Seasonal Dynamics of Soil Water Content in Typical Vegetation and Its Response to Precipitation in a Semi-arid Area of the Chinese Loess Plateau (Postprint)

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Abstract

Soil water content is a key limiting factor for vegetation growth in the semi-arid area of Chinese Loess Plateau and precipitation is the main source of soil water content in this area. To further understand the impact of vegetation types and environmental factors such as precipitation on soil water content, we continuously monitored the seasonal dynamics in soil water content in four plots (natural grassland, Caragana korshinskii, Armeniaca sibirica and Pinus tabulaeformis) in Chinese Loess Plateau. The results show that the amplitude of soil water content fluctuation decreases with an increase in soil depth, showing obvious seasonal variations. Soil water content of artificial vegetation was found to be significantly lower than that of natural grassland, and most precipitation events have difficulty replenishing soil water content below a depth of 40 cm. Spring and autumn are the key seasons for replenishment of soil water by precipitation. Changes in soil water content are affected by precipitation, vegetation types, soil evaporation and other factors. The interception effect of vegetation on precipitation and the demand for water consumption by transpiration are the key factors affecting the efficiency of soil water replenishment by precipitation in this area. Due to artificial vegetation plantation in this area, soil will face a water deficit crisis in the future.

Full Text

Preamble

Seasonal Dynamics of Soil Water Content in Typical Vegetation and Its Response to Precipitation in a Semi-Arid Area of the Chinese Loess Plateau

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Abstract: Soil water content is a key limiting factor for vegetation growth in the semi-arid Chinese Loess Plateau, where precipitation serves as the primary source of soil moisture. To further understand how vegetation types and environmental factors such as precipitation influence soil water content, we continuously monitored seasonal dynamics in four plots (natural grassland, *Caragana korshinskii*, *Armeniaca sibirica*, and *Pinus tabulaeformis*) throughout 2020. Our results show that the amplitude of soil water content fluctuations decreases with increasing soil depth, while exhibiting pronounced seasonal variations. Soil water content under artificial vegetation was significantly lower than that under natural grassland, and most precipitation events failed to replenish moisture below 40 cm depth. Spring and autumn emerged as critical seasons for precipitation-driven soil water replenishment. Changes in soil water content were influenced by precipitation, vegetation type, soil evaporation, and other factors. The interception of precipitation by vegetation and water consumption through transpiration represent key factors affecting the efficiency of soil water replenishment in this region. Due to artificial vegetation plantations, the soil will likely face a water deficit crisis in the future.

Keywords: soil water content; vegetation type; precipitation; seasonal change; evaporation

1 Introduction

Soil water content is a critical factor governing vegetation growth and survival in semi-arid regions (Shao et al., 2014) and plays a vital role in ecosystem ecohydrological cycles (Daly and Porporato, 2005). At the plot scale, the independent and interactive effects of precipitation, vegetation types, soil properties, and other factors create extreme heterogeneity in soil water content (Grayson et al., 1997). Precipitation serves as the main source of soil water replenishment in semi-arid areas and represents a key factor influencing soil moisture dynamics (Wilson et al., 2004). Due to high potential evapotranspiration in semi-arid regions, small precipitation events often have minimal impact on soil water content (Kurc and Small, 2007). When precipitation amounts increase, water can penetrate deeper soil profiles (Schwinning and Sala, 2004). Additionally, vegetation type plays a crucial role in precipitation effectiveness (Schlueter et al., 2013). Vegetation influences soil water input through canopy interception, hydraulic redistribution, and soil organic matter content (Odindi and Kakembo, 2011), while affecting output through evaporation, transpiration, and infiltration processes (Pan et al., 2008). Through regulating these inputs and outputs, vegetation can achieve a stable dynamic equilibrium (Yu et al., 2018), though this may result in continuous soil water depletion (Zhao et al., 2017). For instance, transpiration-induced soil water depletion in shrublands tends to be more severe than in grasslands (Schlueter et al., 2013). Therefore, vegetation type is a key regulating factor of the water cycle in water-scarce semi-arid regions (Wu et al., 2016). The patterns of soil water content change under different vegetation coverages, depths, and seasons differ significantly (Yu et al., 2017; Hou et al., 2018).

