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Responses of vertical soil moisture to rainfall pulses and land uses in a typical loess hilly area, China

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Abstract

Soil moisture plays a key role in vegetation restoration and ecosystem stability in arid and semiarid regions. The response of soil moisture to rainfall pulses is an important hydrological process, which is strongly influenced by land use during the implementation of vegetation restoration measures. In this study, vertical soil moisture variations of woodland (*Pinus tabulaeformis*), native grassland (*Stipa bungeana*), shrubland (*Hippophea rhamnoides*), cropland (*Triticum aestivum*) and artificial grassland (*Onobrychis viciaefolia*) in five soil profiles were monitored in a typical loess hilly area during the 2010 growing season. The results demonstrated that rainfall pulses directly affected soil moisture variation. A multi-peak pattern of soil moisture appeared during the growing season, notably in the surface soil layer. Meanwhile, the response of each vegetation type to rainfall was inconsistent, and a time-lag effect before reaching the peak value was detected, following a heavy rainfall event. The response duration of soil moisture, however, varied markedly with the size of rainfall events. Furthermore, higher soil water content was detected in grassland and shrubland. Woodland was characterized by relatively lower soil moisture values throughout the investigation period. Our research suggests that vegetation restoration efforts should give priority to grassland and shrubland at the research site. We suggest that more studies should be focused on the characteristics of community structure and spatial vegetation distribution on soil moisture dynamics, particularly within the grass and shrub ecosystems.

1 Introduction

Soil moisture is widely recognized as a key factor influencing the success of vegetation restoration and rehabilitation efforts in semi-arid regions (Chen et al., 2007; Fernández-Gálvez et al., 2006; Legates et al., 2011; Porporato et al., 2002; Zhao et al., 2013). Consequently, it is imperative to survey the relationship among the water, soil and vegetation interactions, and to explore the synergy effect and feedback mechanisms of the responses of vegetation to precipitation (Cerdà, 1995; Ziadat and Taimeh, 2013; Gao et al., 2014). It follows that soil moisture is the core element functioning as a "cohesive tie" between vegetation and precipitation.

The receipt of water through precipitation is one of the primary factors controlling vegetation dynamics and net primary production in a specific territory. Pulsed rainfall regimes, in turn, affect and control belowground processes via soil wet–dry cycles (Austin et al., 2004). In the semi-arid ecosystem, soil wet–dry cycles are influenced by various aspects, such as soil properties, land cover, micro-landforms and meteorological environments (Legates et al., 2011; Yang et al., 2012). In addition, soil moisture dynamics are closely related to infiltration, evaporation, up take of water by roots and as a regulator controlling runoff between different organisms. Typically, soil moisture depends heavily on precipitation patterns (Koster et al., 2004; Weltzin and Tissue, 2003). In general, with regards to soil moisture responses to precipitation pulse, large precipitation event leads to significant soil moisture pulsation, whereas small rainfall events result in shallow infiltration of precipitation (Schwinning and Sala, 2004). Previous research revealed that soil water infiltrated continuously after surface soil was saturated when rainfall events exceeded 5.0 mm, which supplements the root layer effectively (Cerdà, 1997, 1999; Wei et al., 2008). Water balance and the hydrological cycle have always been the critical issues in vegetation restoration in water-controlled ecosystems. Therefore, effectively managing water resources and selecting appropriate vegetation types under limited rainfall conditions are the main tasks of re-vegetation projects in such areas.

The Loess Plateau of China is situated in the upper and middle reaches of the Yellow River. It is a transitional zone between the humid monsoon climate in the southeast and the dry climate in the northwest (Shi and Shao, 2000). Severe water erosion in this region has led to widespread environmental degradation. In order to improve the local eco-environment and prevent soil and water loss, the "Grain-for-Green" project was carried out by the central government in 1999. Most of the sloping crop-lands were converted to artificial forests and shrublands, and some farmlands were allowed to go fallow as grasslands. Additionally, this area has a unique environment in terms of vegetation survival hilly and gully, with intensive and extensive soil erosion and little, but centralized precipitation. Fast growing trees and shrubs have been introduced extensively in this region. Due to water restriction, however, the plants initially grew well but degraded over time, inducing severe soil desiccation (Li, 2001). Small aged trees with heights of 3–5 m were widely distributed and led to low ecosystem productivity. It is necessary to select the suitable vegetation patterns in terms of soil water balance. Therefore, understanding the response of vegetation to soil moisture dynamics is essential for optimizing vegetation structures and achieving the long-term sustainability of ecosystem restoration.

Several studies have demonstrated the effects of vegetation restoration on hydrology processes in the Loess Plateau and other similar regions around the world (Chen et al., 2010; Fu et al., 2013; Qiu et al., 2001; Shangguan and Zheng, 2006; Yang et al., 2014). For example, Chen (2008a) concluded that water hardly reached soil below 200 cm on the Loess Plateau, both under natural and simulated rainfall conditions. Li (2001) explored how soil infiltration impacted by rainfall events could reach 100 to 300 cm, with an average of 200 cm. Liu et al. (2010) found that shrubs were more adapted to annual rainfall variation than grasses were. Nevertheless, it is difficult to make generalizations concerning rainfall pulses and soil moisture dynamics. For instance, a series of small rainfall events is not equal to the same amount of rainfall occurring as a single event, which may lead to greater infiltration and runoff (Schwinning and Sala, 2004). In a way, rainfall distribution coupled with land uses, determines different variations of soil moisture for different vegetation types. In addition, many studies have focused on soil desiccation and investigated the excessive depletion of deep soil layers by artificial plants under long-term inadequate rainfall supply on the Loess Plateau (Chen et al., 2008b; Wang et al., 2004, 2011). However, an understanding of the deep mechanisms regarding the responses of soil moisture variation to rainfall pulses and land use remains incomplete. The major purpose of this paper, therefore, is to determine the response of soil moisture variations to rainfall pulses by in-situ consecutive monitoring of five typical vegetation types in the loess hilly area of China, including artificial grassland, cropland, shrubland, woodland and native grassland both during and after each rainfall pulse at plot scale.

2 Materials and methods

2.1 Study site

The study was conducted in the Anjiapo catchment, at the Dingxi Institute of Soil and Water Conservation Experimental Station (35°33′–35°35′ N, 104°38′–104°41′ E), which belongs to the Chinese Soil and Water Conservation Monitoring Network (Fig. 1). The study site represents a typical hilly region with gullies and elevations ranging from 1900 to 2240 m. The area of experimentation is located in a semi-arid temperate zone with an annual mean precipitation of 408 mm (1958–2004), more than 80 % of which falls from May to September. The mean annual temperature and, daily maximum and minimum temperatures are 6.3 °C, 34.3 °C in July, and –27.1 °C in January, respectively. The mean annual potential transpiration is 1510 mm. The mean length of the frost-free season is 141 d.

