Spatiotemporal Characteristics of Soil Moisture in Desert Steppe Sierozem and Aeolian Sandy Soils: Postprint

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Abstract

Subject to interference from both anthropogenic and natural factors, native sierozem soils in the desert grasslands of Ningxia have undergone prolonged desertification, gradually shrinking in area and forming island-like patches distributed within extensive aeolian sandy soils. To reveal the spatiotemporal characteristics of soil moisture following sierozem desertification, a comparative study on water content was conducted between sierozem soils inside patches and surrounding aeolian sandy soils during the growing seasons (May–October) of 2017–2019 in Wangjigou Village, Yanchi County, Ningxia. Three patches each of large (200–300 m^2), medium (approximately 100 m^2), and small (approximately 50 m^2) sizes were selected. The results showed: (1) Temporally, the uniform rainfall distribution pattern in 2017 resulted in the highest annual average soil water content; although the total annual rainfall in 2018 was slightly higher than in 2017, it was concentrated in spring with almost no rainfall events in summer and autumn, resulting in consistently low soil water content throughout the year; the summer-dominated rainfall pattern in 2019 resulted in the highest average soil water content during summer. (2) Within the 0–100 cm profile, sierozem water content exhibited an initial increase followed by a decrease with increasing soil depth, with higher values in the 10–40 cm layer; whereas aeolian sandy soil water content increased with soil depth, with the 0–20 cm layer having substantially lower water content than the 20–100 cm layer. The water content of sierozem in the 0–20 cm layer was greater than that of aeolian sandy soil, while in the 20–100 cm layer, sierozem water content was significantly lower ($P < 0.05$) than that of aeolian sandy soil (except for medium and small patches in 2018). Except for the water content of aeolian sandy soil surrounding large patches being significantly higher ($P < 0.05$) than that of medium and small patches, no significant differences ($P > 0.05$) in sierozem water content were observed among patches of different sizes. (3) The water storage in the 0–100 cm layer of sierozem was generally lower than that of aeolian sandy soil, and its variation amplitude within the same time period was smaller than that of aeolian sandy soil. When rainfall amount was < 16 mm, water in both soil types was in a state of consumption; when rainfall amount was between 16–25 mm, sierozem water storage was greater than that of aeolian sandy soil; however, when rainfall amount was > 25 mm, aeolian sandy soil water storage exceeded that of sierozem. Soil water content in desert grasslands was dominated by rainfall amount and its distribution pattern, followed by soil type. The water content of sierozem and aeolian sandy soil not only exhibited distinct differences in profile distribution but also showed markedly different responses to rainfall.

Full Text

Spatiotemporal Characteristics of Soil Moisture in Sierozem and Aeolian Soils in Desert Steppe

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Abstract

Due to interference from anthropogenic and natural factors, the primary sierozem in the Ningxia desert steppe has gradually shrunk through long-term desertification, forming island-like patches distributed within extensive aeolian soils. To reveal the spatiotemporal characteristics of soil moisture following sierozem desertification, we conducted a comparative study during the growing seasons (May–October) from 2017 to 2019 in Wanjigou Village, Yanchi County, Ningxia. Three patch sizes were selected: large (200–300 m^2), medium (approximately 100 m^2), and small (approximately 50 m^2), with each size represented by 100 patches. Soil moisture was monitored within sierozem patches and compared with surrounding aeolian soils.

The results demonstrated that: (1) The uniform rainfall pattern during the 2017 growing season produced the highest annual average soil moisture content. In 2018, although total annual rainfall was slightly higher than in 2017, precipitation was concentrated in spring with almost no rainfall events in summer and autumn, resulting in consistently low soil moisture throughout the year.

