proved that it played an important role in reducing evaporation and increasing soil temperature and crop production compared with flat planting, in areas with low air temperature and rainfall (Gan *et al.* 2013; Mak-Mensah *et al.* 2021). However, this measure changes the underlying surface micro-relief and roughness, by constructing alternately parallel ridges and furrows on slightly sloping (<20°) ground, thus the spatial distribution patterns of soil moisture in the plots may be different from those on the flat slopes and of the other measures, but few studies focused on this point. Additionally, this technique also has drawbacks. Through mulching ridges and channelling water into the furrows, this measure may increase the runoff and sediment loss along the sloping land under heavy rainfall. And, in practice, this measure is also limited to the expensive costs of time and labor.

In recent decades, various soil amendments have been increasingly adopted by farmers as new water-saving techniques in agriculture, especially in dry farming, to maintain soil moisture content, reduce soil erosion and increase crop yield (Zare *et al.* 2021). Among them, super absorbent polymer (SAP), because of its properties of being relatively low cost, non-toxic, and eco-friendly to the environment, and excellent water absorbency and water-releasing ability, was popularly used for augmenting crop productivity under water-stressed conditions (Patra *et al.* 2022). SAP is a type of water-absorbing polymer, made of starch, chitosan, acrylic, lignin, etc., and can absorb water and swell its original size to several hundred times when it comes in contact with water (Patra *et al.* 2022). Studies indicated that SAP could improve the water-use efficiency of rainfed crops, and reduce deep percolation of water, especially in regions with uneven rainfall and poor soil water retention (Abrisham *et al.* 2018). For example, Yang *et al.* (2014) investigated the influence of SAP on water retention, seed germination and plant survival by absorbing and spraying laboratory experiments on a 60° rocky slope, and found that SAP-treated soils significantly increased the soil water retention and seed germination rate. Abrisham *et al.* (2018) tested the effects of SAP on soil attributes and plant growth in the arid land reclamation of Iran and indicated that application of SAP increased available water content and seedling establishment rates under drought stress. However, current studies mainly focused on the development of new products of SAP, and its effects on soil physicochemical properties, crop growth, and soil water movement (Adjuik *et al.* 2022; Patra *et al.* 2022), but few focused on evaluating its effect on temporal and spatial variations of soil water content on the sloping land, and comparing its performance in soil water retention with other conventional measures under the natural rainfall conditions.

Although many studies have demonstrated that the measures of ridgefurrow rainwater harvesting (with or without plastic mulching) and the addition of SAP amendment have the great ability to improve soil moisture condition and enhance soil water infiltration, little is known about how these measures impact the soil water infiltration and retention capacities under natural rainfall conditions and which measure is more suitable for use on the sloping farmlands in the loess region. Focusing on this question, four different treatments were adopted in this study at the runoff plots located at a sloping land in the loess region of northwest China. Through periodically monitoring soil water content at different soil depths and different slope positions at these plots, the present study aimed to (1) assess the temporal and spatial variations of soil water content under these treatments; (2) compare the differences in soil water content among different slope positions and different treatments; (3) evaluate the differences in soil water storage changes responding to a large rainfall event among these treatments and discuss the major factors. The results in the present study could provide a perspective for an in-depth understanding of rainfall-related soil hydrological processes under the different treatments, and provide a reference for the selection of the appropriate soil and water conservation measures on the sloping lands to effectively use the scarce water resources in the arid and semi-arid region.

MATERIALS AND METHODOLOGIES

Study area

Our experiments were conducted on the sloping lands in a loess region in northwest China, which is located at the Xiaoqingshan National Soil and Water Conservation Demonstration Park, in Heping town, Yuzhong District, Lanzhou City in Gansu province (103°56′40″ E, 36°01′37″ N). This area is characteristic of a beam loess hill landform, with the high terrain in the southwest but the low terrain in the northeast. It belongs to the semi-arid continental monsoon climate in the north temperate zone, with a high potential for evapotranspiration but light precipitation events with less amount. According to the 30-year data (1971–2000) from Lanzhou meteorological station, the annual average precipitation was 311.7 mm, the annual average evaporation was 1,468 mm, the annual average temperature was 9.8 °C, the active accumulated temperature $\geq 10\,^{\circ}\mathrm{C}$ was 3,354.6 °C, the extreme maximum and minimum temperature was 39.8 and −21.8 °C, respectively, and the annual average wind speed was $0.9\ \mathrm{m\ s^{-1}}$. Due to the influence of monsoon, the seasonal distribution of precipitation was extremely uneven, and the precipitation from July to September accounted for more than 60% of the total annual precipitation. The soil type is lime-calcic soil with a low nutrient content and strong collapsibility, and the organic matter content is only around 0.4%. In 2021, the total precipitation was 210 mm, and the average air temperature was 11.23 °C, thus it was a relatively dry year compared to the multi-year average level (Figure 1). The vegetation is mainly the artificial forest, and its coverage is around 85%. The dominant tree species are *Platycladus orientalis (L.) Franco, Populus alba L.*, and *Robinia pseudoacacia L.*, the primary shrubs are *Tamarix chinensis Lour.*, and the herbaceous plants are mainly *Achnatherum inebrians (Hance) Keng, Plantago asiatica L.*, and *Artemisia Linn.*

Experimental design and field management

This study was implemented in a randomized complete block design with four treatments and three replicates: SAP amendment (SCR), the measure of ridge–furrow rainwater harvesting with plastic mulching (CRP), the same tillage technique with CRP but without mulching (CRN), and flat planting (FSN, control). Among these treatments, flat planting was considered as the control measure to compare and evaluate the effects of different soil and water conservation measures on soil water content variations. All these treatments and replicates were randomly assigned to the adjacent 12 runoff plots, with the slope gradients of 15°, the slope aspects of southeast facing, and the sizes of 5-m width multiplied by 15-m length. This arrangement could control the effects of potential variable environmental conditions such as non-uniformity of rainfall characteristics, air temperature, solar radiation, and humidity on soil moisture during the study period. For treatment SCR, SAPs were introduced as an admixture for soil expecting to enhance its ability to accommodate moisture variations. The ridge–furrow rainwater harvesting technique has been widely applied in arid and semi-arid regions to collect rainwater and reduce the risks associated with drought under rain-fed conditions, and its combination with plastic film mulching is also an efficient way to reduce water deficit and promote crop production. This study focused on the effects of different measures on soil water content variations under natural rainfall conditions, thus in order to avoid the impacts of vegetation properties, we conducted the control tests for these treatments by using similar planting densities.

