Soil Moisture Dynamics During the Growing Season and Its Response to Rainfall in the Mu Us Sandy Land Based on Continuous Observation Data: Postprint

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Abstract

Water availability is a key abiotic factor constraining plant growth, development, and ecological restoration in semi-arid sandy lands. Continuous observations of soil moisture at 0-100 cm depth were conducted during the growing seasons (April-October) of 2008-2010 and 2018-2021 in mobile, semi-fixed, and fixed sandy lands of the Mu Us Sandy Land, systematically analyzing the dynamic variation patterns of soil moisture in sandy lands with different degrees of fixation and their responses to rainfall. The results showed that: (1) Influenced by seasonal rainfall variation, seasonal changes in soil moisture at different depths in mobile, semi-fixed, and fixed sandy lands generally exhibited a -shaped or bimodal pattern, with soil moisture content at 10 cm and 30 cm depths showing greater fluctuations, while those at 60 cm and 100 cm depths showed smaller fluctuations. (2) The growing-season soil moisture dynamics differed significantly among the three types of sandy lands with different fixation degrees. Overall, mobile sandy land exhibited the best soil moisture conditions with relatively stable soil moisture content, fixed sandy land showed the poorest soil moisture conditions with the most drastic variations in soil moisture content, and semi-fixed sandy land was intermediate between the two. Fixed sandy land had better soil moisture conditions at 10-30 cm depth than semi-fixed and mobile sandy lands, whereas the opposite was true at 30-100 cm depth. (3) Rainfall pattern was the primary factor shaping the spatiotemporal pattern of soil moisture. As rainfall amount increased with rainfall events, the infiltration depth of rainfall gradually increased; however, deep replenishment of soil moisture in fixed sandy land required stronger rainfall events and longer time periods. Rainfall events during the growing season were dominated by small rainfall events, leading to more drastic fluctuations in surface soil moisture. In the early growing season, rainfall was scarce and dominated by small rainfall events, making it difficult to replenish soil moisture below 10 cm depth, resulting in poor soil moisture conditions. Mobile and semi-fixed sandy lands had better soil moisture conditions at 10-30 cm depth than at 30-100 cm depth, while fixed sandy land exhibited the opposite pattern. The research results can provide a scientific basis for near-natural vegetation restoration and stability maintenance of sand-fixing vegetation in desertified lands of semi-arid regions.

Full Text

Dynamic Changes of Soil Moisture and Its Response to Rainfall During the Growing Season in Mu Us Sandy Land Based on Continuous Observation Data

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Abstract

Soil moisture is a crucial abiotic factor that constrains plant growth and ecological restoration in semi-arid sandy regions. This study conducted continuous observations of soil moisture at depths of 0-100 cm in shifting, semi-fixed, and fixed sandy lands in the Mu Us Sandy Land during the growing seasons (April-October) from 2008-2010 and 2018-2021. The dynamic patterns of soil moisture and its response to rainfall across different degrees of sand fixation were systematically analyzed. The results show that: (1) Affected by seasonal rainfall variation, soil moisture at different depths in shifting, semi-fixed, and fixed sandy lands generally exhibited unimodal or bimodal seasonal patterns. Soil moisture in the 10 cm and 30 cm depth layers showed greater fluctuations, while that in the 60 cm and 100 cm layers exhibited smaller variations. (2) Significant differences in soil moisture dynamics during the growing season were observed among the three fixation types. Overall, shifting sandy land had the best soil moisture status with relatively stable changes, fixed sandy land had the poorest status with the most dramatic fluctuations, and semi-fixed sandy land was intermediate. The 10-30 cm soil moisture in fixed sandy land was better than that in semi-fixed and shifting lands, whereas the opposite was true for the 30-100 cm layer. (3) Rainfall pattern was the primary driver of soil moisture spatiotemporal distribution. As rainfall amount increased, infiltration depth gradually increased, but deep soil moisture replenishment in fixed sandy land required stronger rainfall events and longer time periods. Small rainfall events dominated the growing season, causing more intense fluctuations in surface soil moisture. At the beginning of the growing season, low rainfall and small events failed to replenish soil moisture below 10 cm, resulting in poor moisture conditions, particularly in fixed sandy land. Shifting and semi-fixed sandy lands had better moisture at 30–100 cm than at 10–30 cm, while the opposite pattern occurred in fixed sandy land. These findings provide a scientific basis for near-natural vegetation restoration and sustainable management of sand-fixing vegetation in semi-arid desertified lands.