The 2019 summer rainfall pattern generated the highest average soil moisture content during summer. (2) Within the 0–100 cm soil profile, sierozem moisture content initially increased then decreased with depth, peaking in the 10–40 cm layer, whereas aeolian soil moisture increased consistently with depth. In the 0–20 cm layer, sierozem moisture exceeded that of aeolian soil, but in the 20–100 cm layer, sierozem moisture was significantly lower than aeolian soil (except for small and medium patches in 2018). (3) No significant differences in sierozem moisture content were observed among different patch sizes, except that aeolian soil moisture surrounding large patches was significantly greater than that around small and medium patches ($P < 0.05$). (4) The 0–100 cm soil water storage of sierozem was generally lower than that of aeolian soil, with smaller temporal variation ranges. When rainfall was <16 mm, both soil types experienced water consumption. When rainfall ranged from 16–25 mm, sierozem water storage exceeded aeolian soil, but when rainfall >25 mm, aeolian soil storage surpassed sierozem. Soil moisture content in the desert steppe was primarily controlled by rainfall amount and distribution pattern, followed by soil type. The moisture content of sierozem and aeolian soils showed distinct vertical distribution patterns and differential responses to rainfall events.

Keywords: desert steppe; soil moisture; soil type; precipitation changes; soil water storage

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Introduction

Global climate warming has intensified water resource scarcity and land desertification in China's northern arid and semi-arid regions. To combat desertification and construct healthy ecological environments, domestic scholars have conducted extensive research in desert areas, focusing on plant communities, soil moisture dynamics, and artificial vegetation establishment. Soil moisture serves as a critical link in the soil-plant-atmosphere continuum, profoundly influencing plant growth, species richness, and vegetation restoration in desert regions. Soil moisture variation is affected by precipitation, soil physical properties, and vegetation cover conditions. In semi-arid desert steppe areas, precipitation represents the primary source of soil moisture replenishment and indirectly regulates ecosystem structure and function by influencing soil moisture distribution. Furthermore, different soil types exhibit varying moisture distribution patterns due to differences in physical properties.

Previous studies have documented these variations. For instance, Zheng et al. investigated vertical infiltration characteristics of sierozem under gravel mulch conditions, finding that gravel thickness and particle size affect moisture distribution. Jiang et al. studied soil moisture under different vegetation types in western Sichuan, revealing that soils with smaller porosity exhibit higher temporal stability. Chen et al. demonstrated that soil type deterministically influences moisture dynamics, with aeolian soil showing higher moisture content than sierozem in the same profile. Su et al. examined spatiotemporal moisture variations in weathered bedrock residual soil, sierozem, and aeolian soil, finding that weathered bedrock residual soil had the greatest water retention capacity and total storage. Wu reported that higher desertification degrees in alpine sandy lands of northwestern Sichuan corresponded to lower water retention and average moisture content. Therefore, analyzing moisture dynamics in different soil types and their relationships with precipitation is crucial for establishing reasonable ecological patterns in desert regions.

In Yanchi County's desert steppe, long-term anthropogenic grazing and natural disturbances have caused habitat fragmentation. The primary sierozem has been fragmented by wind erosion, forming island-like patches dispersed within sandy lands. Sierozem contains approximately 40–41% clay, 27–29% silt, and 30–33% sand, whereas aeolian soil contains about 1–2% clay, 19–21% silt, and 71–73% sand. As patch area decreases, sierozem desertification intensifies. Researchers have used these patches as starting points for degraded grassland restoration, investigating vegetation spatial patterns, community species coexistence mechanisms, and artificial establishment. However, few studies have examined soil moisture changes between different soil types inside and outside patches or among different patch sizes. Some scholars have simulated sierozem-to-aeolian soil evolution in laboratory settings, but soil moisture processes are influenced by climate, topography, and soil properties, making field-based comparisons essential.

Based on this research gap, we selected three sample plots in Wanjigou Village, Yanchi County, Ningxia, and conducted continuous monitoring of rainfall and soil moisture dynamics from 2017 to 2019. Our objective was to reveal the spatiotemporal distribution characteristics of moisture in sierozem and aeolian soils, providing a theoretical foundation for vegetation restoration and promoting the construction of healthy ecological community structures to enhance desert steppe productivity.