Before 20 April 2021, after being ploughed, harrowed, and leveled, the surface soil under treatments CRP and CRN was transformed into the alternate ridges and furrows which oriented along contours in the plots. The ridges for rainwater harvesting were 60-cm wide and 15-cm high, and the leveled furrows used as the planting zones were 30-cm wide. Each plot consisted of 16 ridges and 17 furrows. For treatment CRP, the rainwater harvesting ridges were mulched with transparent plastic film, whose width was 80 cm and the thickness was 0.008 mm. For treatment SCR, a rate of 30 kg hm^{-2} of SAP was applied to the slope positions corresponding to the furrows of CRP and within a depth of 20 cm following the manufacturer's recommendation, this application rate at the seeding stage was also recommended for potato production in the mountainous area of south Ningxia (Hou *et al.* 2018). During the application of SAP, the surface soil of 5 cm thickness was removed and placed aside, and the soil of 5–20 cm depth was mixed with SAP, then the original surface soil was backfilled. This process effectively reduced the water repellency, promoted soil water infiltration and increased soil moisture content (Chen *et al.* 2020). The SAP used in this study was purchased from Zhuhai Demi New Material Co., Ltd, Guangdong Province, China, which is a cross-linked polyacrylamide (PAM) and polyacrylate copolymer with a particle size ranging from 0.02 to 0.05 mm.

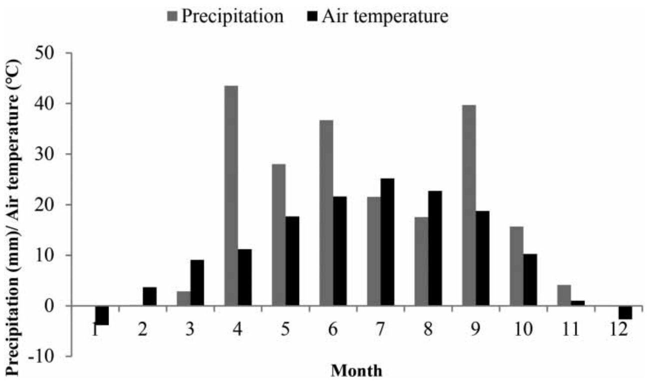


Figure 1 | Monthly distribution of precipitation and average air temperature at the study site in 2021.

On 10 May 2021, an indigenous variety of potatoes (Longdou No. 10) was planted in the furrows or the corresponding positions for all the treatments, with a planting spacing of 30 cm and a planting density of 53,000 plants hm^{-2}. The rates of 225 kg hm^{-2} of urea (N 46%) and 750 kg hm^{-2} of superphosphate (P_2O_5 14%) were applied in a single dose. Before cultivation, the installation of instruments and soil sampling were conducted under these treatments. Access tubes (PVC pipes with a diameter of 25 mm and a length of 1 m) for measuring soil moisture were installed at the planting zones on the up-slope (0–5 m), mid-slope (5–10 m), down-slope (10–15 m), respectively, at each plot. These tubes had a horizontal spacing of 2 m between the pipes and a distance of 1.5 m from the left or right boundaries. Additionally, at the beginning of the experiment, the initial soil water content under these treatments was measured and all close to 0.08–0.1 cm^3 cm^{-3}.

Sampling and measurements

To examine the effects of soil properties on soil moisture, the vertical profile of 100 cm depth was extracted at each plot, and the undisturbed soil samples were collected at different depths of 0–10, 10–20, 20–30, 30–40, 40–60, and 60–100 cm, by using a steel cutting-ring sampler with a diameter of 50.46 mm, a height of 50 mm, and a volume of 100 cm^3. Five replicates were taken from each soil layer. These samples were brought back to the laboratory and weighed immediately, and the bulk densities were determined by using the standard oven drying method. Other soil samples were also collected from these depths by using a shovel and packaged into plastic bags, then brought into the laboratory for natural air-dry and passed through a soil screen with a 2 mm aperture. The soil textures of these samples were determined by using a laser particle size analyzer (Mastersizer 3000, Malvern Instruments, Malvern, England).

During the study period, soil moisture was measured by using the Portable Soil Profile Moisture Meter (PR2-6, Delta-T Devices Ltd, UK), which can measure the volumetric soil moisture quickly, accurately, and reliably. Based on the advanced FDR technology, this instrument can measure the soil water content at different depths (i.e., 10, 20, 30, 40, 60, and 100 cm, respectively) within a single soil profile at the same time, using six soil moisture probes distributed on a sealed polycarbonate rod. The detection range of probes is 10 cm in diameter. The cylindrical soil samples with a height of 5 cm above and below probes determined 95% of the sensitivity for the measured values. To avoid the effect of soil properties on the accuracy of measurements, we conducted the soil-specific calibration for the instrument by analyzing the linear relationship between the soil moisture measured manually and that measured using the sensors. The measurement was conducted at 8 o'clock, with the frequency of about once every 7–10 days according to the soil water condition and weather status, and lasted 3 months during the middle-growing season (from early June to late August). The measurement was also conducted before and after the significant rainfall event to illustrate the effect of different measures on soil water storage. For each access tube installed, three replicates of measurements were done by repeatedly taking the readings and rotating the rod 120° at each time. For each depth in a profile, the soil moisture was determined by taking the arithmetic mean of three replicates. The periodical measurements from the six access tubes installed at a specific plot were used to evaluate the temporal variation of soil moisture, and the measurements from six depths were used to evaluate the spatial variation of soil moisture in the profile. Meteorological data were measured by using an automatic meteorological station (WX-NY8, WANXIANG environment Co., China) located less than 50 m from the study plots.

DATA PROCESSING AND STATISTICAL ANALYSIS

Soil water content and its variation

To evaluate the differences in soil water content among the different slope positions or treatments, we calculated the mean soil water content $\overline{\theta_j}$ at various depths, at a certain slope position or treatment, which was the arithmetic mean of soil water content at depth j, at a spatial scale of slope position or treatment, calculated using Equation (1):

$$\overline{\theta_j} = \sum_{i=1}^{N} \theta_{ij}/\mathrm{N} \tag{1}$$

where θ_{ij} is the ith measurement of soil water content at the soil depth j, cm^3 cm^{-3}, N is the number of the total measurements at the soil depth j at a certain slope position or treatment.

The coefficient of variation (C_v, Equation (2)) was used to show the variations of soil water content with time or in the vertical profile. According to the classical statistical theory, variability was considered as weak when $C_v\% \leq 10\%$, moderate when $10\% < C_v\% < 100\%$, and strong when $C_v\% \geq 100\%$ (Brocca *et al.* 2009; Yi *et al.* 2023):

$$C_v = \frac{SD}{\theta_{mean}} \times 100\% \tag{2}$$

where SD represents the standard deviation of the volumetric soil water content during the study period or in the profile under specific treatment, and θ_{mean} was the mean value of soil water content during the study period or in the profile.

Soil water storage

SW (mm), which quantifies the total amount of water stored in the soil profile of the plant active root zone, was calculated using Equation (3):

$$\mathrm{S} = \bar{\theta}_{10} \times 100 + \bar{\theta}_{20} \times 100 + \bar{\theta}_{30} \times 100 + \bar{\theta}_{40} \times 100 + \bar{\theta}_{60} \times 200 + \bar{\theta}_{100} \times 400 \tag{3}$$

where $\bar{\theta}_{10}$ was the mean soil water content at 10 cm depth, $\mathrm{cm}^3\ \mathrm{cm}^{-3}$, representing the average soil water content in the soil layer of 0–10 cm depth. The meanings of $\bar{\theta}_{20}$, $\bar{\theta}_{30}$, $\bar{\theta}_{40}$, $\bar{\theta}_{60}$, and $\bar{\theta}_{100}$ were similar with $\bar{\theta}_{10}$.

