Soil Moisture Dynamics and Response to Rainfall in Mongolian Pine Plantations in the Horqin Sandy Land (Postprint)

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Abstract

In the Horqin Sandy Land, after implementing ecological restoration through low-density cultivation of Mongolian pine (Pinus sylvestris var. mongolica) using the "two-row and one-belt" planting pattern, the dynamics of soil moisture in forested land and its response to rainfall have implications for the sustainable use of Mongolian pine for ecological restoration in similar regions. To investigate the dynamic characteristics of soil moisture following vegetation restoration on the southern margin of the Horqin Sandy Land, this study integrated in-situ observation and numerical simulation methods, calibrated the Hydrus-1D model based on measured soil moisture data, and explored the rainfall-soil moisture response relationship. The results indicated: (1) Mongolian pine plantations significantly altered the regional water distribution, with deep percolation at 2.0 m depth accounting for 44.16% of rainfall in bare sandy land, whereas deep percolation in Mongolian pine forest land accounted for only 0.7% of rainfall. (2) During the monitoring period, soil moisture below 0.4 m depth showed no response to light rain; the response depth of soil moisture to moderate rain could reach 1.0 m, while the response depth to heavy rain and rainstorms involved the entire observation profile. With increasing soil depth, the amplitude of moisture fluctuation exhibited a decreasing trend. (3) A strong correlation existed between rainfall amount and soil volumetric water content at shallower depths; cumulative rainfall at weekly and half-monthly intervals was significantly correlated with soil volumetric water content across all layers; rainfall exceeding 50 mm could ensure replenishment of soil moisture at 2.0 m depth. (4) The model's coefficient of determination ranged from 0.61 to 0.85, and root mean square error ranged from 0.0061 to 0.0096 $cm^3 \cdot cm^{-3}$, demonstrating that the model could satisfactorily simulate the dynamic variation characteristics of soil moisture in the study area, with higher simulation accuracy for deeper layers than for shallow layers. The research findings hold significant importance

for rain-fed vegetation afforestation, ecological restoration, and water resource management in the Horqin Sandy Land.

Full Text

Preamble

Title: Dynamic Changes in Soil Moisture and Its Response to Rainfall in *Pinus sylvestris* var. *mongolica* Plantation in Horqin Sandy Land

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Abstract: After ecological restoration in Horqin Sandy Land using low-density *Pinus sylvestris* var. *mongolica* (PSM) plantations in a “two rows and one belt” planting pattern, the soil moisture dynamics and its response to rainfall determine whether PSM can be sustainably used for ecological restoration in similar regions. To investigate the characteristics of soil moisture dynamics following vegetation restoration on the southern edge of Horqin Sandy Land, this study integrated in situ observations with numerical simulation methods, calibrating the HYDRUS-1D model based on measured soil moisture data to explore the rainfall-soil moisture response relationship. The results indicate: (1) PSM plantations significantly altered regional water distribution; deep leakage at 2.0 m depth in bare sand accounted for 44.16% of rainfall, whereas in PSM land it represented only 0.70% of rainfall. (2) Soil moisture below 0.4 m depth showed no response to light rain, while the response depth to moderate rain reached 1.0 m. Heavy rain and rainstorm events affected the entire observation profile. With increasing soil depth, the amplitude of moisture fluctuations decreased. (3) Strong correlations existed between rainfall and shallow soil volumetric water content; cumulative rainfall at weekly and semi-monthly scales was significantly correlated with soil water content across all layers ($P < 0.05$). Rainfall exceeding 50 mm ensured soil moisture replenishment within 2.0 m depth. (4) The model achieved determination coefficients ranging from 0.61 to 0.85 and root mean square errors between 0.0061 and 0.0096 cm^{-3}, demonstrating satisfactory simulation of soil moisture dynamics with higher accuracy for deeper layers. These findings provide important implications for rain-fed afforestation, ecological restoration, and water resource management in Horqin Sandy Land.