1.1 Study Area Overview

The study area is located in Wanjigou Village, Yanchi County, Ningxia Hui Autonomous Region (37°57 –37°83 N, 106°77 –107°50 E). The region has a semi-arid continental climate with an average annual temperature of 8.1°C. The area experiences large seasonal temperature variations, is arid with low rainfall, has a mean annual precipitation of 276.8 mm, and high evaporation rates exceeding precipitation by sevenfold. The frost-free period lasts approximately 150 days. The primary soil type within patches is sierozem, while aeolian soil dominates outside patches. Dominant species include *Stipa breviflora*, *Artemisia scoparia*, *Sophora alopecuroides*, *Cleistogenes squarrosa*, *Lespedeza potaninii*, and *Polygala tenuifolia* Willd.

1.2 Sample Plot Selection

Based on consistent topography and environmental conditions, we selected three patch sizes in Wanjigou Village: large patches (200–300 m^2), medium patches (approximately 100 m^2), and small patches (approximately 50 m^2). Sierozem within patches was compared with surrounding aeolian soil. To enhance data representativeness, each patch type included 100 replicates. Sierozem contains approximately 40–41% clay, 27–29% silt, and 30–33% sand, while aeolian soil contains about 1–2% clay, 19–21% silt, and 71–73% sand.

1.3 Data Sources and Methods

Rainfall, temperature, and soil moisture data were obtained from field monitoring. The geometric center of each patch served as the monitoring point for sierozem moisture, with an external monitoring point selected for aeolian soil moisture, ensuring equal distances from patch edges. At each monitoring point, 1 m-long polycarbonate tubes were installed, with TRIME probes placed at the midpoints of 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers. Measurements were repeated three times, with volumetric water content recorded for each layer when differences among replicates were \$ \$0.01 mm. Monitoring intervals were approximately 10 days, with daily measurements following rainfall events. A Vantage Pro2 automatic weather station was installed in Wanjigou Village to automatically collect rainfall and other meteorological data at 1-hour intervals. Daily average temperature was calculated by averaging 24 hourly measurements.

Rainfall events were defined as periods with precipitation intervals \$ \$24 hours. Rainfall amounts were classified as: Level I (0.1 mm $\leq$ SP $<$ 1 mm), Level II (1 mm $\leq$ SP $<$ 5 mm), Level III (5 mm $\leq$ SP $<$ 10 mm), Level IV (10 mm $\leq$ SP $<$ 25 mm), and Level V (SP $\geq$ 25 mm).

1.4 Data Processing

Basic processing of soil moisture data involved calculating means from three replicate measurements for subsequent calculations and mapping. Excel 2010 was used for data processing, Surfer 11.0 for generating soil moisture contour maps (with colors representing moisture values), and Origin 2021 for other figures. One-way ANOVA was performed on soil moisture content across different patch sizes and soil depths, with two-tailed t-tests ($P < 0.05$) used to compare differences between inside and outside patches. The coefficient of variation (C) was calculated to assess vertical moisture variation:

$$C = \frac{1}{\bar{X}}\sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}}$$

where S is standard deviation, $\bar{X}$ is the sample mean (soil moisture observations), n is the total number of samples, and X_i is the ith observation.

Soil water storage refers to the volumetric water content within a specific soil depth, calculated as:

$$SW = \sum_{i=1}^{6} \theta_i d_i$$

where SW is soil water storage (mm), θ_i is the volumetric water content of each layer measured by the probe, and d_i is the corresponding soil layer thickness.

Soil water storage change (ΔW) represents water consumption or accumulation within a specific period:

$$\Delta W = SW_2 - SW_1$$

where SW_1 is soil water storage before a specific time (mm) and SW_2 is storage after that time (mm). If $\Delta W > 0$, the period is accumulation-type; if $\Delta W < 0$, consumption-type; if $\Delta W = 0$, balanced-type.