Keywords: Mu Us Sandy Land; growing season; spatiotemporal pattern of soil moisture; rainfall event; rainfall

1 Introduction

Soil moisture constitutes a vital component of terrestrial ecosystem water cycling and serves as an important medium for land-atmosphere interactions. It exhibits strong spatiotemporal heterogeneity due to influences from climate, soil, vegetation, and other environmental factors. In arid and semi-arid regions with limited precipitation and scarce water resources, soil moisture represents the primary ecological constraint on plant growth and significantly influences vegetation distribution. Atmospheric precipitation is the main source of soil moisture, and its dynamic changes are closely related to rainfall patterns. Plant growth status, biological soil crust development, and soil composition and structure all affect rainfall infiltration processes and soil moisture dynamics.

The Mu Us Sandy Land, one of the major deserts in northern China, features a mosaic distribution of fixed, semi-fixed, and shifting sandy lands. Shifting and semi-fixed sandy lands have sparse vegetation and strong wind erosion, resulting in relatively uniform soil texture and structure. Fixed sandy lands have higher vegetation coverage, often accompanied by biological soil crust development, more stable surfaces, and higher silt and organic matter content in surface soils. Compared with shifting and semi-fixed lands, fixed sandy lands have stronger water-holding capacity in surface soils, which hinders rainfall infiltration and affects precipitation effectiveness.

Although numerous studies have investigated soil moisture in the Mu Us Sandy Land, most have relied on periodic, fixed-point sampling to analyze soil moisture characteristics under typical landform conditions. These approaches involve limited data with low continuity, making it difficult to comprehensively reflect dynamic soil moisture patterns and rainfall response characteristics. This study selected fixed, semi-fixed, and shifting sandy lands dominated by *Artemisia ordosica* as the constructive species, continuously monitoring rainfall and soil moisture content at different depths during growing seasons to reveal dynamic patterns of sandy land soil moisture and analyze differences in rainfall responses across different fixation degrees. The objective is to provide a scientific basis for near-natural vegetation restoration and sustainable maintenance of sand-fixing vegetation in semi-arid desertified lands.

2 Methods

2.1 Data Observation

This study employed the Pullman soil temperature and moisture measurement system (equipped with ECH2O EC-5 soil moisture sensors suitable for sandy soils) for continuous soil moisture observation. Permanent plots were established in typical flat sandy lands at Tuke Town (108°37 -108°39 E, 38°08 -38°10 N) and Sulide Sumu (108°24 06 E, 38°20 58 N) in Uxin Banner. The sensors were installed in May 2008 for continuous monitoring of soil moisture in fixed, semi-fixed, and shifting sandy lands. Sensors were installed at depths of 10 cm, 30 cm, 60 cm, and 100 cm, with data recorded at 30-minute intervals. Precipitation data were measured by automatic weather stations installed near the plots, with recording precision of 0.10 mm and 0.25 mm at 30-minute intervals. To minimize errors from soil disturbance during instrument installation, this study analyzed soil moisture and precipitation data from the growing seasons (April–October) of 2008–2010 and 2018–2021. Due to instrument failure, soil moisture data for shifting sandy land in May 2018 were missing.

The study area is located in the hinterland of the Mu Us Sandy Land, administratively belonging to Uxin Banner, Ordos City, Inner Mongolia Autonomous Region (108°37 -108°39 E, 38°08 -38°10 N). The region has a temperate semi-arid continental monsoon climate, with a growing season from April to October, mean annual temperature of 8.4 °C, and mean annual precipitation of 300–350 mm. Precipitation shows large interannual variation, with wet years receiving up to three times that of dry years, and uneven intra-annual distribution with July–August precipitation accounting for approximately 60% of the growing season total. The annual evaporation rate is 1800–2500 mm. Vegetation consists of sparse, low-growing psammophytes, with *Artemisia ordosica* as the dominant constructive species whose roots are mainly distributed in the 0–100 cm layer. Growing season mean vegetation coverage is >50% in fixed sandy land, 30–50% in semi-fixed land, and generally <10% in shifting land. Biological soil crusts are widely distributed in fixed sandy land. Groundwater depth exceeds 1200 m.

During the observation period, vegetation and biological soil crust coverage showed little variation. At the Tuke Town site, vegetation coverage in fixed, semi-fixed, and shifting sandy lands was 88.73%, 39.21%, and 18.75%, respectively, with biological soil crust coverage of 37.80%. At the Sulide Sumu site, vegetation coverage was 74.85%, 41.67%, and 24.52%, respectively, with biological soil crust coverage of 7.89%.