The soil at the study site is of the Calcic Cambisol group in the FAO-UNESCO classification system (FAO-UNESCO, 1974). It exhibits a unique texture composed of 50 % silt (0.01–0.05 mm), 39 % clay (< 0.01 mm) and 11 % sand (> 0.05 mm). The soil field capacity and organic matter at the study site are 18–24 % and 0.4–1.3 %, respectively. The soil bulk density ranges from 1.09 to 1.36 $\mathrm{g\,cm^{-3}}$ in the first 2 m of depth and the soil thickness varies from 40 to 60 m in the same region (Chen et al., 2007).

With the implementation of the Grain-for-Green project, Chinese pine (*Pinus tabulaeformis* Carr.), oriental arborcitae (*Platycladus orientalis*), purple alfalfa (*Medicago sativa*), sea buckthorn (*Hipporhae rhamnoides* L.) and littleleaf peashrub (*Caragana microphylla*) were widely planted. At present, land cover patterns in the study area include abandoned cropland, arable land, sloping cropland, native grassland, artificial grassland, shrubland and tree plantations. The main crops are millet (*Panicum miliaceum*), spring wheat (*Triticum aestivum* L.), potatoes (*Solanum tuberosum* L.), soybeans (*Vigna angularis*), sorghum (*Sorghum* spp.), and major grasses include *Stipa breviflora*, *Stipa bungeana* and *Thymis mongolicus*.

2.2 Experimental design and field installation

Twenty experimental plots were distributed on the hill slopes between 10 and 20° slopes, on which rain-fed crops (e.g. wheat, millet and potatoes) had been grown before the plots were constructed. Sample plots used for shrubland and pine woodland were 10 m × 10 m in size, and 10 m × 5 m in size, for the sloping cropland, artificial grassland and native grassland. The pine and sea buckthorn were planted in 1978, while the artificial grassland was planted when the plots were constructed in 1986. Cement ridges 30 cm above the ground were constructed at the plot borders, while an H-flume was used to measure the surface runoff at the outlet of each plot (Fig. S1). Four replications were investigated for each vegetation pattern.

Pine trees were planted in the woodland plots with a mean density of 3.0 m × 1.5 m. Little grass was scattered on the surface of the plots. The shrubland plot was dominated by sea buckthorn (*Hippophea rhamnoides*), with 1 m distance between rows. During the growing season, dense grasses and thick litter provided a closed cover. For the research, plant residues were kept in the plots. *S. bungeana*, a dominant native species was sown in the semi-natural grassland plots. In the cropland, *T. aestivum* was sown in April and harvested manually at the end of July or the beginning of August, and the plant residues were kept in the plots. Additionally, the artificial grassland plots were covered with Sainfoin (*Onobrychis viciaefolia*) with a height of approximately 0.50 m, which was also harvested manually for livestock.

A total of 10 soil moisture and temperature smart sensors were installed in every plot at 5 depths below the ground. Both the soil moisture and temperature levels of 0–100 cm profiles were measured for every 20 cm of depth from May to September (the growing season) of 2010. A pit of appropriate width was dug to allow the probes

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to be inserted into the soil profile of each plot. Then, the probes were inserted into the unaltered side of the pit and were fixed horizontally in the direction of the maximum slope of each plot. The pits were refilled carefully after the probes were inserted into the soil profile. During this process, it was necessary to avoid any perturbations to the greatest extent possible. The completion of the probe took place at the end of 2009, and the monitoring was not begun until the soil settled, approximately three months later.

2.3 Measurement sensor

Soil moisture smart sensors with S-SMC-M005 probes were installed to measure the moisture of the soil profile. Meanwhile, 12 bit temperature smart sensors with S-TMB-M006 probes were prepared to monitor the soil profile temperature. Both the soil moisture and temperature smart sensors were designed to work with smart sensor-compatible HOBO data loggers (Decagon Devices Inc., Pullman, WA).The S-SMC-M005 soil moisture smart sensor is capable of providing reading outside the standard volumetric water content range with an accuracy of ±1.0 %. All the data were recorded every 10 min using HOBO data loggers. At the same time, the precipitation from each natural rainfall event was measured using a tipping-bucket gauge. The meteorological parameters (solar radiation, air temperature and, wind velocity) were collected as 10 min averages by an automatic weather station installed in the meteorological garden approximately 1000 m away from the plot.

2.4 Statistical analysis

Since the experiments were carried out at the plot level, the environment factors exhibited homogeneous characteristics for different vegetation types. Therefore, the temporal dynamics of soil moisture and its relationship with vegetation type were analyzed. The average soil moisture of specific vegetation types and depths were calculated using Eq. (1), as follows (Chen et al., 2007):

$$S_{ij} = \frac{1}{4 \times n} \sum_{m=1}^{4} \sum_{k=1}^{n} S_{ijmk} \tag{1}$$

Where S_{ij} is the volumetric soil water content ($\text{cm}^3\,\text{cm}^{-3}$) of ith vegetation pattern at jth depth; S_{ijmk} is the actual value of volumetric soil water content ($\text{cm}^3\,\text{cm}^{-3}$) measurement each time; n is the total number of volumetric soil water content monitoring from May to September in 2010 and number 4 is the replications.

At the same time, we assumed that the volumetric soil water content was measured with probes precisely matching different layers in the soil profile (Wang et al., 2012). According to the principle of soil water balance, the cumulative water loss can therefore be calculated by Eq. (2), as follows:

$$\text{WL}_i = (S_{\text{b}i} - S_{\text{e}i}) \times D \tag{2}$$

Where WL_i is the cumulative loss water (mm) of ith vegetation type; $S_{\text{b}i}$ is the initial volumetric soil water content ($\text{cm}^3\,\text{cm}^{-3}$) of ith vegetation type and $S_{\text{e}i}$ is the volumetric soil water content ($\text{cm}^3\,\text{cm}^{-3}$) of ith vegetation type at the end stage. D is the depth (mm) of the measurement.

Data on soil moisture and soil temperature were analyzed to provide mean and standard deviation (SD) for each variable measured at every depth in each plot. Analysis of variance was performed using the MIXED procedure in SAS, which computes Wald-type F-statistics using generalized least squares (GLSE) based on restricted maximum likelihood estimates of the variance components (Littll et al., 1996). In the case of significant differences in the Wald-F-statistic at $P < 0.05$, treatment means were compared using a LSD test. All statistical analyses were conducted using the SAS software package (SAS, 2000).