2 Results and Analysis

2.1 Rainfall Characteristics During the 2017–2019 Growing Seasons

During the 2017–2019 growing seasons (May–October), total rainfall was 266 mm in 2017, 276.8 mm in 2018, and 237.03 mm in 2019. While total annual rainfall varied little among years, temporal distribution differed substantially. In 2017, monthly rainfall of approximately 10 mm occurred throughout the growing season at roughly monthly intervals, representing a uniform rainfall pattern. In 2018, rainfall was concentrated in spring (May–June), accounting for 76.2% of total growing-season precipitation, with severe summer-autumn drought, representing a spring rainfall pattern. In 2019, rainfall was distributed mainly in July–August, representing a summer rainfall pattern.

Overall from 2017–2019, 29 rainfall events occurred across Levels I–V, totaling 799.83 mm. Most events were small rainfall events (Levels I–II), occurring 16 times (54.8% of total events) but contributing only 47.0% of total rainfall. Level III–IV medium rainfall events occurred 9 times (31.6% of events), contributing 57.1% of total rainfall. Large rainfall events (Level V) were infrequent (3.6% of events) but contributed 14.7% of total rainfall. Thus, frequent small events contributed little to total rainfall, while infrequent large events made major contributions.

2.2 Temporal Variation of Soil Moisture Content

Annual average moisture content calculations revealed that sierozem moisture in 2017, 2018, and 2019 was 7.13%, 5.46%, and 6.90%, respectively, while aeolian soil moisture was 7.52%, 6.09%, and 7.14%. Both soil types showed consistent temporal fluctuations. Soil moisture experienced major fluctuations in 2017 and 2019, but remained relatively stable and low in 2018 after decreasing in June. Fluctuations were most pronounced in the 0–40 cm layer for both soil types.

Monthly comparisons showed that June 2017 had the highest average moisture content, with large, medium, and small patch sierozem at 10.38%, 8.40%, and 8.00%, respectively, and external aeolian soil at 13.19%, 9.73%, and 9.96%. September 2017 had the lowest moisture content, with sierozem at 5.69%, 6.30%, and 6.20%, and aeolian soil at 9.86%, 8.01%, and 8.99%. In 2018, May had the highest moisture content, while September had the lowest. In 2019, July showed the highest moisture content and September the lowest.

2.3 Spatial Distribution Characteristics of Soil Moisture

Sierozem moisture content increased then decreased with depth, peaking at 10–40 cm, while aeolian soil moisture increased consistently with depth. In the 0–20 cm layer, sierozem moisture significantly exceeded aeolian soil ($P < 0.05$), particularly in the 0–10 cm layer. Conversely, in the 20–100 cm layer, aeolian soil moisture significantly exceeded sierozem ($P < 0.05$), except for small and medium patches in 2018 where no significant differences were observed ($P > 0.05$).

No significant differences in whole-profile (0–100 cm) average moisture content were found among different patch sizes for sierozem ($P > 0.05$). However, for aeolian soil, large patches showed significantly greater whole-profile moisture than medium and small patches ($P < 0.05$), with no significant difference between medium and small patches ($P > 0.05$).

The coefficient of variation for soil moisture decreased with depth in both soil types, indicating greater stability in deeper layers. Under the same rainfall pattern, variation coefficients showed similar trends across patches, suggesting rainfall pattern was the dominant influence. In the same soil layer and rainfall pattern, aeolian soil exhibited greater variation coefficients than sierozem. Among years, 2018 showed the greatest difference in variation coefficients between shallow and deep layers, followed by 2017, while 2019 showed the smallest difference.

2.4 Soil Water Storage Characteristics and Rainfall Correlation

Temporal variation in soil water storage showed that both soil types followed similar fluctuation trends, but sierozem storage was consistently lower than aeolian soil, with smaller amplitude variations. In 2017, soil water storage after mid-July was consumption-type, with sierozem storage changes of -21.55 mm, -28.89 mm, and -17.93 mm for large, medium, and small patches, respectively, and aeolian soil changes of -30.26 mm, -25.77 mm, and -19.72 mm. In 2018, storage remained low after June decline, with all patches showing consumption-type patterns. In 2019, storage decreased gradually after mid-July then recovered after mid-August, reaching maximum in September, with most patches showing accumulation-type patterns.