2.2.1 Soil Moisture Data Correction

The ECH2O EC-5 soil moisture sensor exhibits significant output errors in sandy soils and requires field-specific calibration. This study applied a calibration equation established for the Mu Us Sandy Land to all soil moisture data:

$$\theta = 0.1516 - 1.501 \times 10^{-3} \times mV + 3.218 \times 10^{-6} \times mV^2$$

where θ is volumetric soil water content (cm^3 cm^{-3}) and mV is the sensor output value.

2.2.2 Calculation of Soil Moisture Content at Different Depths

Daily mean soil moisture content for depth layer i was calculated using:

$$DSWC_i = \frac{1}{t}\sum_{t=1}^{t} SWC_t$$

where $DSWC_i$ is the daily mean soil moisture content for layer i (cm^3 cm^{-3}), SWC_t is the soil moisture content measured at time t for layer i (cm^3 cm^{-3}), and t is the number of measurements per day.

Monthly mean soil moisture content for depth layer i was calculated using:

$$MSWC_i = \frac{1}{m}\sum_{T=1}^{m} DSWC_{iT}$$

where $MSWC_i$ is the monthly mean soil moisture content for layer i (cm^3 cm^{-3}), $DSWC_{iT}$ is the daily mean soil moisture content for layer i on day T (cm^3 cm^{-3}), and m is the number of days in the month.

2.2.3 Rainfall Event Statistics

Rainfall events were classified based on 24-hour precipitation amounts: $ $5 mm, 5-10 mm, 10-20 mm, 20-30 mm, and >30 mm. The frequency and total precipitation of each event type were statistically analyzed.

2.2.4 Precipitation Year Type Classification

The drought index (DI) was used to classify precipitation years:

$$DI = \frac{P - M}{\sigma}$$

where DI is the drought index, P is annual precipitation (mm), M is the multi-year mean precipitation (mm), and σ is the standard deviation of multi-year precipitation. Years were classified as relatively wet ($DI > 0.35$), relatively normal ($-0.35 \leq DI \leq 0.35$), and relatively dry ($DI < -0.35$).

2.2.5 Soil Moisture Interpolation Method

The Origin 20.0 software was used to create interpolation maps of soil moisture distribution (10-100 cm depth) across different sandy land fixation types using the Kriging interpolation method.

2.2.6 Statistical Analysis

SPSS 19.0 was used for one-way ANOVA to test differences in soil moisture content among different fixation types. Excel 2016 and Origin 20.0 were used for data processing and mapping.

3 Results

3.1 Precipitation Characteristics

Annual precipitation during the observation period was 346.25 mm (2008), 361.25 mm (2009), 304.50 mm (2010), 393.60 mm (2018), 332.90 mm (2019), 256.90 mm (2020), and 244.40 mm (2021). Growing season precipitation accounted for 65-85% of annual totals. The 2008-2010 and 2019 growing seasons were relatively normal years ($DI \approx 0$), 2018 was a relatively wet year ($DI > 0.35$), and 2020-2021 were relatively dry years ($DI < -0.35$). Small rainfall events ($ $5 mm) dominated the growing season, accounting for 60-70% of total events, while large events (>30 mm) occurred least frequently (<5% of events). In normal and dry years, no events >30 mm occurred.

3.2.1 Seasonal Variation of Soil Moisture

Soil moisture showed clear seasonal variation across all sites and depths. Most depth layers in different fixation types exhibited similar patterns. At the beginning of the growing season (April-May), soil moisture was relatively high, then gradually decreased to a minimum in June-July, before increasing to a maximum in August-September, and declining again in October, forming a unimodal pattern. Alternatively, some layers showed low initial moisture that increased to a peak in August-September then declined, forming a bimodal pattern. The 10 cm and 30 cm layers showed the greatest fluctuations, while deeper layers were more stable.

In normal precipitation years (2008-2009, 2019), seasonal patterns were similar across years. In wet years (2018), soil moisture was higher overall. In dry years (2020-2021), moisture was lower with reduced fluctuations. Shifting sandy land consistently showed the best moisture status with relatively smooth changes. Fixed sandy land showed the poorest status with the most dramatic fluctuations. Semi-fixed land was intermediate. In fixed sandy land, 10-30 cm moisture was better than in semi-fixed and shifting lands, while 30-100 cm moisture showed the opposite pattern.

