Soil Moisture Response to Precipitation and Simulation in Restored Grasslands on the Loess Plateau: A Postprint

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Abstract

Precipitation is the primary source of soil moisture in arid and semi-arid regions and holds significant importance for vegetation restoration in these areas. This study employed EC-5 soil moisture sensors to continuously monitor soil moisture at 0–120 cm depth during 2014–2015, investigating the dynamic changes of soil moisture in grasslands with different restoration ages after farmland abandonment and the response of soil moisture at 0–40 cm depth to precipitation at a 10-min temporal scale. The results indicated that soil moisture gradually decreased from 5-year restored grassland to 15-year restored grassland, and this decreasing trend weakened in 30-year restored grassland. The 5-year restored grassland exhibited the smallest increase in soil moisture and the fewest response events. During individual rainfall events, both the soil moisture increase process and the decay process conformed to the Logistic model. The 5-year restored grassland had the longest duration of relatively stable period (plateau phase); the 15-year restored grassland showed the fastest soil moisture increase rate in the surface layer (0–5, 5–10 cm), while in the lower layer (20–40 cm) the increase rate slowed and the response time lagged; the 30-year restored grassland exhibited the fastest increase rate in the lower layer (20–40 cm). It is recommended that appropriate measures should be taken for restored grasslands to promote the conversion of rainfall into deep soil moisture and to reduce the duration of the plateau phase during the initial restoration period.

Full Text

Research and Modeling of Soil Moisture Response to Precipitation in Restored Grasslands on the Loess Plateau

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Abstract

Soil moisture dynamics and its response to precipitation are critical for vegetation growth and ecological restoration in arid and semi-arid regions. This study employed EC-5 soil moisture sensors to continuously monitor soil moisture at 0–120 cm depth from 2014 to 2015, examining the temporal variations of soil moisture in grasslands with different restoration ages and the response of 0–40 cm soil moisture to precipitation at a 10-minute timescale. Results showed that soil moisture gradually decreased from 5-year restored grassland (RG5) to 15-year restored grassland (RG15), but this decreasing trend weakened in 30-year restored grassland (RG30). RG5 exhibited the smallest increase in soil moisture and the fewest response events. During individual rainfall events, both the growth and decay processes of soil moisture conformed to the Logistic model. RG5 displayed the longest stable period (plateau phase) duration, while RG15 showed the fastest increase in surface layers (0–5, 5–10 cm) but slower response with time lag in deeper layers (20–40 cm). RG30 demonstrated the fastest increase in the deeper layer (20–40 cm). We recommend implementing appropriate measures in restored grasslands to promote the conversion of rainfall into deep soil moisture and reduce the duration of the plateau phase during the initial restoration stage.

Keywords: restored grassland; Logistic model; precipitation response; soil moisture; Loess Plateau

Introduction

The Loess Plateau is one of the most severely eroded regions in the world, characterized by a semi-arid continental monsoon climate. Since 1998, China has implemented large-scale vegetation restoration measures in this region, including the Grain for Green program and natural vegetation enclosure, which have achieved remarkable success. However, recent studies have revealed that vegetation restoration has occasionally caused negative soil water balance phenomena such as soil desiccation layers under semi-arid and semi-humid conditions on the Loess Plateau, posing a potential threat to the effectiveness of current vegetation restoration efforts. Soil moisture is the primary limiting factor for vegetation restoration in arid and semi-arid regions and has long been a focus of research. Natural precipitation is the main, and often only, source of soil water recharge in non-irrigated areas of this region. Investigating soil water response to precipitation is therefore crucial for understanding soil moisture dynamics and guiding vegetation restoration efforts.

Soil moisture is a challenging component in hydrological cycle and water balance studies because it is influenced by both climatic conditions such as rainfall and underlying surface properties including vegetation, topography, and geomorphology. While precipitation significantly affects soil moisture variations, soil moisture in turn plays a major controlling role in the precipitation-runoff response process. Vegetation exhibits delayed responses and response thresholds to precipitation, and rainfall characteristics, vegetation, and soil properties collectively determine how soil water responds to precipitation under vegetated conditions, with soil moisture response forming the basis for vegetation response. Current research on soil moisture response to precipitation during grassland restoration is relatively limited, with most studies focusing on infiltration processes, infiltration depth, and soil water recharge amounts, while the complete response process and temporal characteristics of soil moisture to precipitation remain understudied. The response of soil moisture to precipitation generally undergoes three phases: a growth period, a relatively stable period, and a decay period. The response mechanisms and precipitation-runoff generation processes differ across these periods as soil moisture changes. Moreover, affected by precipitation amount, intensity, and duration, the response speed and duration vary among different soil depths. This study examined grasslands at different restoration stages through two years of continuous field monitoring of precipitation and soil moisture, investigating soil moisture dynamics and the response process to typical single precipitation events. We used Logistic growth and decay models to fit the complete response process, aiming to provide a theoretical basis for understanding soil moisture dynamics and precipitation resource utilization during vegetation restoration through quantitative analysis of precipitation response processes in grasslands restored for different durations (5, 15, and 30 years).