Increasing or decreasing rate of soil water storage

To compare the performance of soil water retention among these treatments, the increasing or decreasing rate of soil water storage ΔSW (%) responding to the soil wetting or drying, during the different periods after a significant rainfall event, was determined by using Equation (4):

$$\Delta\mathrm{SW}\ (\%) = \frac{SW_t - SW_0}{SW_0} \times 100\% \tag{4}$$

where SW_t and SW_0 were the soil water storages at the end and beginning of time during a certain period, mm.

Statistical analysis

The one-way analysis of variance (ANOVA) was used to test if there was a statistically significant difference in the mean soil water content or the soil physical properties among these treatments when the assumptions of data normality and homogeneity of variances were met. The Shapiro–Wilk test was used to test the data normality. In this method, the null hypothesis is that the distribution is normal, a significant test result (p value less than 0.05) suggests that the distribution is not normal and interpretations may be affected. While the Levene test was used to test the homogeneity of variances. The null hypothesis for this test is that group variances are equal, a significant test result $p \leq 0.05$ indicates that the homogeneity of variance assumption is violated, whereas the one-way ANOVA is only an omnibus test statistic and cannot determine which specific groups are statistically significantly different from each other. To achieve this, the least significant difference (LSD) method, one of the simplest methods, would be used for the post hoc multiple comparisons to determine which specific groups differed from each other. In this method, a difference was calculated that was judged to be the smallest difference that was significant. The difference between each pair of means was then compared with the LSD to determine which means were different. Otherwise, when the two prerequisites of data normality and homogeneity of variances were not simultaneously satisfied, a nonparametric test method for comparing multiple independent samples (Kruskal–Wallis H) would be used, to determine whether or not there was a statistically significant difference between the medians of these treatments. This test was the nonparametric equivalent of the one-way ANOVA and was typically used when the normality assumption was violated. The entire statistical analyses were performed using IBM SPSS Statistics 24.0 software at a 0.05 significance level. The graphical presentation was performed using R4.1.2 software.

RESULTS

Temporal variation of soil water content and its spatial variation in the profile

During the study period, soil water content and its C_v in the profiles for these treatments showed that (Figure 2(a) and 2(b)), impacted by rainfall infiltration and plant evapotranspiration, soil water content at various depths presented the corresponding increases or decreases, but the ranges of variations among these treatments were different, i.e., SCR and CRN relatively

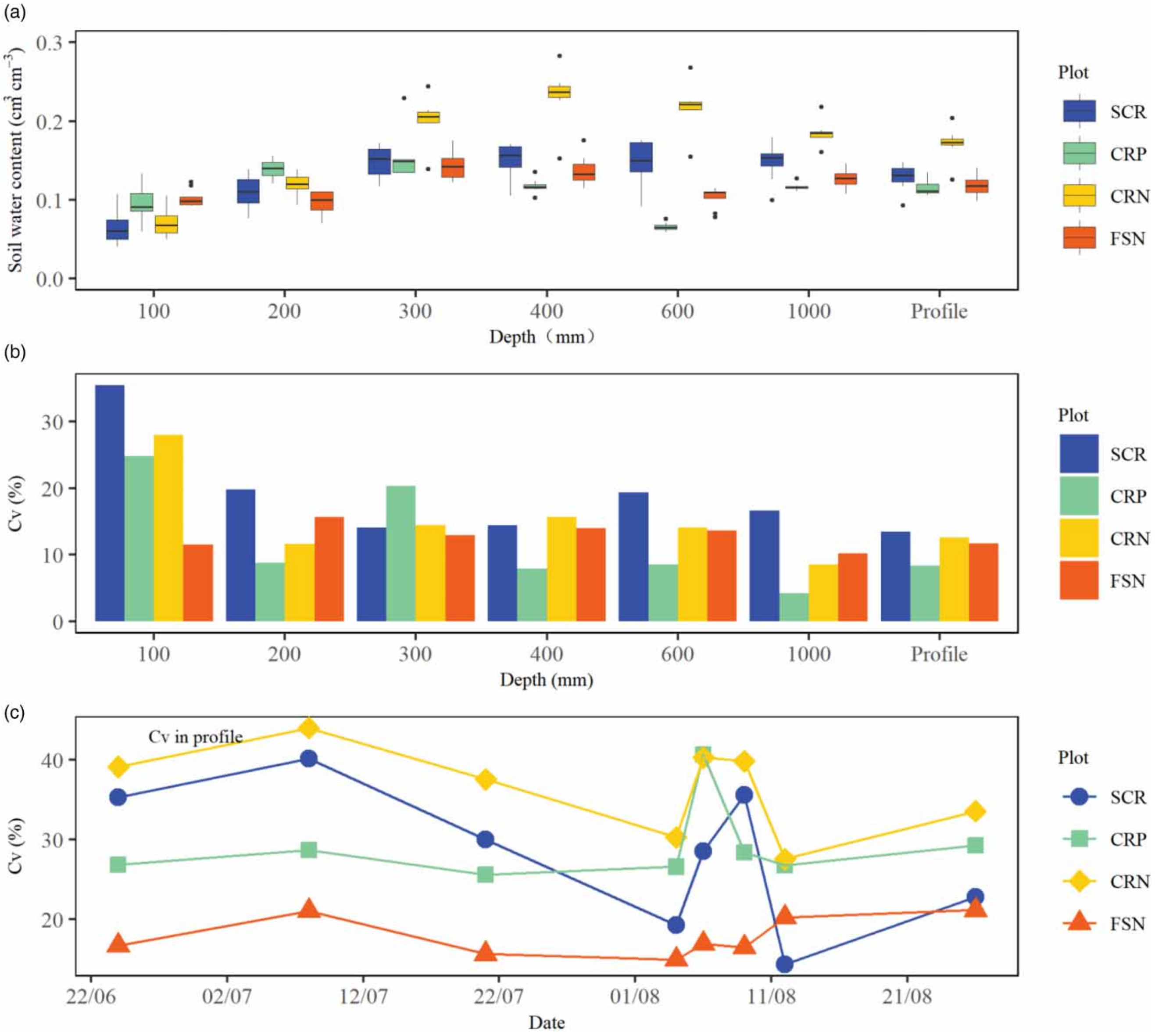


Figure 2 | Soil water content variations during the study period in the profiles under the four treatments (a), vertical distribution of C_v during the study period (b), and temporal variations of C_v in the profiles (c). C_v is the coefficient of variation of soil water content. Profile is the mean soil water content or C_v in the profile.

greatly varied with time, while CRP and FSN changed less (Figure 2(a)). The soil water content, especially in the surface soil, initiated at a relatively low level (less than 0.1) on 24 June, then fluctuated only slightly in the following days. But after being replenished from a heavy rainfall event (with precipitation of 17.8 mm) on 3 August, the soil water content increased obviously, especially in the shallow 0–30 cm soil, then started to decrease under the dual effects of evapotranspiration and soil water percolation. Compared to treatments SCR and CRN, the reason for the fewer variations of soil water content at treatments FSN and CRP may be the effects of flat slope and plastic mulching which potentially facilitated the formation of runoff but reduced the rainwater infiltration and the lateral water leakage from the upper slope.