The Loess Plateau in China is the world' s largest loess accumulation area (D' Odorico et al., 2007) and has long faced severe ecological problems such as soil erosion and vegetation degradation (Zhang et al., 2008). To control soil erosion and improve environmental conditions, China implemented the world' s largest "Grain for Green" project in this region (Zhou et al., 2012). While this project significantly increased vegetation coverage and carbon sequestration potential in semi-arid western China (Zhou et al., 2012), it also enhanced soil water consumption (Zhang et al., 2020), leading to ecological issues such as deep soil desiccation in forest lands (Liang et al., 2018). In the water-limited environment of the Loess Plateau' s semi-arid areas, different vegetation types have adopted distinct water-use strategies (Hou et al., 2018; Yu et al., 2018), resulting in varied influences on hydrological processes including soil water storage, migration, and transformation (Cheng et al., 2020).

In recent years, global warming has exacerbated soil water shortages in semi-arid regions (Zhang et al., 2020), and factors affecting soil water content may change drastically with seasons (Zhu et al., 2014). Seasonal dynamics of soil water content under different vegetation types have become an important research topic in ecohydrology (Mei et al., 2019; Yu et al., 2019). Further quantification of how precipitation, vegetation types, and other factors influence soil water content heterogeneity in semi-arid areas is necessary (Zhao et al., 2017; Yu et al., 2018). Therefore, we used TEROS12 sensors (METER Group, Pullman, USA) to monitor soil water content in typical vegetation types in a semi-arid area of the Chinese Loess Plateau from January 1 to December 31, 2020. Real-time meteorological monitoring allowed us to compare soil water dynamics across different depths and examine seasonal response patterns to precipitation in four vegetation types: natural grassland, *Caragana korshinskii*, *Pinus tabulaeformis*, and *Armeniaca sibirica*.

2.1 Study Area

This study was conducted at the Gansu Provincial Field Scientific Observation and Research Station of Mountain Ecosystems, China (35°58 20 N, 104°20 6 E). The region has an average altitude of 2000 m a.s.l., an annual mean temperature of 7°C, and average annual precipitation of 300–350 mm. We selected sample plots with typical 60-year-old plantations to monitor soil water content. Four vegetation types were chosen under similar environmental conditions and planting ages: natural grassland, *C. korshinskii*, *A. sibirica*, and *P. tabulaeformis* (Fig. 1 [Figure 1: see original paper]). The main species in natural grassland included *Artemisa sacrorum*, *Ajania fruticulosa*, and *Stipa bungeana*, while understory vegetation in the other three plots was dominated by *A. sacrorum*.

Vegetation types, total vegetation coverage, soil bulk density, and soil particle size composition of the sample plots are shown in Table 1 .

3.1 Precipitation

Figure 2 [Figure 2: see original paper] shows that 73 precipitation events occurred during the study period, with summer accounting for 62.73% of annual precipitation (338.3 mm). Precipitation events below 5 mm were most frequent but contributed only 13.09% of the annual total. Events of 5–10 mm and 10–20 mm occurred in spring, summer, and autumn, primarily concentrated in summer, accounting for 23.00% and 42.21% of annual precipitation, respectively. Precipitation events exceeding 20 mm occurred only in summer, representing 34.59% of summer precipitation and 21.70% of annual precipitation.

3.2 Soil Water Content

Table 2 shows variation in average soil water content across soil depths for different vegetation types. Average soil water content followed the trend: natural grassland > *P. tabulaeformis* > *C. korshinskii* > *A. sibirica*. The coefficient of variation (CV) exhibited the reverse sequence: *P. tabulaeformis* > *C. korshinskii* > *A. sibirica* > natural grassland, indicating that natural grassland showed the smallest variation. Changes in daily average temperature and vapor pressure deficit reflect the region' s typical continental monsoon climate, with rapid changes observed in spring and autumn. These climatic characteristics of concurrent rainfall and heat drastically altered soil water content (Fig. 3 [Figure 3: see original paper]). Analysis of variance showed significant differences between maximum and minimum soil water content values at each depth ($P < 0.05$), confirming that soil water content was significantly affected by vegetation, precipitation, and other environmental factors.

Soil water content varied with depth across vegetation types. The maximum soil water content occurred at 10 cm depth; however, moisture at this depth was significantly lower than at 20 cm ($P < 0.05$). Except for the *C. korshinskii* plot, the CV of soil water content was largest at 10 cm depth, while the minimum content was observed at 80 cm depth, indicating that precipitation most strongly influenced the 10 cm layer. In the *P. tabulaeformis* plot, soil water content at

40 cm depth was higher than at other depths, though the maximum content occurred at 20 cm, suggesting this layer is important for water storage.