1.1 Study Area Description

The experiment was conducted in Shenmu County, Yulin City, Shaanxi Province (110°21 -110°23 E, 38°46 -38°51 N), located in the Liudaogou watershed of the wind-water erosion crisscross zone on the Loess Plateau. The region has a mid-temperate semi-arid climate with dramatic inter-annual and intra-annual climate variations, characterized by dry and windy winters and springs with rainy summers and autumns. Precipitation is scarce and concentrated, with a multi-year average of 437.4 mm, approximately 80% of which occurs from June to September. The area represents a transition zone from hilly forest-steppe to desert and dry steppe. Natural secondary vegetation consists mainly of xerophytic grasses and meso-xerophytic Artemisia species, including *Stipa bungeana*, *Astragalus adsurgens*, *Astragalus melilotoides*, *Setaria viridis*, and *Artemisia capillaries*. Since the implementation of the Grain for Green program in 1998, over 90% of sloping farmland has been retired from cultivation, dramatically altering the regional environment. Average vegetation coverage now exceeds 70%, and barren hills have been largely covered by vegetation.

1.2.1 Sample Plot Selection

The experiment was conducted during the growing seasons (June–September) of 2014–2015. To minimize factors causing spatial heterogeneity of soil itself, three sample plots with similar site conditions were selected, representing grasslands restored for 5, 15, and 30 years (RG5, RG15, RG30). The basic characteristics of these plots are shown in Table 1.

Table 1 Site characteristics of the three restoration grasslands with different restoration ages

Restoration Age	Altitude (m)	Slope (°) & Aspect	Sand Content (%)	Dominant Species
RG5	1250–1260	20–25, W	52.3	*Artemisia capillaris*, *Salsola collina*, *Setaria viridis*
RG15	1250–1260	20–25, W	52.3	*Stipa bungeana*, *Artemisia capillaris*, *Astragalus melilotoides*, *Lespedesa davurica*
RG30	1250–1260	20–25, W	52.3	*Stipa bungeana*, *Astragalus melilotoides*, *Lespedesa davurica*, *Polygala tenuifolia*

1.2.2 Experimental Observations

In each of the three experimental plots, a U30-NRC automatic soil moisture monitoring system was installed. EC-5 soil moisture sensors continuously monitored soil moisture changes at depths of 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, and 80-120 cm. Time domain reflectrometry (TDR) and the oven-drying method were used for data calibration. Precipitation was measured using a self-recording rain gauge (RG3-M, Onset, USA).

1.2.3 Logistic Model Construction

(1) Logistic Model Overview

The Logistic model is a growth model also known as the Verhulst-Pearl model, widely applied in ecology and demography. The differential form of the Logistic model is:

$$= cs(1-) \tag{1}$$

where s is population size, t is time, a is environmental capacity, and c is the intrinsic growth rate. The solution of equation (1), the integral form of the Logistic model, produces an S-shaped curve known as the Logistic or Pearl curve, reflecting the process of initiation, development, maturation, and approach to saturation (limit). Parameter b in equation (2) is a coefficient to be determined.

(2) Logistic Model Development

At the 10-minute scale, the soil moisture response process to rainfall can be divided into three periods: growth, relative stability, and decay. Both the growth and decay processes exhibit S-shaped curves that conform to three-parameter Logistic equations, as shown in equations (3) and (4):

Figure 1 Soil moisture response curve [Figure 1: see original paper]

$$\theta(\text{growth}) = \theta_0 +$$

$$\theta(\text{decay}) = \theta_0 +$$

By calculating the third derivative of the function (t), two inflection points of the model can be determined:

$$d_t^3 = 0, \text{ yielding } t_1 =$$

$$t_3 = -$$

$$t_4 = -$$

$$\theta_{\max} = \theta_0 + a$$

$$R_{\max} = a\times$$

where t_1 is the initial response time in the growth period, t_2 is the time when the relative stability period (plateau phase) begins, t_3 is the start time of the decay period, and t_4 is the end time of soil moisture decay. $_0$ is the initial soil water content before precipitation, is the maximum soil water content at stability, and parameters a, b, and c are as defined in equations (1) and (2). R represents the maximum growth or decay rate.