The spatial variations of soil water content in the vertical profiles were also distinct differences among these treatments. In general, the soil moisture in the shallow soil layer (0–30 cm), an active root zone that intensively responded to the changing weather, had larger changes than in the lower soil and generally decreased with depth. As shown in Figure 2(b), soil water content at these depths had moderate variations, with the larger C_v than in the deeper soil, i.e., 14–35%, 12–28%, 9–25%, 12–16%, for treatments SCR, CRN, CRP, and FSN, respectively. While in the soil deeper than 30 cm, the soil water content had weak or moderate variations, and C_v ranged between 4 and 19% for these treatments. The soil moisture profiles showed the different shapes among these treatments (Figure 2(a)), i.e., the soil moisture at SCR slightly increased with the depth; the soil moisture at CRP decreased with the depth until the depth of 60 cm, then turned to increase; the soil moisture of CRN continued to increase until the depth of 40 cm then started to decrease; while the soil water content at treatment FSN was distributed relatively uniformly, and fluctuated around 0.11 $cm^3\,cm^{-3}$. Additionally, during the study period, the values of C_v in the profiles at these treatments also varied with the time (Figure 2(c)). Generally, the orders of these coefficients were sorted by CRN > SCR > CRP > FSN, and they all belonged to moderate variation except for FSN, which had a weak variation.

Comparison of soil water content among different slope positions

The magnitudes of average soil water content among the slope positions clearly varied for these treatments (Figure 3). Overall, at most of the measuring depths under these treatments, the highest soil moisture was at the middle-slope, followed by the down-slope, then by the up-slope, whether the soil moisture was relatively dry (21 July) or wet (6 August). The statistical tests indicated that, in the profile level, the soil water content at the up-slope was significantly lower than those at the middle-slope, while generally not significantly different from those at the down-slope. For these treatments, however, because of the different effects of these measures on the water infiltration and soil water-holding capacities, the differences in soil water content among the slope positions were obviously different.

As seen from Figures 3(a) and 3(e), the vertical distribution of soil water content among the slope positions at SCR was roughly similar, although the soil water content at the middle-slope was statistically significantly higher. At all the measuring depths, on 21 July, the variation ranges of median soil water content were 0.05–0.26, 0.06–0.18, and 0.04–0.19 $cm^3\,cm^{-3}$, respectively, for the middle-slope, down-slope, and up-slope, while on 6 August, these values were 0.14–0.24, 0.07–0.15, 0.05–0.15 $cm^3\,cm^{-3}$, respectively. The result indicated that the application of SAP may produce a relatively homogenous pattern of water infiltration along the slopes thus resulting in little discrepancies in soil water content among the different slope positions.

In contrast, for CRP (Figures 3(b) and 3(f)), at most of the depths at the middle-slope, the soil water content was obviously higher than those at the up- and down- slopes. The median soil water content had the variation ranges of 0.13–0.29, 0.02–0.12, 0.02–0.09 $cm^3\,cm^{-3}$ for the middle-slope, down-slope, and up-slope, respectively, on 21 July, while the ranges of 0.13–0.33, 0.02–0.10, 0.02–0.12 $cm^3\,cm^{-3}$, respectively, on 6 August. It indicated that the mulching treatment enlarged the differences in soil water content among the slope positions, by increasing the soil water content at the middle-slope, but decreasing the soil water content at the up- and down-slopes.

For treatment CRN, in contrast, without the effects of plastic mulching, the differences in the median soil water content were reduced between the middle-slope and other slope positions, as shown by the vertical distribution of soil water content (Figure 3(c) and 3(g)). As everywhere more rainwater was infiltrated into the soil and the lateral soil water movement from ridges to furrows increased, the shapes of the vertical distribution of soil water content among the different slope positions were similar. And the median soil water content had variation ranges of 0.02–0.32, 0.07–0.28, 0.05–0.14 $cm^3\,cm^{-3}$ for the middle-slope, down-slope, and up-slope, respectively, on 21 July, while the ranges of 0.09–0.28, 0.09–0.27, 0.10–0.17 $cm^3\,cm^{-3}$, respectively, on 6 August.

For treatment, FSN (Figures 3(d) and 3(h)), the vertical profile of soil water content among the different slope positions had similar shapes, but the values were close to each other and extremely lower than the other treatments. i.e., the median soil water content had the variation ranges of 0.05–0.2, 0.05–0.14, 0.03–0.07 $cm^3\,cm^{-3}$ for the middle-slope, down-slope, and up-slope, respectively, on 21 July, and the ranges of 0.04–0.17, 0.04–0.14, 0.03–0.08 $cm^3\,cm^{-3}$, respectively, on 6 August. The possible reason was that the relatively flat ground with the low surface roughness enhanced the water flow over the ground and was unfavorable for the water infiltration.

Comparison of soil water content among different treatments

The different measures of soil and water conservation may cause the different properties of water infiltration, thereby the different regimes of soil water content in the plots. Thus, we compared the soil water content among the four treatments in the whole profile, in the topsoil (0–20 cm), and in the deep soil (20–100 cm), respectively (Figure 4(a)–4(c)). In the whole profile (Figure 4(a)), generally, the highest soil water content occurred at treatment CRN (with the mean values ranging