3.2.2 Spatiotemporal Patterns of Soil Moisture During the Growing Season

Interpolation maps (Figures 4 and 5) illustrate spatiotemporal soil moisture patterns across different fixation types. Overall, Sulide Sumu had better soil moisture conditions than Tuke Town due to differences in vegetation and biological soil crust coverage.

Clear differences existed among fixation types. Shifting sandy land had the best overall moisture status with relatively stable temporal changes. Fixed sandy land had the poorest status with the most intense fluctuations. Semi-fixed land was intermediate. Fixed sandy land showed better moisture at 10–30 cm depth but poorer moisture at 30–100 cm compared to other types. A pulse-like pattern was particularly evident in the 10–30 cm layer of fixed sandy land at Sulide Sumu, and to a lesser extent in fixed and semi-fixed lands at Tuke Town.

During early growing season months with low rainfall, soil moisture was low throughout the profile, especially below 10 cm. As the season progressed and rainfall frequency and intensity increased, surface layers (10–30 cm) showed more dynamic pulse-like fluctuations, while deeper layers remained relatively stable.

3.3.1 Response of Seasonal Soil Moisture Variation to Seasonal Rainfall Patterns

Seasonal rainfall variation generally showed unimodal or bimodal patterns, with low rainfall in April–May and high rainfall in July–August. Soil moisture at 10 cm and 30 cm depths closely tracked these rainfall patterns, exhibiting corresponding unimodal or bimodal curves. At 60 cm and 100 cm depths, the response to seasonal rainfall was dampened but still reflected overall seasonal trends.

In fixed sandy land, the response was delayed and required more rainfall to reach deeper layers. For example, in 2008 (a normal year with bimodal rainfall), 10 cm and 30 cm soil moisture showed clear bimodal patterns, while deeper layers showed only minor fluctuations. In 2019 (another normal year but with different rainfall distribution), the moisture patterns adjusted accordingly, demonstrating the direct link between rainfall seasonality and soil moisture dynamics.

3.3.2 Differences in Soil Moisture Response to Rainfall Events Across Fixation Types

Figure 7 shows the relationship between rainfall amount and infiltration depth. As rainfall increased, infiltration depth increased progressively. However, for the same rainfall level, infiltration depth in fixed sandy land was lower than in semi-fixed and shifting lands, and required more time to reach equivalent depths.

Specifically: - To infiltrate to 10 cm depth: \$ $4mmrainfallwasneededinshiftingandsemi-fixedlands($ \$6.5 h), while fixed land required \$ $5.6mm($ \$10 h) - To 30 cm depth: \$ $10.5mminshiftingland($ \$10 h), \$ $14.0mminsemi-fixedland($ \$14 h), and \$ $18.6mminfixedland($ \$20 h) - To 60 cm depth: \$ $14.5mminshiftingland($ \$14 h), \$ $20.0mminsemi-fixedland($ \$30 h), and \$ $24.1mminfixedland($ \$42 h) - To 100 cm depth: \$ $25.8mminshiftingland($ \$45 h), \$ $26.4mminsemi-fixedland($ \$60 h), and \$ $31.25mminfixedland($ \$70 h)

3.3.3 Response of Soil Moisture Spatiotemporal Patterns to Rainfall Patterns

Figure 9 shows rainfall pattern variations during the growing season. April-May had low rainfall frequency dominated by \$ \$5 mm events, while July-August had high frequency with shorter intervals between events and more high-intensity rainfall.

Soil moisture spatiotemporal patterns closely followed these rainfall patterns. Because small events dominated and infiltrated less deeply in fixed sandy land, surface soil moisture (10 cm) fluctuated more dramatically in shifting and semi-fixed lands. At the beginning of the growing season, low rainfall and small events failed to replenish moisture below 10 cm, resulting in poor conditions, especially in fixed sandy land.

In 2019 (a normal year but with more 10-20 mm events in July-August), soil moisture conditions were better than in 2008 (also normal but with different distribution). In 2018 (a wet year with frequent >10 mm events), soil moisture was well replenished throughout the growing season.

4 Discussion

4.1 Causes of Seasonal Soil Moisture Variation

Seasonal soil moisture variation is primarily driven by seasonal rainfall patterns. The Mu Us Sandy Land exhibits extremely uneven rainfall distribution during the growing season, with clear seasonal characteristics—generally low in April-May and high in July-August, when rainfall can account for over 60% of the growing season total. Soil moisture in different fixation types shows corresponding seasonal patterns.