3 Results

3.1 Rainfall features in the study area

As shown in Fig. 2, seventy-six rainfall events occurred during observation period (1 April–31 October) in 2010, with the cumulative rainfall reaching 322.6 mm. The total rainfall for the growing season (1 May–30 September) was 292.8 mm, accounting for 90.1 % of the observation period. The maximum and minimum daily rainfall was 27.8 and 0.2 mm, respectively. Daily rainfall greater than 25 mm occurred on four occasions: 25 May (25.8 mm), 29 June (27.8 mm), 16 July (25.0 mm) and 7 August (27.8 mm), respectively, accounting for 32.9 % of the total rainfall for the growing season. On six occasions, daily rainfall was greater than 10 mm, and eleven times it was between 10 and 5 mm. On 47, daily rainfall events less than 5 mm occurred during the growing season. Overall, the study area mainly experienced small rainfall events, with heavy rainfall events occurring less frequently. The total rainfall during the growing season, however, was strongly influenced by the heavy rainfall regimes. Therefore, the rainfall characteristics of the experimental site were typical pulse rainfall events of the semi-arid zone.

3.2 Seasonal variation pattern and pulse of soil moisture

The trends of soil moisture variation of the five vegetation types exhibited a similar seasonal variation during the growing season, particularly in the 0–20 cm soil layer (Figs. 2 and 3). Native grassland had the highest soil moisture (5 June) while the cropland had the lowest (2 August). In the top soil layer (0–20 cm), the seasonal changes in soil moisture were apparent, and each vegetation type had four peak values based on time under rainfall conditions. However, there was no consistency in the way each vegetation type to reached its peak value. Furthermore, three-peak, double-peak and single-peak phenomena were obviously present during the growing season (Fig. 2), particularly after heavy rainfall (> 25 mm) at 0–20 cm. Additionally, a hysteresis effect was apparent following a heavy rainfall event when the peak value was reached. For instance, during the investigation period from 25 May to 28 June, after the heavy rainfall pulse (25 May, 25.8 mm) occurred, different types of vegetation exhibited three peak value phenomena in the top soil layer, with the three peak times for the shrubland taking place on 27 May, 4 and 10 June; for the crop land on 27 May, 1 and 8 June; the artificial grassland on 29 May, 3 and 9 June; while the woodland on 26 May, 2 and 10 June, and the native grassland on 26 May, 1 and 11 June, respectively. These times, therefore, represented the relatively wetter conditions of the soil. The degree of the soil moisture variation dramatically decreased with increased soil depth.

As shown in Fig. 4, little rainfall occurred from 5 to 14 July, 20 July to 3 August, 22 to 28 August and 8 to 19 September. Meanwhile, no rainfall event happened from 9 to 28 June. During these periods, soil volumetric water content declined continuously. However, the minimum mean value for each vegetation type occurred at different times in various decreasing stages. For instance, during the experimental period from 9 to 28 June, before the second heavy rainfall event happened during the growing season (29 June, 27.8 mm), no rainfall was recorded on these days. The minimum mean value took place on 27 June for the cropland ($0.074\,\mathrm{cm^3\,cm^{-3}}$), the woodland ($0.079\,\mathrm{cm^3\,cm^{-3}}$) and the shrubland ($0.085\,\mathrm{cm^3\,cm^{-3}}$) on 29 June, and the native grassland ($0.090\,\mathrm{cm^3\,cm^{-3}}$) on 28 June. In contrast, the minimum mean value for the artificial grassland ($0.089\,\mathrm{cm^3\,cm^{-3}}$) appeared on 30 June, after the second heavy rainfall event. These days represented the time at which the drier soil conditions occurred for the various vegetation types. In general, for all of the rainfall regimes during the investigated growing season, largely similar curves with obviously different trends in soil moisture variation were clearly exhibited among the different vegetation types. There was no doubt that the variability in soil moisture depended heavily on precipitation.

3.3 Soil moisture variation of different types of vegetation

The mean volumetric water contents of the 0–100 cm soil profile were shown in Table 1. Soil moisture variation was different at different soil depths. There was no significant difference between all types of vegetation at the depth of 60–80 and 80–100 cm during the growing season. For the cropland and shrubland, the volumetric water contents exhibited significant differences at different depths in different months ($P < 0.05$). For the other 3 vegetation types, in contrast, no significant differences were observed during the entire observation period ($P > 0.05$). Taking cropland as an example, in May, the volumetric water content at the 10–20 and 20–40 cm levels were significantly greater than at 80–100 cm ($P < 0.05$), while there was no significant difference among the 0–20, 20–40 and 40–60 cm levels ($P > 0.05$). Although the volumetric water content in the 20–40 cm level was significant higher than the 80–100 cm level ($P < 0.05$), no significant difference was observed among the 20–40, 40–60 and 60–80 cm levels ($P > 0.05$). The significant difference of the cropland in May was consistent with June. In July, August and September, the volumetric water content in the 10–20 cm level was significantly greater than the 60–80 and 80–100 cm levels ($P < 0.05$), whereas no significant difference exhibited between 0–60 and 20–100 cm ($P > 0.05$). On the whole, the value of volumetric water content was higher in the grassland and the shrubland sites, whereas the woodland showed lower soil moisture values.

The average soil temperature showed similarly the same regime among different cover patterns (Fig. 5). The lowest soil temperature was recorded in the shrubland (18 May) while the highest soil temperature was recorded in the cropland (31 July). There was a significant linear correlation between the soil temperature and the atmospheric temperature for each vegetation type during the investigation period ($P < 0.01$). Clearly, shrubland and woodland have lower soil temperatures than the other three vegetation patterns. The mean minimum daily soil temperature of each vegetation type appeared in May, and it did not decrease gradually until the end of August. The mean daily maximum soil temperature was at the end of July or the beginning of August. Although the soil temperature gradually declined in September, the monthly average soil temperature of each vegetation type in September was still higher than in May.

3.4 Soil moisture decreases

In light of the responses of soil moisture variation to the rainfall pulse, stepwise regression was used to analyze the soil volumetric water content profile distributions from 9 to 28 June, 5 to 14 July and from 20 July to 3 August (Fig. 6). At the same time, three typical decreasing periods in these 3 stages were selected to depict the differences in the water loss rate of different vegetation types. The slope of regression equation between soil depth and soil moisture indicated that the characteristics of differences in soil volumetric water content were along the soil profile. Regression analysis showed that different vegetation types responded differently to the rainfall events at different periods. For example, from 9 to 28 June, the slope was smallest in the woodland and greatest in the shrubland. Artificial grassland, native grassland and cropland showed an intermediate level, successively. From 5 to 14 July, the slope was also greatest in shrubland, followed by native grassland, woodland and cropland, respectively. Artificial grassland had the smallest slope. From 20 July to 3 August, the slope was smallest in artificial grassland, while greatest in woodland and shrubland. This result indicated that the soil volumetric water content of woodland and shrubland changed dramatically with the increase in soil depth, and the comparison of soil volumetric water content profile distributions revealed that it was easier for water to travel vertically in this stage. Generally speaking, the slope was smaller in cropland and grassland, while shrubland and woodland showed a higher slope, relatively.