Figure 3 also shows fluctuations in soil water content at each depth during the experimental period. The 10 cm depth peak corresponded strongly with precipitation events, whereas fluctuations in deeper layers were observed only during large, continuous summer precipitation events. Otherwise, soil water content remained relatively stable. During summer, when precipitation was concentrated, soil water content in deeper layers (60 and 80 cm) dropped to its lowest values (Fig. 3d and e). Except for natural grassland, maximum water content at 80 cm depth in other plots was less than 12%, indicating soil water depletion during the experimental period. Except for natural grassland, soil water content was low at the experiment' s end, showing a negative water balance (Fig. 3).

3.3 Response of Soil Water Content to Precipitation

Precipitation events of less than 5 mm had minimal impact on soil water content. We selected three precipitation categories (5-10 mm, 10-20 mm, and >20 mm) to evaluate their effects (Fig. 4 [Figure 4: see original paper]). Response patterns to a 6.8 mm event were similar across all plots (Fig. 4a1, b1, c1, and d1). This precipitation increased soil water content at 10 cm depth and infiltrated to 20 cm after one day. The effect of 18.4 mm precipitation on natural grassland and *C. korshinskii* plots resembled that of the 6.8 mm event (Fig. 4a2, b2, c2, and d2). In *A. sibirica* and *P. tabulaeformis* plots, 18.4 mm precipitation penetrated to 40 cm depth after two days (Fig. 4c3 and d3). The 25.1 mm event caused infiltration to 80 cm depth in natural grassland and *P. tabulaeformis* plots (Fig. 4a3 and c3), while infiltrating only to 40-60 cm in *C. korshinskii* and *A. sibirica* plots (Fig. 4b3 and d3). With increasing precipitation, soil water content varied across depths (Fig. 4). Natural grassland and *P. tabulaeformis* plots showed the greatest variation. The 25.1 mm event was the largest during the study period and was sufficient to replenish soil water content to 80 cm depth in natural grassland and *P. tabulaeformis* plots after three days.

3.4 Dynamics of SWS Capacity and Response to Precipitation

Soil water storage (SWS) capacity in natural grassland was significantly higher than in other plots ($P < 0.05$), while *A. sibirica* showed the lowest capacity ($P < 0.05$; Table 3). Except for natural grassland in spring, SWS capacity was significantly higher in autumn than in other seasons ($P < 0.05$) and exhibited low CV values (Table 3). Annual SWS capacity reached its minimum in summer, following the descending order: natural grassland > *P. tabulaeformis* >

C. korshinskii > *A. sibirica*. Natural grassland showed the lowest CV in SWS capacity, while *C. korshinskii* showed the highest.

SWS and precipitation were significantly correlated during the experimental period ($P < 0.05$). Seasonal variation in SWS capacity was pronounced (Fig. 5 [Figure 5: see original paper]). Except in winter, SWS response to precipitation was higher in *P. tabulaeformis* plots than in others (Fig. 5a, b, and c); however, in winter, natural grassland showed the strongest response (Fig. 5d). SWS capacity efficiency was highest in spring for *A. sibirica* and *P. tabulaeformis* plots (Fig. 5a), followed by winter (Fig. 5d) and summer (Fig. 5b). For natural grassland and *C. korshinskii* plots, the highest SWS capacity occurred in winter (Fig. 5d), followed by spring (Fig. 5a) and autumn (Fig. 5c).

4.1 Variation in Soil Water Content and Its Influencing Factors

Our results indicate that soil water content trends in each vegetation type correspond with precipitation changes (Fig. 3), confirming precipitation as an important factor. However, the response is complex, with vegetation type, soil depth, and environmental factors all affecting dynamics. Soil evaporation and vegetation transpiration patterns are primary drivers of soil water content variation (Kakembo, 2009). We confirmed significant differences in annual SWS capacity among vegetation types (Table 3), with natural grassland showing much higher capacity than other plots. Soil water content in *A. sibirica* plots declined due to water depletion (Laio et al., 2001), posing a serious risk to vegetation. Prolonged low soil water content limits vegetation growth and can cause mortality (Yu et al., 2018; Yu et al., 2019).

Soil water content decreases with depth due to weak precipitation influence on deeper layers (Fu et al., 2003; Zhao et al., 2017). As shown in Figure 3a, surface soil water content at 10 cm depth was most sensitive to precipitation, showing the highest values. With increasing depth, more compact soil structure reduced infiltration capacity, stabilizing deep soil water content. We found the lowest soil water content at 60–80 cm depth. Furthermore, CV values reflected stability—lower water content in deep soil corresponded to reduced influence from precipitation and other factors (Yu et al., 2017). Deep soil roots have become an important factor affecting soil water content (Fu et al., 2003). *C. korshinskii*, *A. sibirica*, and *P. tabulaeformis* plots all showed larger CVs at 40–80 cm depth (Table 2) because artificial vegetation has stronger root systems at these depths (Xu et al., 2017).