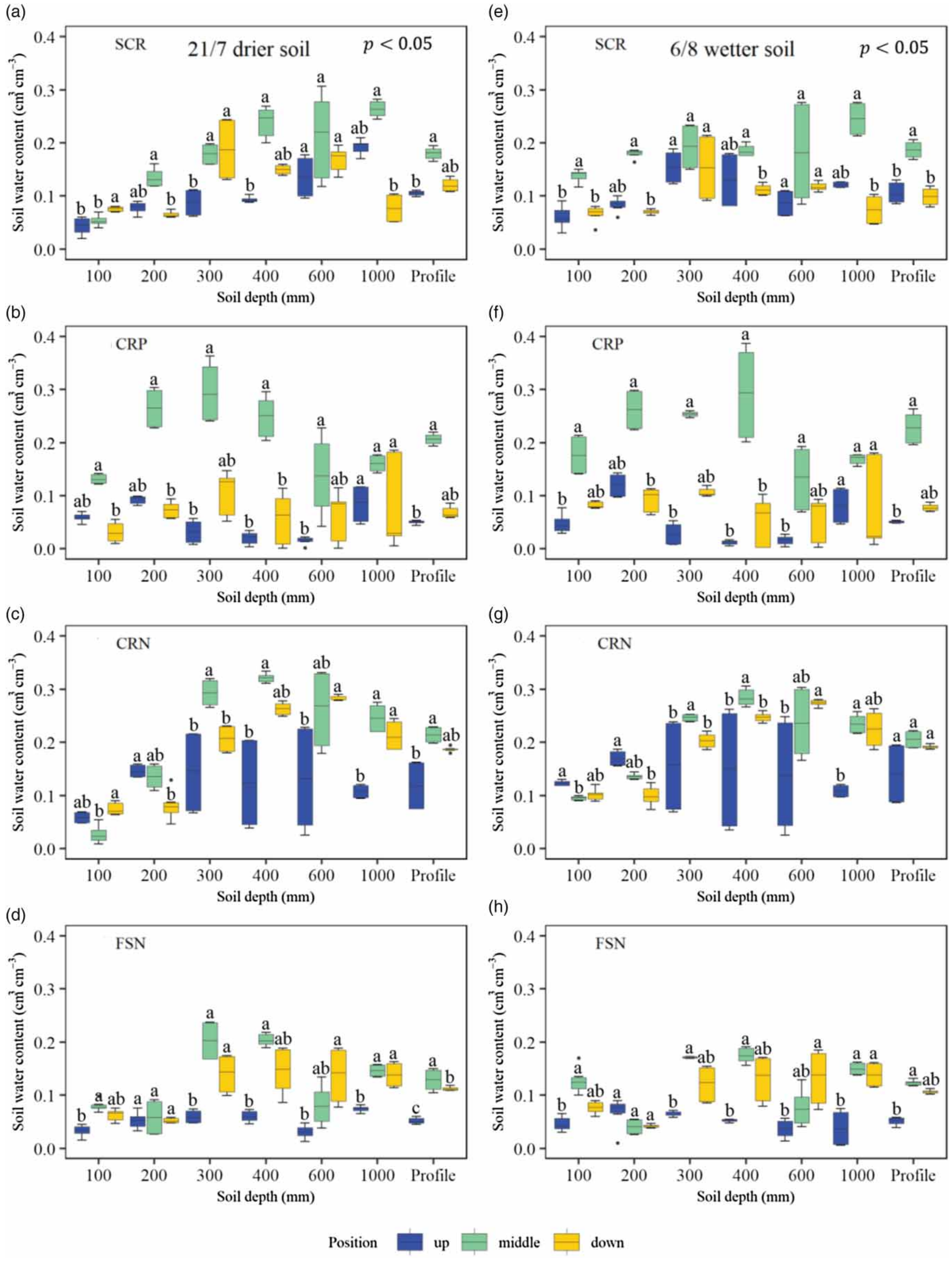


Figure 3 | Comparison of soil moisture among different slop positions for these treatments when soil was drier (21 July) (a–d) or wetter (6 August) (e–h). 'Profile' in the *x*-axis is the mean soil water content in the profile. Different letters indicate the differences of soil water content among different slope positions were significant ($p < 0.05$).

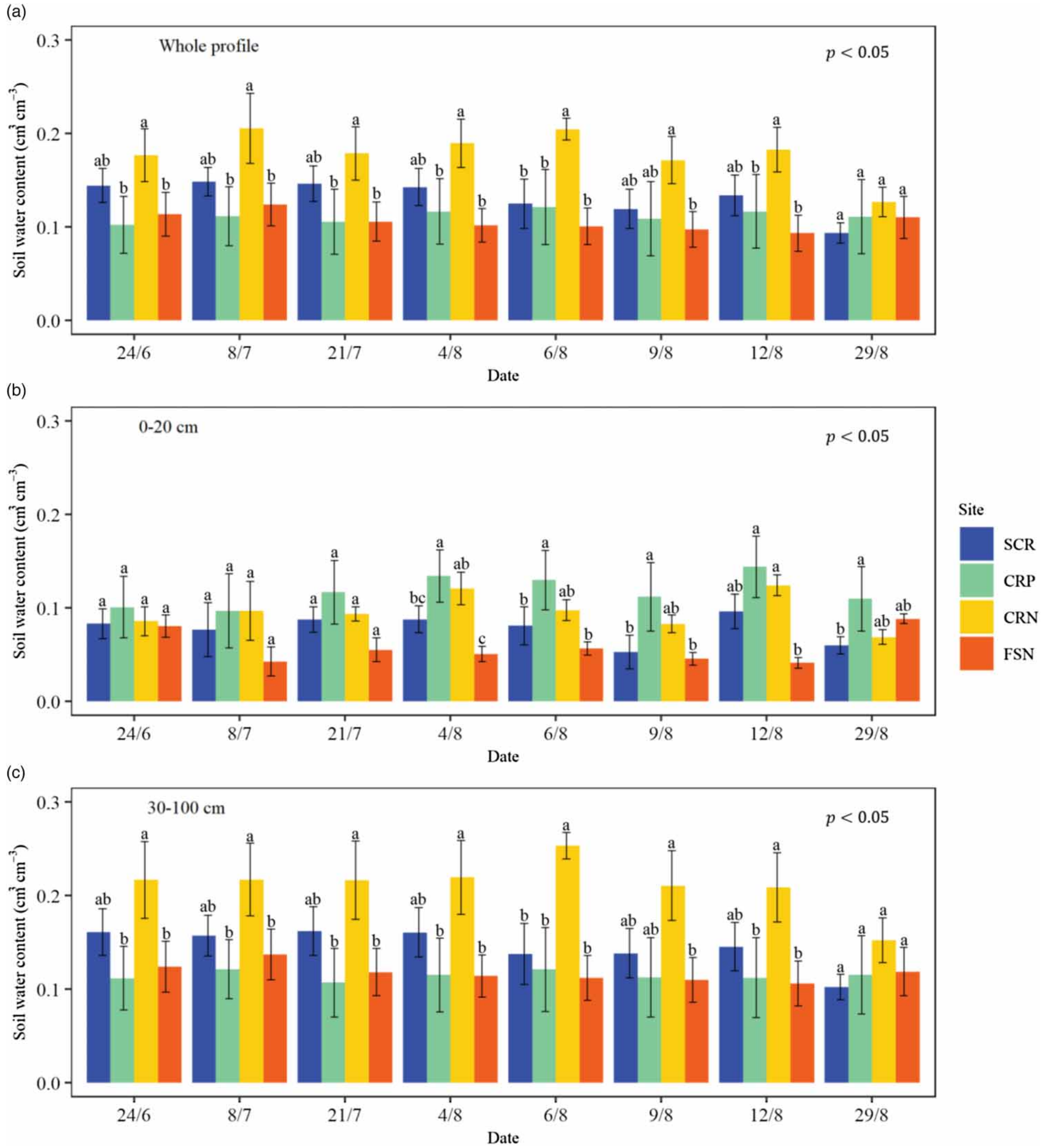


Figure 4 | Comparison of soil moisture among different treatments during the different periods. Different letters indicate the differences of soil water content among different treatments were significant ($p < 0.05$).

between 0.126 and 0.205 $cm^3\ cm^{-3}$), followed by SCR (with the mean values ranging from 0.093 to 0.148 $cm^3\ cm^{-3}$), while the soil water content at treatments CRP and FSN were relatively lower, with the variation ranges of 0.102–0.121, and 0.093–0.124 $cm^3\ cm^{-3}$, respectively. Statistically, the soil water content at CRN was significantly higher than those at treatments CRP and FSN, but among treatments SCR, CRP, FSN, it did not show significant differences. Compared to FSN (control), the soil water content at treatments CRN, SCR, and CRP increased by 55–103%, 19–43%, and 0–24%, respectively, indicating that the treatments CRN and SCR had the good effects on water infiltration and water retention capacity, thereby can reduce the drought impact on the vegetation growth.