Different vegetation types exhibit different daily and cumulative water loss at different periods (Fig. 7). From 11 to 27 June, the beginning of the average soil volumetric moisture content was 0.10 $\mathrm{cm^3\,cm^{-3}}$. The native grassland missed the maximum of water, nearly 23.5 mm in half a month. The daily water loss trend was similar to an inverted "V", whereas the woodland lost the minimum of water, only 2.3 mm. In addition, the daily variation of soil moisture was lower and more stable for the woodland than for the other vegetation types, ranging from 0.1 to 0.4 mm. However, the daily soil moisture of the cropland showed the most variability, with a range of variation from 0.89 to

3.0 mm. The cumulative soil water loss of cropland was 20.8 mm, just behind the native grassland. Finally, the artificial grassland and the shrubland exhibited a medium level of loss, with cumulative water loss of 16.2 and 15.5 mm, respectively. In the meantime, the daily soil water loss of the artificial grassland showed an increasing trend.

During another two investigated periods (from 6 to 16 July and from 20 July to 1 August), there was a corresponding change of soil water loss for different vegetation types. From 6 to 16 July, the cumulative soil water loss of the artificial grassland was lowest (2.9 mm), while it was highest for the native grassland and cropland (10.4 mm). The soil water loss in shrubland was slightly lower than in cropland and the native grassland. The cumulative soil water loss of woodland was lower than the shrubland and higher than the artificial grassland. The daily soil water loss trend of woodland was similar but slightly higher than for the artificial grassland. Meanwhile, cropland and native grassland presented the most variability, ranging from 0.4 to 1.5 mm and from 0.5 to 1.6 mm, respectively. However, from 20 July to 1 August, the cumulative water loss of the artificial grassland was the highest (14.6 mm) and the woodland was the lowest (4.1 mm). The cropland, shrubland and native grassland presented an intermediate level, with average daily losses of 0.85, 0.96 and 1.01 mm, respectively. To summarize, the daily soil water loss trends of shrubland and woodland were more stable than other types during the observation periods, although the cumulative water loss of woodland was relatively lower than in the other types. The daily soil water loss of cropland and native grassland showed more dramatic changes than the other types of vegetation, whereas the cumulative water loss of artificial grassland exhibited strong instability compared with other vegetation types.

4 Discussion

4.1 Effects of rainfall features on soil moisture variation

The hydrological response of semi-arid ecosystems is mainly controlled by rainfall regimes. Temporal variations of soil moisture showed a close relationship with precipitation and varied among different vegetation types and periods. In a word, soil moisture was recharged and regulated by precipitation. In our study, an increasing trend in soil moisture appeared after heavy rainfall events, but there were buffer effects following rainfall events based on the groundcover. The results are consistent with the published values of Fu (Fu et al., 2003), who also conducted studies in a semi-arid region of the Loess Plateau. In addition, in semi-arid ecosystems, small rainfall events that cause surface wetness to occur are more frequent than large events that lead to deeper infiltration (Schwinning and Sala, 2004). Rainfall amount and the number of days between rainfall pulses clearly influenced the soil moisture variation, when events occur in close succession to one another (Loik et al., 2004). Results of the different peak value time of different vegetation types could be explained by the differences in the number of days between rainfall and the physical properties of the soil. Close succession of the rainfall events provided an additive effect. Soil moisture depended strongly on precipitation. Soil moisture variation was basically the same as the rainfall patterns. The "impulse type" both of the soil moisture variation and the rainfall regimes are the direct manifestation, particularly in the top soil layer. However, the peak value time of the 20–40 and 40–60 cm levels exhibited temporal difference compared with the 60–80 and 80–100 cm levels. The soil moisture trend began to flatten with increased soil depth. The result indicated that soil water infiltration was different among different vegetation types. Meanwhile, it also revealed that different vegetation types have different water use strategies in different periods, based on the different types of response to rainfall pulses. Finally, the characteristic of soil moisture variation suggested that the replenishment of precipitation for the deep layer was limited.

Usually, shrubs and grasses have greater root abundance than crops (Jackson et al., 1996), and root decomposition processes change the soil structure and increase rainfall infiltration due to, the channels left after the decomposition. Therefore, the results showed that grassland exhibits marked trends of soil moisture variation in the deep soil layer, whereas cropland, shrubland and woodland exhibited more stable trends. Different vegetation types showed similar seasonal moisture variation but there were differences between certain stages. Particularly, soil moisture variation of shrubland and cropland showed significant differences at different soil depths. The fact that all land use types existed at different water depletion layers is likely related to the differences in the root distributions along soil profiles. Moreover, although some water recharge occurred during the growing season, the soil moisture level at the end of September was obviously lower than at the beginning of early May, with the exception of woodland. Soil moisture of woodland at the end of September was close to what it was in early May, indicating that the rainfall pulse had less effect on the soil moisture of the woodland plot. This is partly due to the interception, as discussed in the next section. Overall, a strong trend of soil water recharge was observed from June to August, whereas only a slight one was observed in September.

4.2 Soil water decreases

Soil moisture is depleted over days and weeks primarily by plant uptake, transpiration and soil evaporation. Soil evaporation takes place at the shallow layer with lower root density and varies temporally based on available energy, as reflected in soil temperature values, which themselves lag behind solar radiation inputs (Loik et al., 2004). Therefore, temperature can be considered one of the key factors leading to soil water loss under high soil moisture content conditions. In our research, artificial grassland, native grassland and cropland exhibited relatively higher soil temperatures, corresponding to greater water loss. However, water loss of artificial grassland showed different trend at different periods. From 5 to 15 July, the smallest regression slope of soil moisture and depth curve were found in artificial grassland compared to other types. This revealed that water more easily travelled vertically in artificial grassland. The amount of infiltration in this process was greater than water loss. At the same time, a relatively higher slope of cropland and native grassland was apparent during the typical decreasing moisture periods, indicating strong interaction between plant uptake and soil moisture as depth increased.