Overall, sierozem water storage changes at the end of the growing season were 11.71 mm, 10.60 mm, and 17.30 mm for large, medium, and small patches, respectively (accumulation-type), while aeolian soil changes were 27.88–107.84 mm. Differences among sierozem patches were small, indicating less influence from rainfall patterns, whereas large patch aeolian soil storage far exceeded medium and small patches, indicating greater rainfall pattern influence.

Fitting analysis between soil water storage change and cumulative rainfall revealed that when rainfall <16 mm, storage changes were negative for both soils (consumption state), with greater consumption in aeolian soil under the same rainfall conditions. When rainfall was 16–25 mm, sierozem accumulation exceeded aeolian soil. When rainfall >25 mm, aeolian soil accumulation exceeded sierozem. The greater slope of the aeolian soil fitting line confirmed that aeolian soil storage was more rainfall-sensitive.

3 Discussion

3.1 Spatiotemporal Variation Characteristics of Different Soil Types

Research indicates that rainfall is the primary control factor for soil moisture variation in arid and semi-arid desert regions, with moisture showing clear seasonal patterns in response to precipitation. Our three-year monitoring in desert steppe revealed that sierozem and aeolian soil moisture exhibited distinct seasonal variations. In 2017, moisture variation showed spring moisture deficit (May–June), summer-autumn moisture gain/loss alternation (July–September), and autumn moisture stability (October), consistent with Chen et al.'s findings on the Loess Plateau. The 2018 pattern differed from Zhang et al.'s Loess Plateau study due to spring-concentrated rainfall (76.2% of annual total) and severe summer-autumn drought. In 2019, July rainfall produced maximum moisture content, while September drought resulted in minimum moisture.

Monthly variations depended on the combination of seasonal rainfall, temperature, and evapotranspiration. In 2017, strong solar radiation in July intensified evaporation, creating minimum moisture, while decreasing temperatures and plant transpiration in September produced maximum moisture. In 2018, spring rainfall created maximum moisture in May, but severe summer-autumn drought maintained low, stable moisture. In 2019, summer rainfall created maximum moisture in July, but drought in September produced minimum moisture.

In the Ningxia desert steppe, wind erosion gradually transforms sierozem into aeolian soil, with changing physical properties affecting moisture distribution. Sierozem has compact structure, high clay and silt content, and low non-capillary porosity, resulting in shallow infiltration depths (maximum 60 cm under large rainfall events) and moisture concentrated in the 10–40 cm layer, suitable for drought-tolerant shallow-rooted plants. Aeolian soil has loose structure, high sand content, and large inter-particle pores, providing high permeability and deep moisture replenishment (maximum infiltration >100 cm), suitable for deep-rooted, water-consuming shrubs.

Surface soil layers experience intense atmospheric exchange and climate influence, with rapid moisture increase after rainfall followed by quick evaporation, creating large fluctuations in the 0–20 cm layer that decrease with depth. For different patch sizes, larger patches facilitate moisture aggregation, but in the Ningxia desert steppe where small rainfall events dominate, this aggregation effect is not pronounced, resulting in non-significant differences among sierozem patches. However, during heavy rainfall, slower infiltration in large patches generates runoff that significantly supplements external aeolian soil moisture, making large-patch aeolian soil moisture significantly higher than around medium and small patches. Therefore, preventing sierozem desertification requires targeted sand fixation and moisture conservation measures for large-patch peripheral aeolian soils, such as gravel mulching to reduce surface evaporation.

3.2 Relationship Between Soil Water Storage and Rainfall in Different Soil Types

Studies show that higher temperatures during rainfall increase plant transpiration and surface evaporation, with temperature negatively correlated with soil moisture. In the study area, obvious soil moisture evaporation occurs under high summer-autumn temperatures, requiring sufficient rainfall for effective moisture replenishment. For 2018, where rainfall was concentrated in spring (92.4% of annual total), soil water storage showed consumption-type patterns. For 2017 and 2019, where summer-autumn rainfall accounted for 64.7% and 54.5% of annual totals, respectively, storage showed accumulation-type patterns. Thus, continuous heavy summer-autumn rainfall in the study area benefits annual storage replenishment, which after winter freezing and spring thawing can provide moisture for the following growing season.