In the top soil, which was more intensively impacted by rainfall infiltration and evapotranspiration, however, the orders of size for these treatments were different from those in the whole profile, and sorted by CRP > CRN > SCR > FSN, and their soil water content had the variation ranges of 0.096–0.143, 0.068–0.124, 0.052–0.096, 0.041–0.088 cm^3 cm^{-3}, respectively. The wetter soil at CRP and CRN could be attributed to the effects of rain harvesting measures of alternatively distributed ridges and furrows. While in the deeper soil, the orders of size for these treatments were similar to those in the whole profile, and sorted by: CRN > SCR > FSN > CRP, and their variation ranges were 0.152–0.253, 0.102–0.162, 0.106–0.137, 0.106–0.121, cm^3 cm^{-3}, respectively. Notably, in the topsoil among the four treatments, the soil water content at CRP was the highest, but in the deep soil, it was the lowest (Figure 4(b)–4(c)). It indicated that the measures using plastic mulching combined with the ridge tillage effectively increased SW in the surface soil through the water-gathering effect of plastic film and ridges, but it was indeed unfavorable for water infiltration into the deeper soil because most of the water collected in the furrows had flowed away quickly along the slopes and little could be infiltrated laterally into the subsurface soil due to the hindrance of mulching.

Comparison of variations of SW among different treatments after a heavy rainfall event

Because the potato roots were usually found within 30-cm depth, the variations of SW after the rainfall event were calculated within the depth of 0–30 cm and 0–100 cm, respectively. As shown in Figure 5(a), one day after the rainfall event, overall, SW under all the treatments tended to increase whether in the profiles of 0–30 cm depth or 0–100 cm depth, compared with those before the rainfall event. Moreover, in the depth of 0–30 cm, among the four treatments, the largest increases of SW occurred

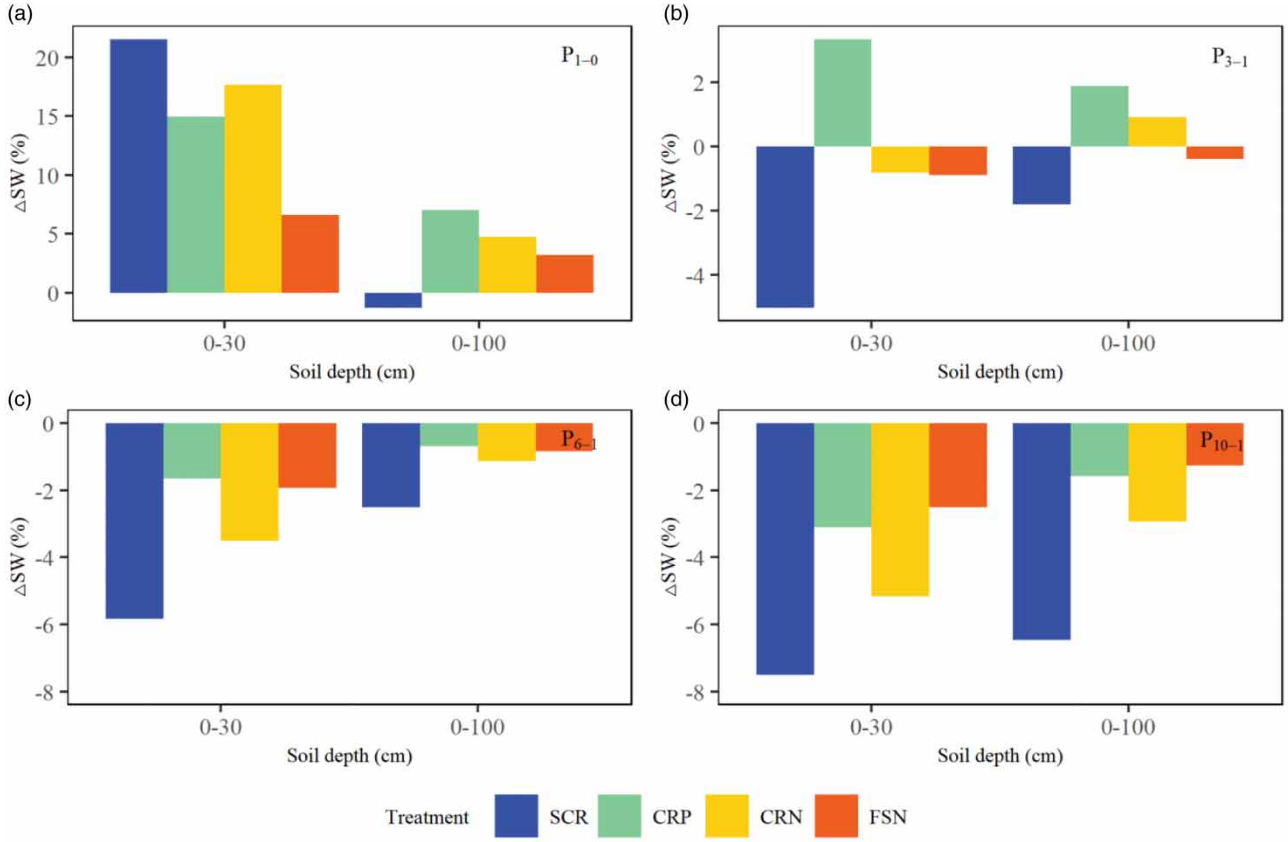


Figure 5 | Increasing or decreasing rates of soil water storage (ΔSW) in different depth ranges for these treatments responding to a large rainfall event. 0 represent the day before the rainfall event occurred on 3 August, the numbers 1, 3, 6, and 10 denote the first day, the third day, the sixth day, the tenth day after the rainfall event, respectively.

at treatment SCR, followed by CRN and CRP, then by FSN, and the increments were 21.5, 17.6, 14.95, and 6.58%, respectively. But in the 0–100 cm depth, the largest increase occurred at CRP, followed by CRN and FSN, and their values were 6.99, 4.72, and 3.20%, respectively, yet SW at SCR slightly decreased by 1.27%. Moreover, the magnitudes of ΔSW in the depth of 0–100 cm were obviously smaller than those in the 0–30 cm depth. When considering the descent gradient of ΔSW with the depth for these treatments, the primary reason for the smaller increments in the whole profile and the decrease at SCR, was perhaps that very little rainwater could be infiltrated into the soil below the 30 cm depth, thus SW at several depths in the lower soil remained or even decreased after the rainfall event, caused by the soil water redistribution driven by soil water potential. Another possible reason was that the application of SAP amendment may only facilitate the water increase in the application layer, but potentially prevented the water from infiltrating into the deeper soil.