On the other hand, for the native grassland and cropland, poor cover types also led to greater daily water losses via direct evaporation at shallow depth. Soil evaporation varies temporally mainly due to available energy. Hence, the daily water loss of cropland and native grassland showed more dramatic changes during the investigated stages. Furthermore, the temperature at the woodland plot was slightly higher than that of the shrubland. This result is consistent with the conclusion of Wang et al. (2012). However, the amount of water loss was smaller compared with the shrubland, cropland and native grassland. The reason for the small amount of water loss in the woodland was interception during the water budget. Crown interception of woodland, clearly, is the first process that diminishes precipitation input to the soil. The foliage has a holding capacity and can intercept all water from small rainfall events, but only a small portion of the water from large rainfall events (Loik et al., 2004; Waring and Running, 2010). During the investigated period, small rainfall events occurred more frequently than heavy rainfall events. The crown interception changed the way and amount in which rainfall came into the soil. Therefore, the smaller the amount of rainfall that infiltrated the woodland, the lower the water loss caused. Throughout the growing season, soil moisture at the end of September was close to that of early May. For the shrubland, the slope of regression equation between soil moisture and depth was the highest. It could be judged that intense interaction occurred between soil moisture and depth, due to the strong root system of the shrub.

4.3 Inspirations for vegetation restoration

Severe scarcity of water resources and land use changes led to the degradation of ecosystem functioning in the semi-arid areas (Cerdà, 1999; Cerdà and Doerr, 2005, 2007; Dickie and Parsons, 2012), also linked to the Loess Plateau of China. Although comprehensive soil and water loss control has achieved some degree of success, it dire challenges remain to be confronted.

As some authors have previously suggested, different mosaic patterns should be implemented in different area of the Loess Plateau (Fu et al., 2013; She et al., 2010). With the implementation of the Grain-for-Green project, most sloping croplands were converted to woodland, shrubland and grassland. The most critical experience factor in remedying soil and water erosion is to make the rainfall infiltrate locally. However, due to the crown interception, the amount of rainfall infiltrating woodland is lower than the amount infiltrating shrubland, artificial grassland and native grassland. Therefore, trees were not suitable for large area vegetation restoration. According to Jiang et al. (2013) in terms of pollen records, herbs rather than 11 trees and shrubs should be used for the vegetation restoration programs, but it was inappropriate to select simple vegetation types during the vegetation restoration on a large scale. On the other hand, because of the efficient impediment effects and high survival rate, shrubland was widely adopted in the semi-arid areas, considering the fact that native grassland and artificial grassland can retain more soil moisture. Consequently, our research advocates that a well-matched mosaic vegetation pattern of planting shrub and grass would be appropriate in the study area. Overall, it is imperative that we take drastic measures in the future to research the mechanisms surrounding the influence of community structure characteristics and spatial distribution patterns on soil moisture dynamics, both of the grassland and the shrubland ecosystem of the Loess Plateau.

5 Conclusions

The responses of vertical soil moisture variation to rainfall pulses and land uses were studied in a typical loess hilly area of the Loess Plateau in the 2010 growing season. At the study site, the only source of water is precipitation. Redistribution of precipitation by different vegetation types probably causes the variability of soil moisture under different rainfall pulses. Soil moisture in the surface layer was significantly affected by precipitation. For the five vegetation types, peak value time of soil moisture appeared after rainfall pulse with a buffer effect and the trend of the soil moisture began to flatten with increased soil depth. The result showed that soil water infiltration was different among the different vegetation types, which indicates that different vegetation may have different water use strategies in different periods. Meanwhile, the characteristic of soil moisture variation suggested that the replenishment of precipitation for the deep layer was limited. During the investigation period, under the influence of interception, smaller amounts of rainfall infiltration occurred under the woodland with lower water loss caused. Grassland and shrubland, however, showed higher soil moisture content. At the same time, the interaction between soil moisture and vegetation has vital implications to optimize vegetation structure and landscape functioning. Our research suggests that vegetation restoration should give priority to shrubland and grassland in the study region. Hence, further studies should mainly attempt to elucidate the influence of community structure characteristics and spatial distribution patterns on soil moisture dynamics, involving both grassland and shrubland ecosystems.

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Table 1. Soil moisture variation of five vegetation types during the growing season.