The durations of the growth period (T_1), relative stability period (T_2), and decay period (T_3) are calculated using equations (11)-(13):

$$T_1 = t_2 - t_1 \tag{11}$$

$$T_2 = t_5 - t_2 + t_3 \tag{12}$$

$$T_3 = t_4 - t_3 \tag{13}$$

2.1 Precipitation Characteristics

Annual precipitation in the study area was 405.4 mm in 2014 and 388.4 mm in 2015, with growing season (June-September) precipitation accounting for 62.3% and 70.5% of the annual totals, respectively (Figure 2 [Figure 2: see original paper]). Rainfall events during the growing season were classified into four categories based on amount: <5, 5-10, 10-20, and >20 mm. The total precipitation for these categories during 2014-2015 was 95.4, 133.1, 172.6, and 125.4 mm, respectively, with occurrence frequencies of 64.8%, 17.6%, 12.1%, and 5.5%.

Figure 2 Precipitations of growth season from June to September [Figure 2: see original paper]

2.2 Soil Moisture Dynamic Variation Characteristics

Based on the degree of soil moisture response to precipitation, soil profiles can generally be divided into three layers: an active layer, a transition layer, and a relatively stable layer. In this study, 0-40 cm represents the active layer where soil moisture fluctuates with precipitation pulses, while 60-120 cm represents the relatively stable layer with minimal fluctuations, showing higher values early in the growing season and consumption during July-August (Figures 3d-3f [Figure 3: see original paper]). In the active layer (Figures 3a-3c), soil moisture response to rainfall differed among grasslands with varying restoration ages, with RG5 showing the smallest increase and fewest response events. In the relatively stable layer (Figures 3d-3f), differences in soil water content among restoration ages emerged, with RG15 maintaining lower moisture levels. Soil moisture gradually decreased from RG5 to RG15, but this decreasing trend weakened in RG30.

Figure 3 Soil moisture temporal variations of different layers of grasslands with different restoration ages from June to September [Figure 3: see original paper]

2.3 Soil Moisture Response Process to Precipitation

Considering herbaceous root distribution and precipitation influence depth, this study analyzed the 0-40 cm soil layer to examine responses across different depths. During a typical heavy rainfall event (June 28, 2015), soil moisture exhibited a characteristic two-inflection-point, three-stage pattern comprising growth, relative stability, and decay periods (Figure 4 [Figure 4: see original paper]). In terms of initial response time, RG5 showed slower response in the 5-10 cm layer, while RG15 responded more slowly in the 20-40 cm layer. Regarding moisture increase magnitude, RG5 showed the smallest increase across all layers, RG15 exhibited larger increases in surface layers (0-5, 5-10 cm), and RG30 demonstrated the largest increase in deeper layers (10-20, 20-40 cm) (Figures 4a-4d). The maximum soil water content at stability was higher in RG15 in surface layers (0-5, 5-10 cm) but significantly lower in the 20-40 cm layer.

Figure 4 Soil moisture response processes of grasslands with different restoration ages in a heavy rainfall event (28th June) [Figure 4: see original paper]

2.4 Simulation of Soil Moisture Response to Individual Precipitation Events

The Logistic model is suitable for simulating soil moisture response to individual precipitation events. However, it is not appropriate for continuous rainfall events without clear growth initiation or decay onset times, nor can it simulate the characteristics of the relative stability period in low-rainfall events lacking a distinct plateau phase.

The Logistic equation was used to fit the growth and decay processes during typical heavy rainfall events. Model parameters were substituted into equations (6)-(13) to derive temporal characteristics and change rates of the soil moisture response process. Simulation results are shown in Figure 4, with correlation coefficients (R^2) exceeding 0.98 for all fits. Temporal characteristics (Table 2) revealed that both the relative stability period and decay period were longest for RG5 across all depths. The duration of RG5' s relative stability period in the 0-5, 5-10, 10-20, and 20-40 cm layers was 3.7, 11.0, 2.4, and 1.1 times that of RG15, and 2.0, 12.4, 1.9, and 1.3 times that of RG30, respectively.

Four major precipitation events during the 2015 rainy season (June 28, July 17, August 3, and September 10) that generated strong soil moisture pulses were selected for growth process fitting, yielding correlation coefficients (R^2) above 0.71. Soil moisture increase rates during these events are presented in Table 3 . Comparing June 28 and September 10 events under similar rainfall intensities, RG15 showed greater variability in growth rate with changing precipitation amount in the 0–20 cm layer. Comparing July 17 and August 3 events with similar precipitation amounts and durations, RG15 exhibited greater variability in growth rate with changing rainfall intensity in the 0–20 cm layer, while RG30 showed greater variability in the 20–40 cm layer. Across soil layers, RG30 demonstrated smaller variability in growth rate with depth, indicating weaker stratification.