On the third day after the rainfall event, SW at SCR decreased by 5.03 and 1.8% in 0–30 cm depth and 0–100 cm depth, respectively, compared with that on the first day (Figure 5(b)). The reason for the smaller decrease in 0–100 cm depth than in the topsoil was that SW in the deeper soil changed less with the depth. On the contrary, SW at CRP in the topsoil and in the whole profile increased by 3.34 and 1.87%, respectively. The possible reason was that the tillage technique of ridges and furrows changed the topographies of surface soil, and enhanced the lateral and vertical soil water redistribution, thus under the effect of evaporation inhibition of plastic film, the water amount laterally replenished from the upper slope positions may exceed the water depletion. As seen from CRN, SW in the depth of 0–100 cm also increased by 0.92%, though decreased by 0.82% in the topsoil. In addition, SW at FSN slightly decreased by 0.9% and 0.4%, respectively, in the topsoil and the whole profile. On the sixth day after the rainfall event, SW at all the depths in the profiles under these treatments decreased compared with those before the rainfall event (Figure 5(c)). The largest decrease occurred at SCR, followed by CRN, then by FSN and CRP. Specifically, SW at SCR, CRN, FSN, and CRP decreased by 5.82, 3.51, 1.93, and 1.65%, respectively, in the topsoil, while they decreased by 2.50, 1.14, 0.83, and 0.68%, respectively, in the depth of 0–100 cm. The reason for the smallest decrease at CRP was that the decrease had been offset by the initial increase of SW in the first 3 days (Figure 5(b)). On the 10th day, SW at all the depths kept a consistently decreasing tendency at all the treatments. Compared with the first day after the rainfall event, their decreasing rates were sorted by SCR > CRN > CRP > FSN (Figure 5(d)). In detail, SW at SCR, CRN, FSN, and CRP decreased by 7.50, 5.16, 3.09, and 2.50%, respectively, in the top soil, while decreased by 6.46, 2.93, 1.57, and 1.26%, respectively, in the whole profile.

DISCUSSIONS

Effects of soil properties, antecedent soil moisture, vegetation characteristics, and environmental factors

Soil moisture variability is a key process in the hydrological cycle of terrestrial ecosystems and is affected by many factors such as rainfall characteristics, soil properties, vegetation types, topographies, antecedent soil water content, and environmental factors. At the plot scale, the independent and interactive effects of these factors make soil water content extremely heterogeneous in space and time. As shown in this study, soil water content among different treatments and depths had obvious differences. As an important factor, precipitation together with soil depth affected the vertical distribution of soil water content and caused the larger C_v in the topsoil, which was consistent with the study by Zhou *et al.* (2021) in the same region. Different measures caused the soil moisture variations by changing the soil structure, infiltration rates, and water retention capacity. Studies have reported that small differences in soil structure, soil texture and soil physical properties will affect the changes in soil moisture (Gaur & Mohanty 2016). The soil mechanical composition and bulk density are the important physical properties of soil, significantly affecting soil permeability and water retention capacity (Sipek *et al.* 2019). For example, sandy soil with weak water-holding capacity and strong water conductivity enables water to infiltrate quickly (Zhang *et al.* 2022). The soil bulk density is an indicator of soil structure and porosity, both of which are involved in water flow (Martinez-Fernandez *et al.* 2021). Thus, in this study, to evaluate the effects of soil physical properties on soil water content, we statistically compared the differences in the soil mechanical composition and bulk density among the four treatments (Table 1).

The results showed that the percentages of sand, silt and clay contents in the soil profiles among the four treatments were similar, i.e., with about 70% of sand, 30% of silt, and less than 1% of clay. According to the triangle map of international soil texture classification, the soil types at these treatments all belonged to the sandy loam soil (Table 1). This result was also aligned with the visual observation when digging the profiles for sampling, and there was no obvious soil stratification. The reason was that the soil in the runoff plots was the manually backfilled soil which was taken from the surrounding

Table 1 | Soil physical properties at the four treatments

Treatment	Soil type	Soil texture (%) Sand (0.02–2 mm)	Silt (0.002–0.02 mm)	Clay (<0.002 mm)	Bulk density (g cm^{-3})
SCR	Sandy loam soil	68.99 ± 2.35	30.25 ± 2.17	0.76 ± 0.19	1.63 ± 0.12
CRP	Sandy loam soil	70.98 ± 2.74	28.46 ± 2.58	0.55 ± 0.15	1.60 ± 0.15
CRN	Sandy loam soil	70.13 ± 2.93	29.33 ± 2.78	0.54 ± 0.19	1.61 ± 0.09
FSN	Sandy loam soil	69.97 ± 2.06	29.39 ± 2.04	0.64 ± 0.12	1.55 ± 0.03

hillsides, thus the soil textures were relatively uniform. The bulk densities at the four treatments were also rather close, i.e., with the average values of 1.63, 1.60, 1.61, and 1.55 g cm^{-3}, for treatments SCR, CRP, CRN, and FSN, respectively. Through the ANOVA analysis, among the four different treatments, there were no significant differences in the percentages of sand, silt and clay contents and bulk densities, even among different depths for a certain measure, indicating that the soil physical properties at the four treatments were rather homogeneous, and the effects of different treatments on soil physical properties appeared to be insignificant. However, Hou *et al.* (2018) reported that the application of SAPs can decrease soil bulk density through an in situ field experiment in a nearby region. The reason for the inconsistency may be the low application rate of SAPs and the differences in background values of soil among these plots. In the topsoil, the largest soil moisture variations and recharge rates responding to a large rainfall event at SCR indicated that the application of SAPs significantly increased soil water-holding capacity, this result was in line with the study by Hou *et al.* (2018), who reported that the application of SAPs can significantly improve soil porosity and soil water conservation capacity. The mulching and configuration of the ridge and furrow regulated the soil water conditions, enhanced water infiltration and helped crops absorb water from the deep soil (Jia *et al.* 2006), as confirmed by the largest recharge rates in the deeper soil at CRP.

The similar soil physical properties indicated that they may not be the primary factor for the differences in soil water content among these treatments, but their effects could not be ignored completely, due to the high spatial variability. Spatial variability of soil texture in the horizontal and vertical directions affected the spatial distribution of soil water content, as confirmed by the different soil moisture among different slope positions and different soil moisture profiles among these treatments. Other factors such as antecedent soil water content and vegetation types were also important factors to affected the soil water content regimes in the different plots. However, in this study, the two factors were generally consistent among these treatments because of the similar initial soil water content and planting densities, thus their effects on differences in soil water content could be considered as negligible. However, during the different vegetation growth periods, the plots with different measures may produce different above-ground (dry weight and plant height) and underground (dry weight and root length) biomass, which could significantly impact soil water content variations by affecting water consumption and evapotranspiration process. The spatial variability of environmental factors may also cause the different soil water content among these treatments, however, in order to reduce their effects, we conducted the field experiments with a randomized complete block design.

Effects of slope positions

Slope position is an important topographic factor, which directly affects the spatial soil water redistribution and indirectly impacts the response of soil moisture to rainfall through changing the amount of water input and flow velocity (Zhang *et al.* 2022), together with other factors such as soil properties and micro-topographies. This study evaluated the effects of slope positions on soil water content under different treatments, the results showed that the highest soil moisture was generally located at the middle-slope, followed by the down-slope, then by the up-slope, whether the soil moisture was relatively dry (21 July) or wet (6 August). This result was in line with the findings by Mak-Mensah *et al.* (2021), who reported that the mean soil water storage on the 7° sloped land cultivated with alfalfa was higher in the middle-slope than in the down-slope, but was lowest in the up-slope. The possible reasons were as follows: due to the short distance of the water flow path and little water accumulation at the up-slope, only a little water could infiltrate into the soil, and most of the rainwater was lost in the form of surface runoff during the rainfall events, resulting in the drier soil and even the relatively sparse vegetation at this slope position (as observed). Moreover, the kinetic energy of raindrops may also intensify the soil densification of the bare ground under vegetation and reduce water penetration (Kebede *et al.* 2022). The water came from the up-slope, in the form of surface runoff or unsaturated water flow gradually migrated into the soil at the mid-slope driven by soil water potential, and resulted in its higher soil water content. However, affected by the slope gradient, a portion of accumulated water at the down-slope with a larger flow velocity, may seep out of the soil and form surface runoff, thus resulting in lower soil moisture content. Additionally, the changes in micro-topographies in the plots may also have a large contribution to the different soil moisture among the slope positions. As seen from Figure 3, at treatments CRP and CRN, whose micro-topographies were changed by adopting the measure of ridge–furrow rainwater harvesting, the discrepancies among the slope positions were obviously larger than those of the other treatments.