Months	Depth (cm)	Volumetric water content (cm^3 cm^{-3})				
		Artifical grassland	Cropland	Shrubland	Woodland	Native grassland
May	0–20	0.12 ± 0.02 Aa	0.12 ± 0.01 Aa	0.12 ± 0.05 Aa	0.08 ± 0.04 Aa	0.11 ± 0.03 Aa
	20–40	0.11 ± 0.02 Aa	0.10 ± 0.02 ABa	0.10 ± 0.04 ABa	0.08 ± 0.03 Aa	0.12 ± 0.04 Aa
	40–60	0.09 ± 0.03 Aa	0.09 ± 0.02 ABCa	0.07 ± 0.02 ABa	0.07 ± 0.04 Aa	0.10 ± 0.04 Aa
	60–80	0.08 ± 0.03 Aa	0.07 ± 0.03 BCa	0.06 ± 0.02 ABa	0.06 ± 0.02 Aa	0.08 ± 0.04 Aa
	80–100	0.07 ± 0.03 Aa	0.05 ± 0.02 Ca	0.06 ± 0.03 Ba	0.06 ± 0.03 Aa	0.06 ± 0.03 Aa
	0–100	0.09 ± 0.03 a	0.08 ± 0.03 a	0.08 ± 0.04 a	0.07 ± 0.03 a	0.10 ± 0.04 a
Jun	0–20	0.13 ± 0.02 Aa	0.11 ± 0.01 Aa	0.14 ± 0.03 Aa	0.11 ± 0.04 Aa	0.12 ± 0.03 Aa
	20–40	0.12 ± 0.02 Aa	0.10 ± 0.02 ABa	0.13 ± 0.02 Aa	0.09 ± 0.03 Aa	0.14 ± 0.04 Aa
	40–60	0.10 ± 0.03 Aa	0.09 ± 0.01 ABCa	0.09 ± 0.03 Aba	0.07 ± 0.04 Aa	0.10 ± 0.02 Aa
	60–80	0.09 ± 0.03 Aa	0.07 ± 0.02 BCa	0.06 ± 0.02 Ba	0.06 ± 0.02 Aa	0.09 ± 0.04 Aa
	80–100	0.07 ± 0.03 Aa	0.06 ± 0.02 Ca	0.06 ± 0.02 Ba	0.06 ± 0.02 Aa	0.07 ± 0.02 Aa
	0–100	0.10 ± 0.03 a	0.08 ± 0.02 a	0.09 ± 0.03 a	0.08 ± 0.03 a	0.10 ± 0.04 a
Jul	0–20	0.10 ± 0.02 Aa	0.10 ± 0.01 Aa	0.12 ± 0.03 Aa	0.11 ± 0.04 Aa	0.12 ± 0.03 Aa
	20–40	0.10 ± 0.02 Aa	0.08 ± 0.01 ABa	0.10 ± 0.02 ABa	0.10 ± 0.03 Aa	0.12 ± 0.04 Aa
	40–60	0.09 ± 0.03 Aa	0.08 ± 0.01 ABa	0.09 ± 0.02 ABa	0.08 ± 0.04 Aa	0.10 ± 0.02 Aa
	60–80	0.09 ± 0.04 Aa	0.07 ± 0.01 Ba	0.07 ± 0.02 Ba	0.06 ± 0.02 Aa	0.09 ± 0.03 Aa
	80–100	0.08 ± 0.03 Aa	0.06 ± 0.02 Ba	0.06 ± 0.02 Ba	0.07 ± 0.02 Aa	0.07 ± 0.04 Aa
	0–100	0.09 ± 0.02 a	0.08 ± 0.01 a	0.09 ± 0.03 a	0.09 ± 0.03 a	0.10 ± 0.04 a
Aug	0–20	0.08 ± 0.01 Aa	0.13 ± 0.05 Aa	0.10 ± 0.04 Aa	0.09 ± 0.02 Aa	0.10 ± 0.04 Aa
	20–40	0.08 ± 0.01 Aa	0.09 ± 0.02 ABa	0.09 ± 0.03 Aa	0.09 ± 0.01 Aa	0.10 ± 0.04 Aa
	40–60	0.07 ± 0.02 Aa	0.08 ± 0.01 ABa	0.08 ± 0.02 Aa	0.07 ± 0.03 Aa	0.11 ± 0.04 Aa
	60–80	0.08 ± 0.03 Aa	0.07 ± 0.01 Ba	0.07 ± 0.02 Aa	0.06 ± 0.02 Aa	0.09 ± 0.03 Aa
	80–100	0.07 ± 0.03 Aa	0.06 ± 0.02 Ba	0.06 ± 0.02 Aa	0.07 ± 0.02 Aa	0.07 ± 0.04 Aa
	0–100	0.07 ± 0.02 a	0.09 ± 0.03 a	0.08 ± 0.02 a	0.08 ± 0.02 a	0.09 ± 0.03 a
Sep	0–20	0.07 ± 0.01 Aa	0.09 ± 0.02 Aa	0.08 ± 0.03 Aa	0.08 ± 0.01 Aa	0.09 ± 0.03 Aa
	20–40	0.07 ± 0.01 Aa	0.08 ± 0.02 ABa	0.08 ± 0.02 Aa	0.08 ± 0.01 Aa	0.10 ± 0.04 Aa
	40–60	0.07 ± 0.01 Aa	0.08 ± 0.01 ABa	0.08 ± 0.02 Aa	0.07 ± 0.02 Aa	0.09 ± 0.03 Aa
	60–80	0.08 ± 0.02 Aa	0.07 ± 0.01 ABa	0.06 ± 0.02 Aa	0.06 ± 0.02 Aa	0.09 ± 0.03 Aa
	80–100	0.06 ± 0.02 Aa	0.05 ± 0.02 Ba	0.06 ± 0.02 Aa	0.07 ± 0.01 Aa	0.06 ± 0.03 Aa
	0–100	0.07 ± 0.01 a	0.08 ± 0.02 a	0.07 ± 0.02 a	0.07 ± 0.01 a	0.09 ± 0.03 a

Values are mean ± SD ($n = 4$ for each vegetation type). Different uppercase letters indicate significant differences in different soil depths, different lowercase letters indicate significant differences in different vegetation patterns ($P < 0.05$).

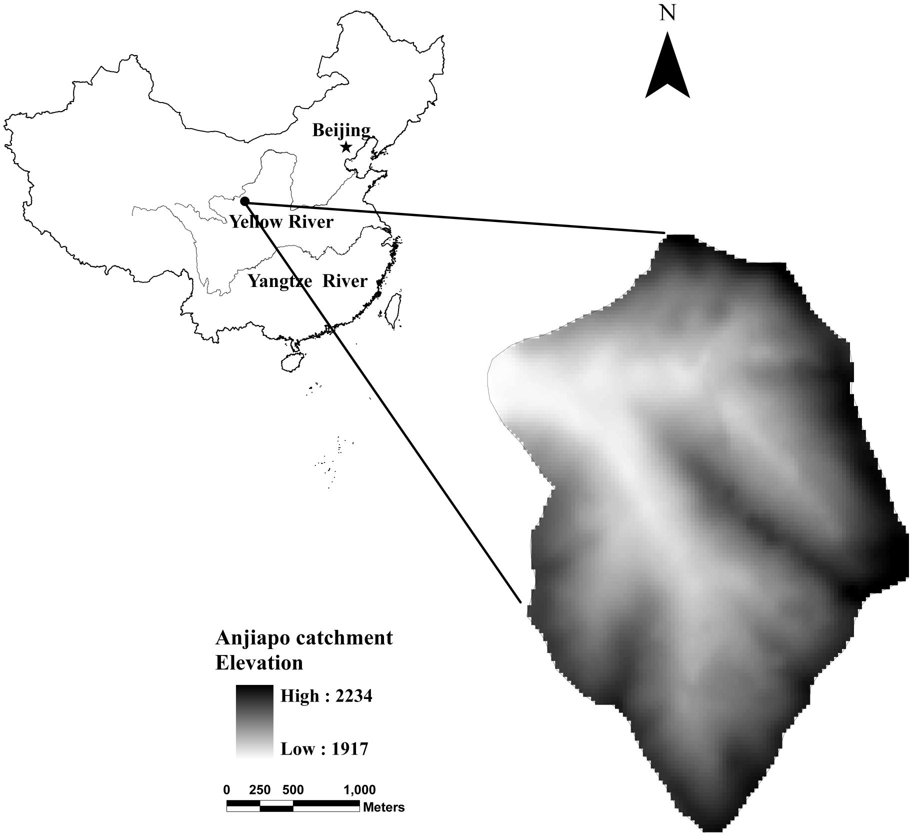

Figure 1. Location of the study site (Anjiapo catchment).