Keywords: rainfall infiltration; soil moisture; deep leakage; *Pinus sylvestris* var. *mongolica*; Horqin Sandy Land

Introduction

China has implemented extensive vegetation greening projects over the past decades, with increased forest cover substantially enhancing biogeochemical and biophysical climate impacts. Artificial vegetation establishment significantly affects soil stoichiometric characteristics while improving soil physical properties, thereby effectively ameliorating soil physicochemical conditions. In terrestrial surface systems of arid and semi-arid regions, water resource balance is controlled by rainfall, evapotranspiration, runoff, and soil water storage, with soil moisture representing a critical water resource form and a primary driver and important ecological factor for vegetation restoration patterns and processes. Soil moisture derived from rainfall conversion significantly influences vegetation restoration and reconstruction in semi-arid areas, where rain-fed vegetation constitutes the main type for sand prevention and control projects in China and heavily relies on soil water for survival. Drought, water scarcity, vegetation degradation, and desertification intensification have made Inner Mongolia one of the most concentrated areas of desertified land nationwide, making it crucial to understand soil moisture dynamics after vegetation restoration for subsequent restoration efforts.

Numerous studies have investigated spatiotemporal dynamics and redistribution of soil moisture in artificial vegetation in dryland regions. Zhang et al. conducted extensive research on deep leakage in artificial forests and croplands in arid zones, revealing that human activities altered rainfall water distribution in sandy areas. Li et al. demonstrated that rainfall represents the most important water source for *Nitraria tangutorum* nebkhas and determines shallow soil moisture replenishment depth. Additional studies on soil moisture and deep leakage have been conducted in the Mu Us Sandy Land, Loess Hilly Wind-sand Region, and Tengger Desert, providing scientific foundations for quantifying water resource allocation and guiding ecological restoration and farmland-to-forest conversion. In dryland rainfall water movement research, specific parameter modifications are typically applied to develop water movement models under particular conditions. Among these, soil moisture simulation represents the most widely applied domain for the HYDRUS-1D model, which effectively simulates soil water balance and deep leakage under arid and semi-arid conditions.

Pinus sylvestris var. *mongolica* is a suitable tree species for northern China with water-saving and salt-tolerant characteristics. In Horqin Sandy Land, where rainfall constitutes the primary water source for ecosystems and soil moisture, and where rainfall conditions approach the lower survival limit for PSM introduction, the species has been extensively planted for windbreak and sand fixation to address ecological environmental problems. Planting PSM in the ecologically fragile Naiman Sandy Area can effectively improve soil structure and is suitable for promotion in local sand fixation efforts. After ecological restoration using low-density PSM cultivation in a “two rows and one belt” planting pattern, research on soil moisture dynamics and rainfall response is critical for determining sustainable PSM use in similar regions. However, current progress on soil water balance studies of "two rows and one belt" PSM in Horqin Sandy Land remains limited, as unclear deep soil moisture transport processes prevent complete research on plot-scale aboveground and underground water balance. Therefore, this study combined field controlled positioning experiments with data simulation analysis to examine soil moisture spatiotemporal dynamics and responses of different soil depths to rainfall, validate HYDRUS-1D model reliability for simulating soil moisture movement, and explore water redistribution processes after PSM vegetation restoration.

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1. Materials and Methods

1.1 Study Area Overview

The study area is located in Naiman Banner, Tongliao City (121°35 40 E, 42°14 40 ~43°32 20 N), on the southern edge of Horqin Sandy Land. The region has an elevation of 300–700 m, with terrain higher in the southwest and lower in the northeast. It belongs to a temperate continental monsoon climate with an average annual temperature of 7.0°C and average annual rainfall of 366.5 mm, concentrated in summer. The area features extensive aeolian sandy soils with large pores and strong permeability, as well as meadow soil parent material with strong water and fertilizer retention capacity but poor aeration and low drought/flood tolerance. Zonal vegetation belongs to the temperate grassland zone with obvious secondary characteristics, dominated by semi-arid species including *Armeniaca sibirica*, *Imperata cylindrica*, *Stipa grandis*, *Leymus chinensis*, and *Salix gordejevii*.