Table 2 Time characteristics of the soil moisture response processes of grasslands with different restoration ages

Soil Layer (cm)	Growth Period Duration (10 min)	Relative Stability Period Duration (10 min)	Decay Period Duration (10 min)
RG5	RG15	RG30	RG5
0–5			
5–10			
10–20			
20–40			

Table 3 The soil moisture increase rate of grasslands with different restoration ages

Date	Precipitation (mm)	Duration (min)	Intensity (mm h^{-1})	RG5	RG15	RG30
				0–10 cm	10–20 cm	20–40 cm

Discussion

In arid and semi-arid regions, soil moisture is a key factor affecting vegetation restoration and reconstruction, while vegetation restoration can improve soil water storage capacity and modify soil structure, thereby increasing soil water content. Some studies have found that soil moisture gradually decreases with increasing restoration age, occasionally leading to soil desiccation layers and ultimately ecological degradation. Research by Hao et al. on abandoned farmland in the Loess Plateau showed that soil structure improved and bulk density gradually decreased with restoration age from 6 to 40 years (excluding 2-year abandoned land affected by tillage), while soil water content peaked in 9-year abandoned communities. Our study found that soil moisture decreased from RG5 to RG15, but this decreasing trend weakened in RG30, suggesting that soil moisture initially declines with restoration age before the decreasing trend slows and partial recovery occurs.

From the perspective of soil moisture response to precipitation, this pattern may result from weaker response and insufficient precipitation utilization during early restoration stages. In our study, RG5 showed the smallest increase and fewest response events in the 0-40 cm layer (Figure 3). During typical individual precipitation events, RG5 exhibited the longest relative stability period (plateau phase) across all 0-40 cm layers (Table 2). During the plateau period, soil moisture approaches saturation and infiltration capacity decreases significantly, causing precipitation loss through surface runoff rather than effective soil recharge, while also causing surface soil erosion. The prolonged plateau period in RG5 may be attributed to two factors: first, shorter abandonment time and influence from previous irrigation resulted in higher initial soil moisture in RG5, and high initial moisture reduces infiltration rates and increases runoff; second, RG5 in the early successional stage is dominated by annual plants with small soil porosity and poor infiltration capacity. As restoration age increases, perennial herbaceous plants become more abundant, and the accumulation of soil organic matter and nutrients from root inputs and surface litter decomposition improves soil structure and significantly enhances infiltration capacity.

Atmospheric precipitation is the primary source of soil water recharge in arid and semi-arid regions, with soil moisture fluctuating in response to precipitation pulses. Precipitation characteristics including amount, intensity, and duration are the most important factors affecting soil moisture variation. Our results show that different restoration ages respond differently to changes in precipitation amount and intensity. As shown in Table 3, in the 0-20 cm layer, RG15 exhibited greater variability in soil moisture growth rate with changing precipitation amount and intensity, while in the 20-40 cm layer, RG30 showed greater variability in growth rate with changing rainfall intensity. Response patterns also varied with depth across restoration ages. Due to the time lag in infiltration, redistribution, and evaporation transmission to deeper layers, surface soil moisture is more strongly affected by precipitation than deeper layers, showing more pronounced responses. RG15 demonstrated the strongest response in surface layers (0-5, 5-10 cm) (Figures 4a-4b, Table 3) but weaker and lagged responses in the deeper layer (20-40 cm) (Figure 4d), indicating high water-holding capacity in the surface layer but weak infiltration to deeper layers. In contrast, RG30 showed the largest increase and fastest growth rate in the deeper layer (20-40 cm) (Figure 4d, Table 3), suggesting that RG30 is more conducive to deep soil water recharge and recovery. During natural grassland restoration on the Loess Plateau, management should focus on optimizing the soil moisture profile and promoting the conversion of precipitation to deep soil water to increase deep-layer responses. To prevent re-degradation of abandoned or enclosed grasslands, we recommend implementing appropriate artificial measures during early restoration stages to increase water infiltration, reduce plateau period duration, and enhance deep soil moisture response to precipitation.

Conclusions

1. Soil moisture gradually decreased from RG5 to RG15, but this decreasing trend weakened in RG30. In terms of precipitation response, RG5 showed the smallest increase in soil moisture and the fewest response events.

2. During individual precipitation events, both the growth and decay processes of soil moisture conformed to the Logistic model. RG5 exhibited the longest relative stability period duration. RG15 showed the largest increase and fastest growth rate in surface layers (0–5, 5–10 cm) but significantly reduced increase and lagged response in deeper layers (20–40 cm). RG30 demonstrated the largest increase and fastest growth rate in deeper layers (20–40 cm).

3. We recommend implementing appropriate artificial measures during the early stages of natural grassland restoration on the Loess Plateau to increase water infiltration, reduce plateau period duration, and enhance deep soil moisture response to precipitation, thereby improving the utilization efficiency of limited rainfall resources.

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