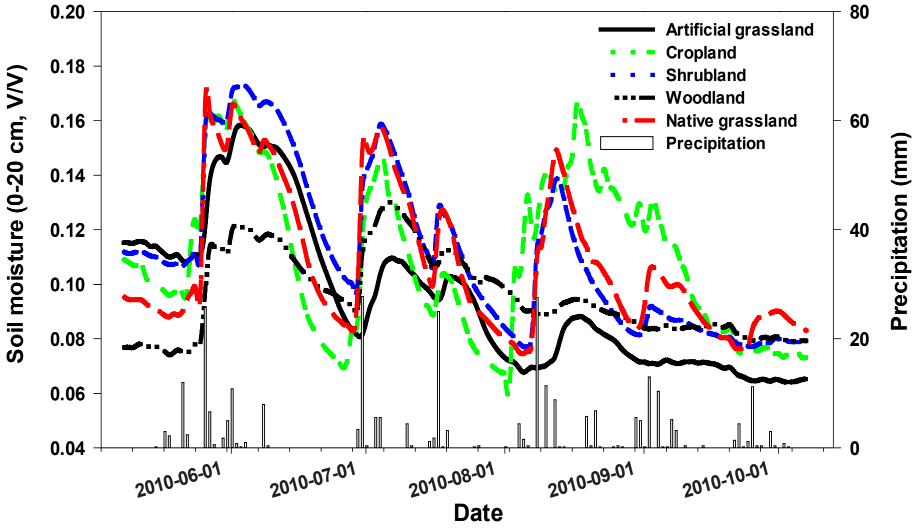

Figure 2. Characteristics of soil moisture variation in the 0–20 cm of five vegetation types.

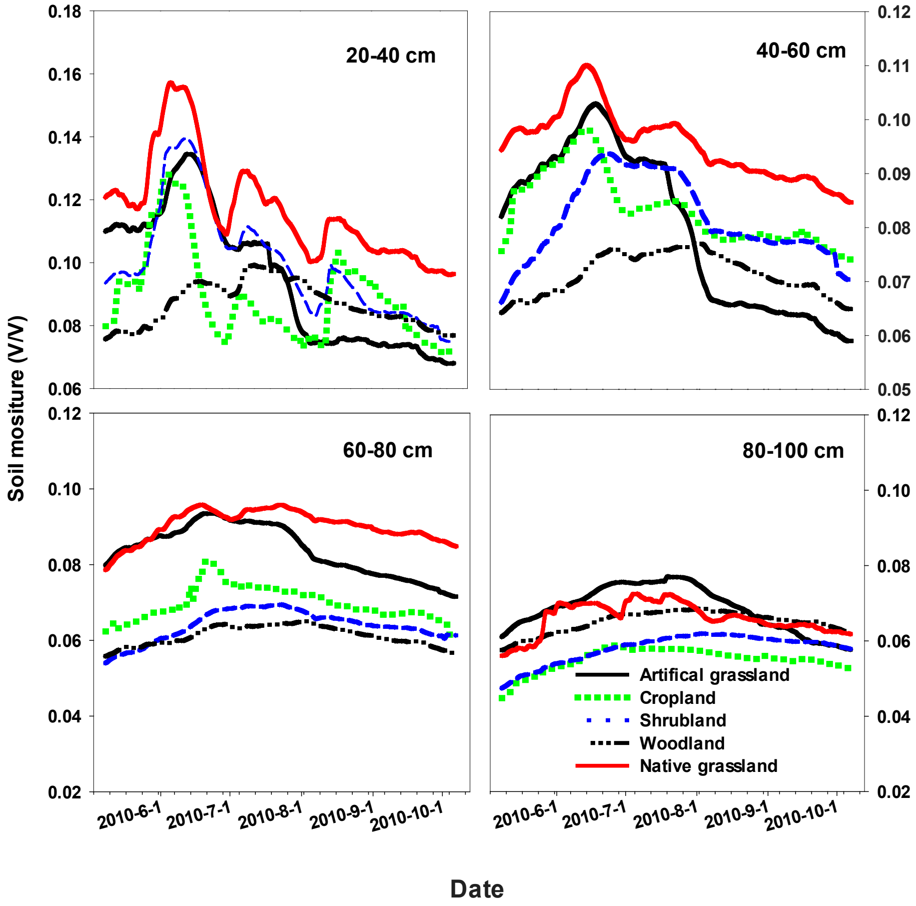

Figure 3. Characteristics of soil moisture variation in the 20–100 cm zone of five vegetation types.

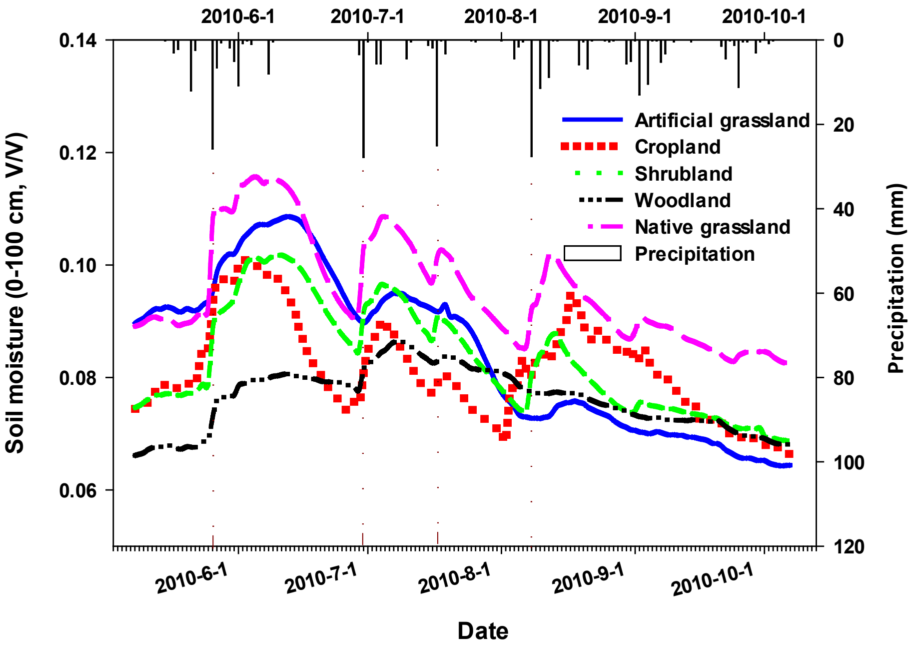

Figure 4. Characteristics of soil moisture variation during the growing season of five types of vegetation.