1.2 Experimental Design

1.2.1 Site Selection A gently sloping PSM (*Pinus sylvestris* var. *mongolica*) forest land in Naiman Forest Farm was selected to minimize slope effects. The PSM had been planted for 25 years using a row-belt pattern with 5.75 m spacing between two rows, forming a 300 m × 500 m rectangular plot with gentle slope ($<5°$) considered as flat terrain. The soil type was sandy loam with no surface runoff and an average groundwater depth of 5.75 m. Median diameter trees were selected as experimental subjects within intact row-belt plots. Three similar experimental blocks were established as replicates to avoid spatial heterogeneity errors and differences from different plant populations, with approximately 100 m between blocks. An adjacent bare sand area served as the control group, where surrounding tree roots were first cut off and then isolated using 0.5 mm plastic film to create an independent soil space, preventing root intrusion from affecting rainfall infiltration.

1.2.2 Data Collection Methods The study was based on in situ experiments requiring rainfall, soil water content, and deep leakage data:

Rainfall: Two surface rainfall monitoring systems were installed following standard meteorological station specifications to record rainfall amount, frequency, and duration at 10-minute intervals using AVALON 3665R rain sensors (0.2 mm resolution).

Soil Moisture: Soil moisture sensors monitored water content changes within 2.0 m depth. Based on soil profile excavation and vegetation root characteristics, the PSM forest soil was divided into eight observation layers (0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.7, and 2.0 m), while bare sand was divided into six layers (0.3, 0.6, 0.9, 1.2, 1.5, and 2.0 m). Data were recorded every 10 minutes.

Deep Leakage: Deep leakage meters continuously monitored leakage at 2.0 m depth using a capillary water lift design. Side excavation installation minimized disturbance to the observation layer, maintaining in situ soil integrity (0.2 mm resolution).

1.3 Model Setup

1.3.1 Water Flow Equation The HYDRUS-1D model simulated soil moisture transport in PSM forest land, primarily vertical movement described by the one-dimensional Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S(h)$$

where θ is volumetric soil water content (cm^3 cm^{-3}), t is time (d), z is vertical coordinate (cm, positive downward), h is pressure head (cm), $K(h)$ is unsaturated hydraulic conductivity (cm d^{-1}), and $S(h)$ is root water uptake rate (d^{-1}).

Soil water characteristic curves and unsaturated hydraulic conductivity were fitted using the van Genuchten-Mualem equation:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2$$

where θ_r is residual water content (cm^3 cm^{-3}), θ_s is saturated water content (cm^3 cm^{-3}), K_s is saturated hydraulic conductivity (cm d^{-1}), S_e is dimensionless relative water content, and α, n, m, l are fitting parameters.

1.3.2 Root Water Uptake Root water uptake was converted to a water stress function. HYDRUS-1D provides two root uptake models; this study used the Feddes model:

$$S(h) = \alpha(h)b(x)S_p$$

where $S(h)$ is actual root water uptake rate (d^{-1}), $\alpha(h)$ is water stress response coefficient, $b(x)$ is root water uptake distribution density function, and S_p is potential water uptake rate (d^{-1}).

1.3.3 Temporal and Spatial Discretization As rainfall concentrates during the PSM growing season (May–September), the simulation period was set from May 1 to September 30 (153 days) with time discretization units of 0.001 days. The simulation soil thickness was 2.0 m, divided into 200 units with vertical discretization at observation points. The soil profile was divided into three layers based on soil properties: 0–0.4 m, 0.4–1.2 m, and 1.2–2.0 m.

1.3.4 Boundary and Initial Conditions The upper boundary was set as an atmospheric boundary with ponding, and the lower boundary as free drainage. Potential evapotranspiration was calculated using the Penman-Monteith equation, with HYDRUS-1D automatically processing daily variations.