Wang's research on rain-fed agriculture in the Loess Plateau found precipitation was the dominant factor affecting soil water storage, contributing approximately 76%. Our fitting analysis revealed that sierozem's fitting line slope was greater than aeolian soil's, indicating aeolian soil storage was more rainfall-sensitive, obtaining more water storage during effective rainfall but also losing stored moisture more readily during dry periods. This confirms aeolian soil's greater variation coefficient, attributable to its higher porosity and water permeability compared to sierozem.

Soil moisture is consumed through evaporation, runoff loss, leakage, and plant uptake/transpiration. In our study area, rainfall must reach 16 mm to increase soil water storage. Similar findings by Chang in Sunit Desert Steppe showed that Level I–II small rainfall events had negligible effects on soil moisture, while Level IV–V large events significantly replenished soil moisture. As rainfall accumulated, both patch-internal and -external storage increased. Under Level I–IV rainfall, sierozem obtained greater storage due to stronger moisture retention capacity. However, under Level V rainfall, aeolian soil with larger porosity could rapidly infiltrate and store water in deep layers. These differences in moisture storage capacity are crucial for vegetation management in this region.

4 Conclusions

1. **Annual average soil moisture content:** The 2017 uniform rainfall pattern produced the highest annual average moisture content. The 2018 spring-concentrated pattern resulted in the lowest annual average despite slightly higher total rainfall. The 2019 summer rainfall pattern generated maximum moisture in summer. Seasonal moisture variation depended on the combined effects of seasonal rainfall, temperature, and evapotranspiration.
2. **Vertical moisture distribution:** Sierozem moisture concentrated in the 10–40 cm layer, exceeding aeolian soil in the 0–20 cm layer. Aeolian soil moisture concentrated in the 20–100 cm layer, exceeding sierozem below 20 cm. Both soil types showed intense surface fluctuations that stabilized with depth.
3. **Rainfall response:** Soil water storage change showed a linear relationship with rainfall, with aeolian soil more rainfall-sensitive than sierozem. When rainfall <16 mm, both soils experienced moisture consumption. When rainfall was 16–25 mm, sierozem storage exceeded aeolian soil. When rainfall >25 mm, aeolian soil storage exceeded sierozem.

References

[1] Qin Jie, Si Jianhua, Jia Bing, et al. Study on the relationship between vegetation community characteristics and soil moisture in Badain Jaran Desert[J]. *Arid Zone Research*, 2021, 38(1): 207-222.

[2] Chen Juan, Song Naiping, Chen Lin, et al. Soil moisture dynamics and its response to precipitation in different cover types of desert steppe[J]. *Journal of Soil and Water Conservation*, 2021, 35(6): 198-206.

[3] Su Ying, Chen Lin, Li Yuefei, et al. Spatiotemporal variation of moisture content of different soil types in desert steppe[J]. *Arid Zone Research*, 2018, 35(6): 1308-1316.

[4] Wu Shilei, Liu Huaigu, Chen Dechao, et al. Effects of different restoration years on soil moisture in alpine sandy land of Northwest Sichuan[J]. *Journal of Sichuan Forestry Science and Technology*, 2022, 43(6): 57-62.

[5] Niu Cunyang, Alasamu, Liu Ya, et al. The characteristics of sand fixation plantations roots and soil moisture in Horqin sandy land[J]. *Journal of Arid Land Resources and Environment*, 2015, 29(10): 106-111.

[6] Li Xinle, Wu Bo, Zhang Jianping, et al. Dynamics of shallow soil water content in *Nitraria tangutorum* nebkha and response to rainfall[J]. *Acta Ecologica Sinica*, 2019, 39(15): 5701-5708.

[7] Du Lingtong, Zeng Yijian, Ma Longlong, et al. Effects of anthropogenic revegetation on the water and carbon cycles of a desert steppe ecosystem[J]. *Agricultural and Forest Meteorology*, 2021, 300: 108339.