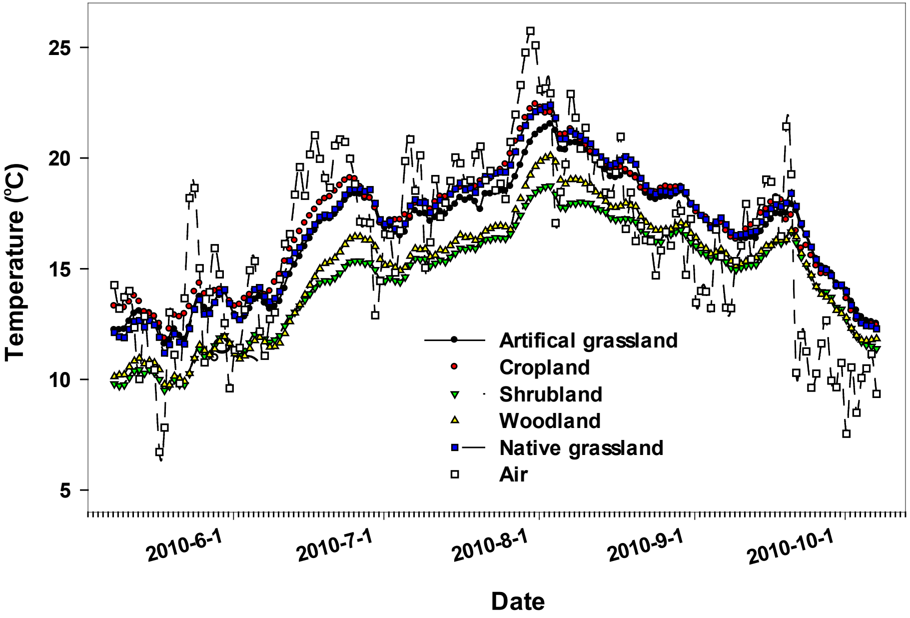

Figure 5. Characteristic of soil temperature variations of five vegetation patterns.

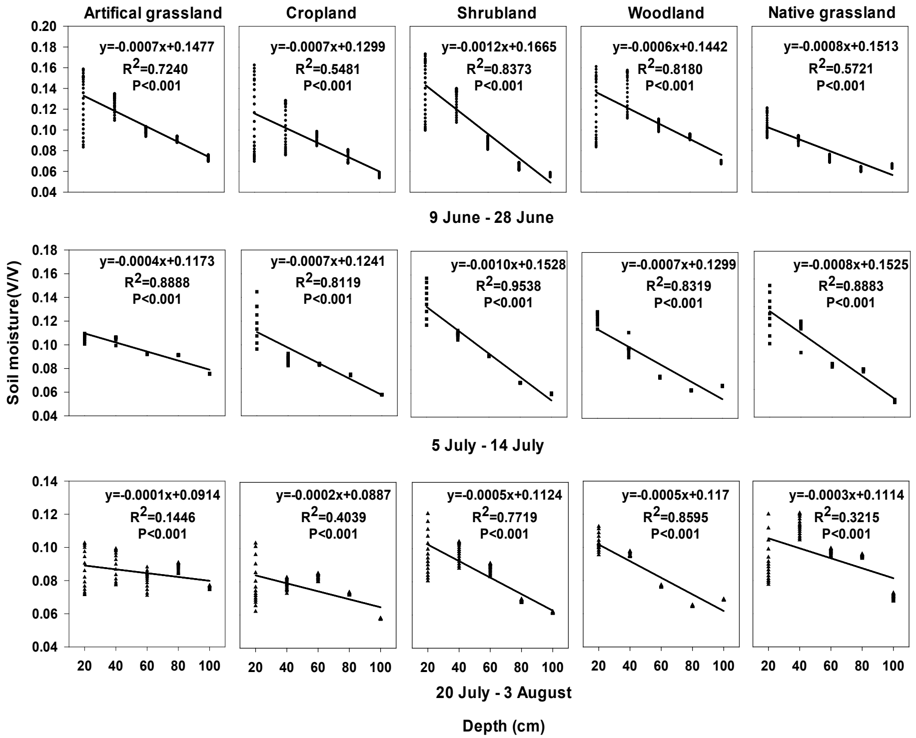

Figure 6. Relationship between soil moisture content and soil depth after each rainfall event.

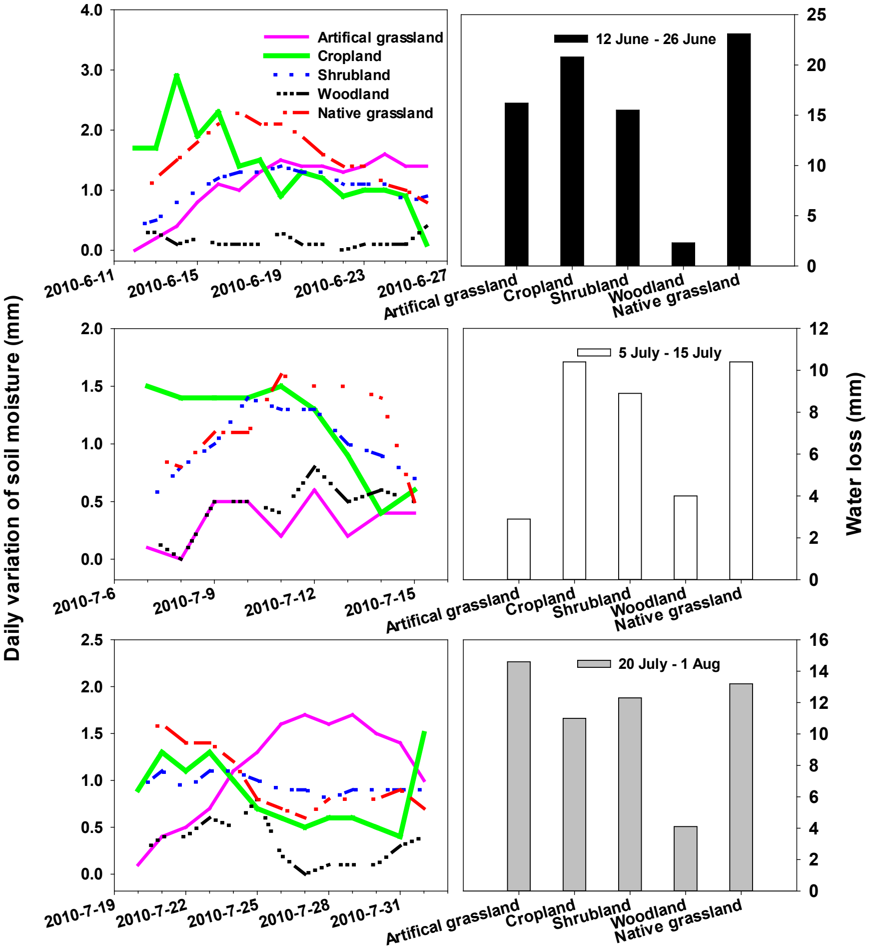

Figure 7. Daily variation of soil moisture and cumulative soil water loss after a rainfall event under five vegetation types.