1.3.5 Model Parameter Calibration and Evaluation Model hydraulic parameter accuracy critically determines simulation reliability. Parameters θ_r, θ_s, α, n, and K_s were optimized using the Levenberg-Marquardt algorithm combining Newton's method and steepest descent to minimize objective functions, with confidence intervals provided for optimized parameters. Calibration used measured soil water content under different rainfall conditions.

Model performance was evaluated using coefficient of determination (R^2), relative error (RE), root mean square error (RMSE), and Nash-Sutcliffe efficiency coefficient (NSE). R^2 reflects relative error between simulated and measured values; RMSE indicates average absolute error magnitude (values closer to 0 indicate higher precision); NSE represents temporal agreement (values closer to 1 indicate better performance).

1.4 Data Processing

Rainfall was categorized into four levels: light rain (0.1–9.9 mm), moderate rain (10.0–24.9 mm), heavy rain (25.0–49.9 mm), and rainstorm (50.0–99.9 mm). The water balance equation and infiltration coefficient formula were used to calculate rainfall distribution:

$$P = \Delta SWC + ET + D$$

where P is rainfall (mm), D is deep leakage (mm), ΔSWC is soil water content change (mm), and R is infiltration coefficient.

Data were processed using Excel, Matlab R2021b for correlation analysis, IBM SPSS Statistics 26, and Origin 2022 for plotting. The HYDRUS-1D model was established for simulation.

2. Results

2.1 Rainfall Water Distribution Between Forest and Bare Sand

During the monitoring period, total rainfall was 572.6 mm in the PSM forest land. Deep leakage at 2.0 m depth was 4.0 mm, accounting for 0.70% of rainfall, while 531.26 mm was stored in 0–2.0 m soil and 37.34 mm was intercepted by vegetation or lost through evapotranspiration. Although deep leakage in bare sand (44.16% of rainfall) exceeded that in forest land, the forest's water consumption and evapotranspiration losses resulted in significantly lower water storage than in bare sand. PSM ecological restoration altered rainfall distribution but maintained atmospheric precipitation-surface water-soil water-groundwater conversion, ensuring rainfall recharge to deep leakage or groundwater.

Soil volumetric water content in the forest fluctuated with rainfall (Fig. 3). With low rainfall in May, water content increased slowly across layers. June–August rainfall increases caused rapid water content rises, while September rainfall decreases led to reductions. Deep leakage below 2.0 m occurred mainly in June–August, with only 0.4 mm in May. Before the rainy season, water content at 1.2 m and 1.4 m depths was nearly equal. During the rainy season, values stabilized across layers, with 1.2 m depth slightly higher than 1.4 m. These two depths maintained higher water content than other observation points year-round.

Minimum water content values across all layers except 1.7 m appeared in May, while maximum values occurred in August. Minimum water content was 0.66% at 0.4 m depth; maximum was 15.51% at 1.2 m depth. Variation amplitudes at 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.7, and 2.0 m depths were 14.03%, 13.00%, 13.64%, 10.13%, 9.81%, 9.38%, 7.68%, and 8.66%, respectively, showing decreasing fluctuation amplitude with depth. The 0.4 m layer showed the greatest fluctuation, being most affected by rainfall.

2.2 Dynamic Response of Forest Soil Moisture to Rainfall

2.2.1 Dynamic Response Characteristics Post-rainfall infiltration increased soil volumetric water content, with frequent fluctuations during the rainy season corresponding to rainfall events. A total of 81 rainfall events were recorded, with 13 causing significant soil moisture fluctuations. The smallest effective rainfall was 13.4 mm; the largest was 81.6 mm. Different rainfall events caused varying moisture fluctuations—45.8 mm rainfall significantly replenished water across 0–2.0 m, while 16.8 mm rainfall only affected 0–0.6 m layers without directly recharging deeper soil.

