Soil Moisture Response to Rainfall Patterns under Grazing Exclusion in Typical Steppe (Postprint)

Authors: Xu Ran

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Abstract

By establishing grazing exclusion and grazing experimental sites in the Xilingol Grassland, meteorological, vegetation, and soil parameters, as well as soil moisture at depths of 5 cm, 10 cm, 15 cm, and 30 cm, were monitored and analyzed to reveal the variation and transformation patterns of rainfall and soil moisture under grazing exclusion conditions in typical steppe. The results indicate that: after three years of grazing exclusion, soil vertical heterogeneity was enhanced, with significant differences in soil water content among various soil layers during rainfall events, while the opposite pattern was observed in grazed areas; the lag time of soil moisture response to rainfall increased with soil depth, and compared with the grazing exclusion area, shallow soil layers (5 cm, 10 cm) in the grazed area exhibited weaker water holding capacity and shorter time to complete infiltration; rainfall events below 5 mm had no significant replenishment effect on soil moisture in either grazing exclusion or grazed areas, when rainfall was continuous and uniform with intensity not exceeding 5 mm · h ^{1} it was most conducive to infiltration, the grazed area required 7.9 mm and greater than 25 mm of rainfall to reach infiltration depths of 15 cm and 30 cm layers respectively, whereas in the grazing exclusion area rainfall greater than 5 mm could infiltrate to the 30 cm soil layer; isolated rainfall events with intensity of 5-6 mm · h ^{1} could only infiltrate into surface soil (5 cm), rainfall with intensity greater than 15 mm · h ^{1} in the grazing exclusion area could rapidly infiltrate through macropores to 30 cm and deeper soil layers, while in the grazed area surface infiltration was faster (0–5 cm) but deep infiltration was slower, leading to surface runoff and even flood disasters. The results of this study can provide references for research on grassland ecohydrological processes and the formulation of rational grazing policies.

Full Text

Preamble

Response of Soil Moisture Content to Rainfall Patterns in Typical Steppe under Grazing Prohibition

XU Ran[1], ZHANG Sheng-wei[1,2,3], ZHU Zhong-yuan[1,2], ZHANG Peng[1], GAO Lu[1]

[1]College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China
[2]Key Laboratory of Protection and Utilization of Water Resources of Inner Mongolia Autonomous Region, Hohhot 010018, China
[3]Inner Mongolia Autonomous Region Key Laboratory of Big Data Research and Application of Agriculture and Animal Husbandry, Hohhot 010018, China

Abstract:
Meteorological, vegetation, and soil factors as well as soil moisture content at depths of 5, 10, 15, and 30 cm were monitored and analyzed to reveal changes in rainfall patterns and soil moisture content under grazing prohibition in the Xilin Gol typical steppe of Inner Mongolia. The results showed that the vertical heterogeneity of soil moisture content increased after implementing three years of grazing prohibition. During rainfall events, differences in soil moisture content across soil layers were significant in the grazing prohibition sites, while the opposite pattern was observed in grazed areas. The lag time of soil moisture response to rainfall increased with soil depth. Compared with grazing prohibition sites, the water holding capacity of shallow soil (5 cm and 10 cm depth) in grazed areas was weaker, and infiltration time was shorter. No obvious replenishment effect on soil moisture was observed when rainfall was less than 5 mm in either grazed areas or grazing prohibition sites. Continuous, uniform rainfall with intensity not exceeding 5 mm · h ^{1} was most advantageous for water infiltration. Rainwater could infiltrate into 15 cm and 30 cm soil layers when rainfall reached 7.9 mm and exceeded 25 mm, respectively, in grazed areas, but could infiltrate into 30 cm soil layer when rainfall exceeded 5 mm in grazing prohibition sites. Water infiltrated into topsoil (0–5 cm) only when independent rainfall intensity was 5–6 mm · h ^{1}, but could rapidly infiltrate into 30 cm soil layer or deeper through macropores when rainfall intensity exceeded 15 mm · h ^{1} in grazing prohibition sites. In grazed areas, rainwater infiltrated rapidly into topsoil (0–5 cm) but slowly into deep soil, leading to surface runoff and even flooding disasters. These results provide valuable insights for research on grassland ecohydrological processes and formulation of rational grazing policies.

Keywords: Xilin Gol Steppe; rainfall pattern; soil moisture content; rainwater infiltration; Inner Mongolia

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1 Introduction

1.1 Study Area

The study was conducted in the Xilin Gol typical steppe region, characterized by a temperate continental climate. The dominant vegetation includes *Stipa grandis*, *Leymus chinensis*, *Carex korshinskyi*, and *Cleistogenes squarrosa*, which together account for over 70% of the plant community composition. The soil type is classified as chestnut soil, with a typical thickness of 200–300 mm. The region experiences an average annual precipitation of approximately 280 mm, concentrated primarily during the growing season from May to September.

1.2 Data Collection

Monitoring was initiated in 2013 within a 200 m × 200 m experimental plot. Soil moisture content was measured using CS616 sensors installed at depths of 5 cm, 10 cm, 15 cm, and 30 cm. Data were recorded at 15-minute, 1-hour, and 1-day intervals depending on the measurement period. Rainfall events were categorized based on intensity and duration, with continuous monitoring conducted throughout the 2014–2015 growing seasons.

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2 Results

2.1 Soil Moisture Monitoring

The correlation between monitored and measured soil moisture values yielded an R^2 of 0.8678 ($P < 0.01$), indicating high measurement accuracy and reliability of the monitoring system [FIGURE 1].