Effects of different soil conservation measures

The soil conservation measures affected the soil water content variations by changing the surface micro-topographies and roughness, which allowed more time for infiltration and reduced surface runoff, thus increased the soil permeability and water retention capacities (Carretta *et al.* 2021). In the present study, the analysis of temporal variation and spatial distribution of soil water content showed that soil water content were intensively affected by the soil conservation measures. As seen from Figure 2, during the study period, the soil water content relatively varied greatly with time at treatments SCR and CRN, but changed less at treatments CRP and FSN. Previous studies showed that the measure of ridge-furrow rainwater harvesting can effectively collect runoff from slopes, promote furrows infiltration, improve soil moisture storage, and reduce water loss and soil erosion during moderate-intensity storms (Wang *et al.* 2018). For example, in the present study, the results showed that in the topsoil of 0–20 cm depth, treatments CRP and CRN had the larger soil water content (Figure 4(b)), and the larger SW increasing rates after the large rainfall event than flat planting (Figure 5(a)). However, compared with the measure without mulching, the plastic film may also cause ridge overtopping and ridge failure in heavy rainfall seasons (Wang *et al.* 2022), and prevent water from penetrating into ridges and thus reduce the lateral water migration and deep infiltration (Gan *et al.* 2013). This point could be confirmed by the findings of the higher soil water content at treatment CRP than at CRN in the topsoil (Figure 4(b)), yet the lower values at CRP than at CRN in the deeper soil (Figure 4(c)). Therefore, although plastic mulching had a significantly positive effect on soil moisture conservation reported by previous studies (Gan *et al.* 2013; Fan *et al.* 2014), it may not be a more preferential measure than the measure without mulching on sloping farmlands.

Our results showed that treatment SCR with the application of SAP had a wetter soil water content than treatments CRP and FSN in the deeper soil (30–100 cm) and in the whole profile (Figures 4(a) and 4(c)), and the largest increases and decreases of SW after a heavy rainfall event (Figures 5(a) and 5(d)). These results were consistent with the findings of the previous study on the hydrological effects of SAP amendment (Adjuik *et al.* 2022). They showed that SAP has good water absorption and release characteristics, and can significantly increase soil water retention through quickly absorbing rainfall water and slowly releasing the absorbed water for crop growth, as soil moisture decreases and crop root pressure increases, and ensure a continual water supply during the crop growth period (Abrisham *et al.* 2018). However, the application of SAP may also reduce soil infiltration rate (Zhao *et al.* 2019). For example, in the topsoil, SW at treatment, SCR, had the largest increase rate of 21.5% after the rainfall event, but in the whole profile, it did not increase yet slightly decreased by 1.27%. The possible reason was that the water absorption and expansion of fine particles of SAP may fill the pores in the soil, reduce the hydraulic conductivity of the surface soil, and form an impermeable layer in the top soil, then prevent the penetration of rainwater into the deeper soil, thereby result in the drier soil water content in the profile than CRN (Figure 5). This phenomenon was similar with the findings on effects of other soil amendments such as PAM and nanofiber amendment on soil water infiltration (Sadeghi *et al.* 2021; Zare *et al.* 2021). For example, Sadeghi *et al.* (2021) reported that the application of PAM was likely to decrease the water infiltration, thus increasing the risk of soil and water loss in the downslope. This result implied the application of SAP in sloping lands with high silt content though could increase the soil water-holding capacity in the topsoil, but also may increase the runoff under extreme rainfall conditions, and be unfavorable for plant growth with deep roots.

Limitations and implications

A major limitation of this research was that it only elaborately compared and evaluated four different measures from the perspective of their effects on soil water content variations, while without being involved in their effects on runoff volumes, sediment yields, and vegetation biomass. Further studies on the costs and soil and water conservation benefits of different measures are needed to establish their adoption and scalability. Other new soil amendments such as nano-biochar, which was proven to have positive effects on soil erosion control (Chen *et al.* 2020), deserve to be further studied and compared with the traditional measures in future experiments. It should be mentioned that previous studies on the effects of different measures on soil and water losses were conducted predominantly using rainfall simulation experiments, there was an absence of studies conducted under natural rainfall conditions. Different crop types such as alfalfa, which was widely planted in the loess region to reduce soil erosion (Wang *et al.* 2022), should also be considered in the experiments.

In this study, SCR and CRN had relatively large soil water content and recharge or depletion rates of SW responding to a rainfall event, indicating that the two measures could improve the water accumulation and infiltration performances, and enhance water availability in the active root zone. Thus from the perspective of water conservation, CRN and SCR could be considered as more suitable for rain-fed crop planting in the sloping farmlands of the loess region. However, the lower soil moisture of SCR in the deeper soil owing to the possible barrier effect of SAP's application on the water penetration downwards, suggested that SAP may be only suitable for the shallow-rooted crops such as vegetables. The lower soil water content of CRP especially in the deeper soil suggested that this measure may produce low infiltration rates due to high flow velocity and short retention times and be not suitable for the farmlands on steep slopes, although it can significantly reduce evaporation and improve soil water storage on the flat land (Jia *et al.* 2006).

CONCLUSIONS

In this study, we evaluated the effects of four different soil and water conservation measures on soil water content variations and discussed the possible factors, through monitoring soil moisture from multiple slope positions and depths in the runoff plots. The results showed that in the top 0–30 cm soil, SCR and CRN relatively greatly varied with time, yet CRP and FSN changed less; while in the deeper soil, soil moisture changed relatively weakly for all the treatments. These treatments showed similar patterns of slope positions, i.e., middle-slope > down-slope > up-slope, and their mean soil water content generally followed the pattern of CRN > SCR > CRP > FSN. We also analyzed the variations of SW responding to a heavy rainfall event. The result showed that the increases and decreases of SW mainly occurred in the soil of 0–30 cm depth, and generally showed similar patterns of SCR > CRN > CRP > FSN; while in the deeper soil, the largest recharge rate occurred at CRP, followed by CRN and FSN, yet SCR had the least. Many factors interactively impacted soil water content variations across these treatments. SCR and CRN could obviously improve the water accumulation and infiltration performances in the topsoil and thus could be considered more suitable for rain-fed crop planting in the sloping farmlands of the loess region. However, CRP may be not suitable for the farmlands with steep slopes due to the possible low infiltration rates caused by high flow velocity and short retention times.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICTS OF INTEREST

The authors declare there is no conflict.

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