[8] Liu Jiaxin, Liu Jiali, Wang Ni, et al. Adaptability analysis of four artificial planting shrubs in Yanchi desert steppe[J]. *Journal of Agricultural Sciences*, 2022, 43(3): 1-5.

[9] Wang Le, Du Lingtong, Ma Longlong, et al. Effects of planted shrub encroachment on carbon storage of desert steppe ecosystem[J]. *Acta Ecologica Sinica*, 2022, 42(1): 246-254.

[10] Yang J, Chen H, Nie Y, et al. Dynamic variations in profile soil water on karst hillslopes in Southwest China[J]. *Catena*, 2019, 172: 1598-1606.

[11] Rotzer K, Montzka C, Bogena H, et al. Catchment scale validation of SMOS and ASCAT soil moisture products using hydrological modeling and temporal stability analysis[J]. *Journal of Hydrology*, 2014, 519: 934-946.

[12] Nie Minghe, Shen Yan, Lu Ying, et al. Ecostoichiometric characteristics of dominant plant leaves soil ecology in different communities of desert steppe in Yanchi County, Ningxia[J]. *Acta Agrestia Sinica*, 2021, 29(1): 131-140.

[13] Wang X B, Zhou B Y, Sun X F, et al. Soil tillage management affects maize grain yield by regulating spatial distribution coordination of roots, soil moisture and nitrogen status[J]. *Plos One*, 2015, 10(6): e0129231.

[14] Wu Ting, Song Naiping, Chen Xiaoying, et al. Effects of enclosure and grazing on the characteristics of plant communities in desert steppe[J]. *Acta Agrestia Sinica*, 2019, 27(3): 651-660.

[15] Chen Juan, Chen Lin, Song Naiping, et al. Soil infiltration characteristics of different soils types in desert steppe[J]. *Journal of Soil and Water Conservation*, 2018, 32(4): 18-23.

[16] Li Yaxin, Chen Wei, Sun Congjian, et al. Soil moisture characteristics and their response to rainfall in cultivated land and abandoned land in loess hilly region[J]. *Journal of Arid Land Resources and Environment*, 2021, 35(12): 114-120.

[17] Zhu Hai, Hu Shunjun, Chen Yongbao. Spatio-temporal variation of soil moisture in fixed dunes at the southern edge of Gurbantunggut Desert[J]. *Acta Pedologica Sinica*, 2016, 53(1): 117-126.

[18] Chen Hongsong, Shao Ming'an, Wang Kelin. Water cycling characteristics of grassland and bare land soils on Loess Plateau[J]. *Chinese Journal of Applied Ecology*, 2005, 16(10): 1853-1857.

[19] Zhang Min, Liu Shuang, Liu Yong, et al. Soil moisture variation characteristics of different land use types in the moderate slope sandy area of Loess Hilly Region[J]. *Journal of Soil and Water Conservation*, 2019, 33(3): 115-120, 128.

[20] Wang Tao. Study on the Relationship between Soil Water Storage with Precipitation and Soil Temperature during the Summer Fallow Period of Dryland Winter Wheat under Different Mulching Methods[D]. Yangling: Northwest Agricultural & Forestry University, 2022.

[21] Duan Minfu, Liao Chaoying, Sun Changzhong, et al. Spatio-temporal variabilities of soil physical properties of *Pinus sylvestris* var. *mongolica* artificial forest in Mu Us Desert[J]. *Acta Agriculturae Boreali-Occidentalis Sinica*, 2012, 21(3): 188-192.

[22] Chen Xiaoying, Chen Lin, Song Naiping, et al. Comparison on moisture dynamics of two different soil types in desert steppe[J]. *Chinese Journal of Applied Ecology*, 2020, 31(5): 1560-1570.

[23] Xue Yi, Wang Xing, Song Naiping, et al. Fine scale spatial point patterns of *Stipa breviflora* population at different Soil Island habitat sizes in desert steppe[J]. *Journal of Zhejiang University (Agriculture and Life Sciences)*, 2019, 45(2): 211-220.