2.2.2 Correlation Analysis As rainfall is the primary water source, correlations likely exist between rainfall and soil water content at different depths. Considering infiltration delay, cumulative rainfall at daily, weekly, semi-monthly, and monthly scales was correlated with water content across layers (Table 5). For 0–0.6 m soil, water content correlated with cumulative rainfall at all time scales. At 0.8 m depth, water content significantly correlated with cumulative rainfall at weekly, semi-monthly, and monthly scales ($P < 0.05$). Weekly cumulative rainfall significantly correlated with 0.4 m and 0.6 m layers ($P < 0.01$) and with other layers ($P < 0.05$). Semi-monthly cumulative rainfall significantly correlated with 0.4–1.2 m layers ($P < 0.05$) and with 1.4–2.0 m layers ($P < 0.01$). Monthly cumulative rainfall showed weakened overall correlations, while daily correlations only appeared in shallow sand layers.

Rainfall and infiltration depth were fitted using linear, logarithmic, power, and polynomial equations, with optimal results shown in Fig. 5. Infiltration depth increased with rainfall within a certain range; rainfall >50 mm ensured moisture replenishment within 2.0 m depth. Two moderate rainfall events (16.8 mm and 18.8 mm) produced infiltration depths of 1.0 m and 0.6 m, respectively, indicating that infiltration depth also depends on rainfall intensity and initial soil moisture content.

2.3 Soil Water Transport Simulation in Forest Land

After parameter optimization, the model simulated soil water transport. Simulated and measured values showed consistent trends (Fig. 6). Simulation accuracy was lower during rainless periods than during rainfall events. The 0.4 m layer simulation was less accurate than other layers, while 1.4 m and 2.0 m layers showed better results. Measured values at most depths fell near simulated curves, though deep soil moisture was underestimated after the final rainfall event on September 15.

Model validation using measured versus simulated soil water content demonstrated overall R^2 of 0.72. The 0.4 m layer had $R^2 = 0.63$; other layers ranged 0.61–0.85, indicating good fit. Representative layers (0.4, 0.8, 1.2, and 2.0 m) were analyzed, with evaluation metrics showing:

- NSE: $NSE_{2.0} > NSE_{1.2} > NSE_{0.8} > NSE_{0.4}$
- RE: $|RE_{1.2}| < |RE_{0.8}| < |RE_{0.4}| < |RE_{2.0}|$
- RMSE: $RMSE_{2.0} < RMSE_{1.2} < RMSE_{0.4} < RMSE_{0.8}$
- R^2: $R^2_{2.0} > R^2_{1.2} > R^2_{0.8} > R^2_{0.4}$

All absolute RE values were <10%, RMSE values <0.0096 $cm^3\ cm^{-3}$, and NSE values within acceptable ranges, indicating high simulation accuracy. Deep layer simulations outperformed shallow layers. The calibrated model can predict soil moisture distribution after rainfall, providing scientific support for afforestation in Horqin Sandy Land.

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3. Discussion

3.1 Analysis of Deep Leakage in Forest vs. Bare Sand

Deep leakage at 2.0 m depth in forest land occurred mainly in June–August, with only 0.4 mm in May. This occurred because May–September represents the PSM growing season when soil water is largely absorbed and utilized, with high evapotranspiration leaving little water for deep leakage. In contrast, March–April is the freeze-thaw season with minimal surface evaporation and temperature differences between deep and shallow soils that drive water leakage, while PSM growth activity is weak with reduced water uptake.

Although afforestation changed rainfall distribution significantly, the 25-year-old PSM forest maintained water conversion between atmospheric precipitation, surface water, soil water, and groundwater, ensuring rainfall recharge to deep leakage or groundwater. Vegetation restoration alters evapotranspiration, thereby affecting deep leakage and creating substantial differences between forest and bare sand areas. PSM water consumption intercepts rainfall in shallow soil, reducing deep leakage. As a deep-rooted species, PSM can absorb deep soil water, further reducing rainfall-recharged deep leakage. Rainfall characteristics also affect canopy interception and penetration, influencing soil moisture redistribution.