Soil water content in different vegetation types showed seasonal differences (Fig. 3f) due to large variations in surface evapotranspiration and vegetation transpiration across seasons (Li et al., 2013; Liu et al., 2017). Soil water content was relatively high in spring but began depleting rapidly as temperature and vapor pressure deficit increased, enhancing transpiration and evaporation (Laio et al., 2001). Both temperature and vapor pressure deficit were relatively high in summer, with pronounced rain-heat fluctuations. The strong input and output processes in summer were reflected by higher CV values in SWS capacity. Therefore, despite high precipitation frequency in summer, SWS capacity did not receive significant supplementation. In autumn, reduced temperature and vapor pressure deficit weakened transpiration and evaporation effects, stabilizing soil water content changes (Kakembo, 2009). Autumn is the primary season for soil water replenishment, with relatively high average SWS capacity across all plots.

4.2 Response of Soil Water Content to Precipitation

Our results indicate that precipitation exceeding 20 mm, which occurs only in summer, is necessary to replenish moisture in deeper soil (>40 cm) (Fig. 4). Such precipitation is crucial for sustainable vegetation growth and survival (Li et al., 2013). Precipitation events of 5-20 mm in spring and autumn may be the main source of soil water replenishment in this region (Wang et al., 2013; Mei et al., 2019). Generally, small precipitation events are quickly offset by evaporation due to limited infiltration depth, whereas large events increase infiltration depth and reduce surface water evaporation (Mei et al., 2019). Additionally, continuous small events may have a superimposing effect by increasing surface soil water content, enhancing replenishment efficiency—an effect that cannot be neglected (Peel, 2009). However, we did not observe a significant superimposing effect, likely because continuous precipitation mainly occurred in summer (Fig. 3), when high temperature and evapotranspiration offset these events (Laio et al., 2001). Soil water content response to precipitation shows seasonal differences, with spring and autumn impacts being more pronounced due to reduced canopy interception, vegetation transpiration, and soil evaporation losses (He and Huang, 2001).

P. tabulaeformis exhibits higher conversion efficiency of SWS capacity from precipitation due to several factors. First, differences in soil physical and chemical properties affect precipitation conversion. The *P. tabulaeformis* plot had relatively high soil organic matter content and porosity, with infiltration rates higher than other plots (Fig. 4) (Guo et al., 2019). Soil water content at 40 cm depth in *C. korshinskii* and *A. sibirica* plots reached the dry soil layer level of the Loess Plateau, with average content at the severe dry layer level (Liang et al., 2018). This indicates that roots of *C. korshinskii* and *A. sibirica* have strong water absorption and consumption abilities, making precipitation infiltration difficult and preventing moist layer formation (Ma et al., 2017). Second, research shows *P. tabulaeformis* adopts active drought resistance strategies such as rainfall interception (Ma et al., 2019) to reduce initial transpiration water loss (Liu et al., 2017; Ma et al., 2017). Consequently, *P. tabulaeformis* had higher SWS capacity efficiency (Fig. 5).

Vegetation restoration measures have been implemented for approximately 60 years, with no irrigation or water sources other than precipitation in this study area. Therefore, deep soil water in artificial plantations is limited (Fig. 4). Under future climate change, increased extreme drought events may cause serious soil water deficit crises for artificial vegetation (An et al., 2017). Future afforestation should be more cautious, with spring being the optimal season (Zhou et al., 2012; Ma et al., 2019) due to high soil water replenishment efficiency (Liu et al., 2017). Simultaneously, necessary management and irrigation measures are essential for existing artificial vegetation to meet deep soil water demands (Gao et al., 2015; Zhao et al., 2017; Mei et al., 2019).

5 Conclusions

Our study confirmed that soil water content variation in the semi-arid Chinese Loess Plateau is significantly affected by precipitation and vegetation type. Moderate precipitation events are the main water source for surface soil. Due to limited precipitation effects on deeper soil layers, particularly in summer with high temperatures and evaporation, artificial vegetation in this region still faces a water deficit crisis. The order of soil water content among vegetation types is natural grassland > *P. tabulaeformis* > *C. korshinskii* > *A. sibirica*. Thus, natural grassland is more suitable for restoration in this area. The proportion of artificial vegetation and natural restoration should be optimized to ensure sustainable water resource development in the Chinese Loess Plateau.

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Note: Figure translations are in progress. See original paper for figures.