In fixed sandy land, as temperatures rise and vegetation enters the recovery phase after the growing season begins, water consumption through transpiration and soil evaporation far exceeds rainfall input, causing soil moisture decline. By July-August, increased rainfall not only meets consumption demands but also replenishes soil moisture, reaching peak content in August-September. After September, reduced rainfall cannot meet consumption needs, and moisture content declines again.

At 60 cm and 100 cm depths, soil moisture shows initial decline followed by stable fluctuations because rainfall events are insufficient to replenish these layers.

In semi-fixed and shifting lands, surface soils easily form dry sand layers that inhibit evaporation and protect deeper soil moisture.

4.2 Causes of Soil Moisture Content Differences Among Fixation Types

Soil moisture content is a key characteristic for evaluating soil moisture dynamics. This study found significant differences among fixation types: fixed sandy land had significantly higher moisture at 10-30 cm depth but lower moisture at 30-100 cm compared to semi-fixed and shifting lands. These differences are closely related to vegetation status and soil physicochemical properties.

Fixed sandy land' s higher vegetation and biological soil crust coverage facilitate soil organic matter accumulation and capture of atmospheric silt particles, reducing wind erosion. Surface soils have higher silt and organic matter content and stronger water-holding capacity. While vegetation transpiration consumes soil moisture, the canopy shade and biological soil crust protection slow surface moisture consumption, maintaining higher surface moisture content.

However, fixed sandy land requires more rainfall to infiltrate to the same depth compared to semi-fixed and shifting lands—a finding consistent with studies in the Horqin Sandy Land and Loess Plateau. In relatively dry years with fewer large rainfall events (e.g., 2020-2021), deep soil moisture replenishment is difficult. The longer intervals between rainfall events (up to 25 days) mean more moisture is lost to evapotranspiration.

At 10-30 cm depth, fixed sandy land' s stronger water-holding capacity allows it to store more water, but this also means more rainfall is required before infiltration to deeper layers can occur. Consequently, 30-100 cm moisture replenishment is less frequent. While plant transpiration and soil evaporation consume some moisture, the rate of moisture loss below the dry sand layer in shifting and semi-fixed lands is much lower than in fixed land. Therefore, comprehensive effects of vegetation coverage, biological soil crust distribution, and soil physicochemical properties result in fixed sandy land having better 10-30 cm moisture but poorer 30-100 cm moisture compared to other types.

4.3 Rainfall Pattern Variation as the Primary Driver of Soil Moisture Spatiotemporal Patterns

Soil moisture spatiotemporal patterns are influenced by rainfall, vegetation, and meteorological factors, with rainfall pattern being the dominant driver. During the growing season, April-May has low rainfall frequency dominated by small events ($ $5 mm), while July-August has high frequency with more intense events. Because small events dominate and infiltrate less effectively in fixed sandy land, surface soil moisture fluctuates more dramatically, especially in shifting and semi-fixed lands.

At the growing season onset, low rainfall and small events cannot replenish moisture below 10 cm, leading to poor moisture conditions, particularly in fixed sandy land. In 2019, despite being a normal year, July–August had frequent 10–20 mm events that improved soil moisture compared to 2008. In 2018, a wet year with frequent >10 mm events, soil moisture remained favorable throughout the season.

5 Conclusions

1) Soil moisture at different depths in shifting, semi-fixed, and fixed sandy lands generally showed unimodal or bimodal seasonal patterns. The 10 cm and 30 cm layers exhibited large fluctuations, while the 60 cm and 100 cm layers showed smaller variations. Seasonal soil moisture changes were primarily driven by seasonal rainfall variation.

2) Significant differences in soil moisture content existed among fixation types during the growing season. Overall, shifting sandy land had the best moisture status, fixed sandy land had the poorest, and semi-fixed land was intermediate. Fixed sandy land showed the most dramatic moisture fluctuations, followed by semi-fixed land, while shifting land had relatively stable moisture. Fixed sandy land had better 10–30 cm moisture status than semi-fixed and shifting lands, while the opposite was true for 30–100 cm moisture.

3) Rainfall pattern was the main factor shaping soil moisture spatiotemporal patterns. As rainfall amount increased, infiltration depth gradually increased. However, the same rainfall level resulted in shallower infiltration in fixed sandy land compared to semi-fixed and shifting lands, requiring more time to reach equivalent depths. The dominance of small rainfall events during the growing season caused more intense fluctuations in surface soil moisture. At the beginning of the growing season, low rainfall and small events failed to replenish moisture below 10 cm, resulting in poor moisture conditions, especially in fixed sandy land.

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