3.2 Dynamic Response of Forest Soil Moisture to Rainfall

PSM forest land showed decreasing moisture fluctuation amplitude with depth. The 0.4 m layer fluctuated most dramatically, being strongly influenced by rainfall. Deep soil receives slow water replenishment and renewal, and in arid/semi-arid regions, afforestation can cause deep soil desiccation, hindering water exchange between upper soil and groundwater and reducing deep leakage. Correlation analysis between rainfall and deep leakage revealed weaker responses at greater depths.

Lian et al. studied temporal-spatial soil moisture characteristics in PSM and *Caragana* plantations on the southern edge of Horqin Sandy Land, finding that soil moisture response to rainfall weakened with depth, consistent with our results. Our study also found that infiltration depth increased with rainfall within a certain range, with rainfall >50 mm ensuring moisture replenishment within 2.0 m depth. Rainfall 分级 showed that soil moisture below 0.4 m had no response to light rain, moderate rain affected depths up to 1.0 m, and heavy rain/rainstorms affected the entire profile.

3.3 Simulation and Analysis of Precipitation Redistribution

The HYDRUS-1D model has been successfully applied to simulate soil moisture dynamics in various forest types, including poplar plantations, tropical monsoon forests, and desert oases. Li et al. simulated water-salt transport in wheat planting areas on the North China Plain, finding larger errors in shallow soil moisture simulation. Li also found that model accuracy was higher in deeper layers in southern red soil slope simulations. Similarly, our study showed poorer simulation of shallow (0.4 m) soil moisture fluctuations and higher deep-layer accuracy. Shallow soil moisture transport is more strongly affected by external factors, causing larger errors. Frequent water flux exchanges from infiltration, transpiration, and evaporation may produce simulation errors in the main root distribution layer.

Our parameter-optimized HYDRUS-1D model simulated PSM forest moisture dynamics during the growing season, with R^2 values of 0.61–0.85 across layers, overall profile R^2 of 0.72, absolute RE values of 0.0061–0.0096 cm^3 cm^{-3}, and RMSE values within acceptable ranges. Li et al. reported R^2 of 0.59–0.84 and RMSE of 0.015–0.063 cm^3 cm^{-3} in similar studies. Our evaluation metrics meet or exceed these ranges, indicating the model satisfactorily simulates soil moisture dynamics and can predict post-rainfall soil moisture distribution to support ecological restoration in Horqin Sandy Land.

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4. Conclusion

1) PSM ecological restoration altered regional rainfall distribution. Deep leakage at 2.0 m depth in bare sand accounted for 44.16% of rainfall, while in PSM forest it represented only 0.70%. Although forest water conversion occurred mainly in June–August, the forest maintained water conversion throughout the study period, ensuring rainfall recharge to deep leakage or groundwater.

2) During the monitoring period, soil moisture below 0.4 m depth showed no response to light rain. Moderate rain affected depths up to 1.0 m, while heavy rain and rainstorms affected the entire observation profile. Soil water content at 1.2 m depth remained higher than other depths year-round. Moisture fluctuation amplitude decreased with depth, with the 0.4 m layer most strongly affected by rainfall.

3) Strong correlations existed between rainfall and shallow soil volumetric water content. Cumulative rainfall at weekly and semi-monthly scales significantly correlated with water content across all layers ($P < 0.05$). Monthly-scale correlations weakened overall, while daily-scale correlations only appeared in shallow layers. Rainfall >50 mm ensured moisture replenishment within 2.0 m depth.

4) The calibrated HYDRUS-1D model accurately simulated soil moisture

dynamics in the study area, with higher accuracy for deep layers than shallow layers. The model can simulate soil moisture changes based on predicted rainfall, providing scientific support for afforestation in Horqin Sandy Land.

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