2.2 Lag Time Analysis

The lag time of soil moisture response to rainfall events increased progressively with soil depth. In the grazing prohibition sites, the response time at 5 cm depth was approximately 1 hour, while at 10 cm and 15 cm depths, lag times extended to 2–4 hours and 4–8 hours, respectively. The 30 cm depth exhibited the longest lag time, typically exceeding 12 hours [FIGURE 2].

2.3 Rainfall Event Characteristics

Rainfall events were classified into five categories based on total precipitation: 10–15 mm, 15–20 mm, 20–25 mm, 25–30 mm, and 35–40 mm. The distribution showed that events of 15–20 mm occurring over 3 days and 25–30 mm occurring over 4 days were most common during the study period [FIGURE 3]. Small rainfall events (<5 mm) accounted for over 60% of total precipitation frequency but contributed minimally to soil moisture replenishment.

2.4 Soil Moisture Response Patterns

2.4.1 Infiltration Depth Thresholds Soil moisture response varied significantly with rainfall intensity and pattern. When rainfall intensity was less than 5 $mm \cdot h^{1}$, water infiltration was limited to the upper 5 cm soil layer. At intensities of 5-6 $mm \cdot h^{1}$, moisture could penetrate to 10 cm depth. However, when rainfall intensity exceeded 15 $mm \cdot h^{1}$, rapid infiltration through macropores allowed water to reach 30 cm depth within 4 hours [TABLE 1].

TABLE 1. Characteristics of rainfall events

Rainfall intensity ($mm \cdot h^{1}$)	Duration (h)	Total precipitation (mm)	Infiltration depth (cm)
10–15	1	10–15	5
15–20	4	15–20	10
20–25	4	20–25	15
25–30	5	25–30	30
35–40	1	35–40	>30

2.4.2 Moisture Variation Under Different Patterns The variation in soil moisture content differed markedly between grazed and grazing prohibition sites. In grazed areas, rainfall events exceeding 7.9 mm were required to replenish moisture at 15 cm depth, while events >25 mm were needed to affect the 30 cm layer. In contrast, grazing prohibition sites showed moisture response at 30 cm depth with rainfall events as small as 5 mm, demonstrating enhanced infiltration capacity [FIGURE 4].

TABLE 2. Variation of soil moisture accumulation

Rainfall (mm)	Grazed area TC8 (cm)	Grazed area UC8 (cm)	Grazing prohibition TC8 (cm)	Grazing prohibition UC8 (cm)
10–15	5	0	10	5
15–20	10	5	15	10
20–25	15	10	20	15
25–30	30	15	30	30
35–40	>30	30	>30	>30

Correlation analysis revealed significant positive relationships between rainfall parameters and soil moisture variation in the grazing prohibition sites, with correlation coefficients of 0.718 ($P < 0.01$) for total rainfall and 0.654 ($P < 0.05$) for rainfall intensity [TABLE 3].

TABLE 3. Correlation coefficients between soil moisture variation and rainfall parameters

Parameter	TC8 (5 cm)	TC8 (10 cm)	TC8 (15 cm)	TC8 (30 cm)	UC8 (5 cm)	UC8 (10 cm)	UC8 (15 cm)	UC8 (30 cm)
Rainfall amount	0.654**	0.622*	0.419	0.511	0.718**	0.714**	0.612*	0.683**
Rainfall intensity	0.481	0.612*	0.390	0.504	0.473	0.620*	0.513	0.438
Duration	0.390	0.178	0.143z	0.322	0.445	0.222	0.128	0.280

- $P < 0.05$, ** $P < 0.01$

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3 Discussion

The implementation of grazing prohibition significantly altered soil physical properties and hydrological processes. The increased vertical heterogeneity of soil moisture content in grazing prohibition sites reflects improved soil structure and enhanced water holding capacity, particularly in the shallow layers. This is attributed to the development of soil aggregates and macropores resulting from reduced trampling and increased organic matter accumulation.

The differential response between grazed and grazing prohibition areas demonstrates that grazing pressure compromises soil infiltration capacity. In grazed areas, soil compaction reduces porosity, leading to rapid surface saturation and limited deep infiltration. Consequently, high-intensity rainfall events generate surface runoff rather than soil moisture replenishment. Conversely, grazing prohibition sites exhibit enhanced infiltration even during low-intensity rainfall events, with water effectively percolating to deeper soil layers.

The threshold behavior of infiltration depth relative to rainfall intensity reveals critical ecological implications. The 5–6 mm·h ¹ intensity threshold for topsoil infiltration and the 15 mm·h ¹ threshold for deep soil penetration provide important parameters for hydrological modeling in steppe ecosystems. These findings align with previous studies on soil-vegetation interactions in arid and semi-arid regions [**?**, **?**].

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4 Conclusion

(1) Grazing prohibition significantly increased the vertical heterogeneity of soil moisture content and enhanced water infiltration capacity, particularly in shallow soil layers (0–15 cm).

(2) The lag time of soil moisture response to rainfall increased with soil depth, ranging from 1 hour at 5 cm to over 12 hours at 30 cm in grazing prohibition sites.

(3) Rainfall events less than 5 mm showed no significant replenishment effect on soil moisture in either grazed or grazing prohibition areas. Optimal infiltration occurred with continuous, uniform rainfall at intensities not exceeding 5 mm · h ^{1}.

(4) In grazed areas, rainfall >7.9 mm was required to affect the 15 cm soil layer, and >25 mm to reach 30 cm. In grazing prohibition sites, rainfall >5 mm could infiltrate to 30 cm depth.

(5) High-intensity rainfall (>15 mm · h ^{1}) facilitated rapid deep infiltration through macropores in grazing prohibition sites, while similar events in grazed areas produced surface runoff.

These results provide scientific basis for understanding grassland ecohydrological processes and developing sustainable grazing management strategies in the Xilin Gol region.

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