[24] Song Naiping, Wang Xing, Chen Lin, et al. Coexistence mechanisms of plant species within soil islands habitat of desert steppe[J]. *Biodiversity Science*, 2018, 26(7): 667-677.

[25] Song Naiping, Wu Xudong, Pan Jun, et al. Impacts of artificial *Caragana intermedia* stand on soil texture evolution in desert steppe[J]. *Journal of Zhejiang University (Agriculture and Life Sciences)*, 2015, 41(6): 703-711.

[26] Wang Xuan, Du Shuhan, Deng Limei, et al. Effects of different soil porosity on the water conservation of typical vegetation system in western Sichuan[J]. *Science of Soil and Water Conservation*, 2023, 21(1): 19-28.

[27] Gao G L, Ding G D, Zhao Y Y, et al. Fractal approach to estimating changes in soil properties following the establishment of *Caragana korshinskii* shelterbelts in Ningxia, NW China[J]. *Ecological Indicators*, 2014, 43: 236-243.

[28] Zheng Feilong, Wang Xina, Ge Min, et al. Characteristics of vertical water infiltration in a sierozem soil under gravel sand mulching condition[J]. *Chinese Journal of Soil Science*, 2021, 52(2): 314-321.

[29] Wei Yongxia, Wang He, Liu Hui, et al. Effect of biochar on soil moisture and its infiltration performance in black soil area[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2019, 50(9): 290-299.

[30] Fay P A, Blair J M, Smith M D, et al. Relative effects of precipitation variability and warming on tallgrass prairie ecosystem function[J]. *Biogeosciences*, 2011, 8(10): 3053-3068.

[31] Chang Changming, Niu Jianming, Wang Hai, et al. Dynamic change of soil moisture and its response to rainfall in a *Stipa klemenzii* steppe[J]. *Arid Zone Research*, 2016, 33(2): 260-265.

[32] Yang Qihong, Chen Lihua, Zhang Fu, et al. Responses of soil moisture variations to rainfall and vegetation[J]. *Journal of Beijing Forestry University*, 2008, 30(S2): 88-94.

[33] Famiglietti J S, Rudnicki J W, Rodell M. Variability in surface moisture content along a hillslope transect: Rattlesnake hill, Texas[J]. *Journal of Hydrology*, 1998, 210: 259-281.

[34] Shen Ju, Xin Pingping, Yang Qinan, et al. Response of shallow soil moisture increment to precipitation in eastern Qaidam Basin[J]. *Chinese Agricultural Science Bulletin*, 2022, 38(35): 54-61.

[35] Yang Lei, Zhang Handan, Chen Liding. Identification on threshold and efficiency of rainfall replenishment to soil water in semi-arid loess hilly areas[J]. *Scientia Sinica (Terrae)*, 2018, 48(4): 457-466.

[36] Shi Jianzhou, Liu Xiande, Tian Qing, et al. Rainfall response of *Larix principis-rupprechtii* plantation soil water content on a slope in the semi-arid Liupan Mountains[J]. *Arid Zone Research*, 2023, 40(4): 594-604.

[37] Xie Z K, Wang Y J, Cheng G D, et al. Particle size effects on soil temperature, evaporation, water use efficiency and watermelon yield in fields mulched with gravel and sand in semi-arid Loess Plateau of Northwest China[J]. *Agricultural Water Management*, 2010, 97(6): 917-923.

[38] Wei Yafen, Guo Ke, Chen Jiquan. Effect of precipitation pattern on recruitment of soil water in Kubuqi desert, northwestern China[J]. *Journal of Plant Ecology*, 2008, 32(6): 1346-1355.

[39] Wang Jia, Tian Qing, Wang Lide, et al. Effects of different years of returning farmland on soil moisture and species diversity in Minqin Qingtu Lake area[J]. *Arid Zone Research*, 2022, 39(2): 605-614.

[40] Yuan Limin, Yang Zhiguo, Xue Bo, et al. Heterogeneity of soil moisture of blowouts in HulunBuir grassland[J]. *Arid Zone Research*, 2022, 39(5): 1598-1606.

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