Surface Soil Moisture Pulses Beneath Two Dominant Shrubs in the Gobi Desert and Their Influencing Factors

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Abstract

In desert ecosystems, shrubs regulate the spatiotemporal dynamics of surface soil moisture through the redistribution of rainfall. However, understanding remains limited regarding the short- and long-term effects of shrub presence and species differences on the spatiotemporal variation of surface soil moisture in deserts. Accordingly, this study focused on two dominant shrub species in the Gobi Desert, Reaumuria songarica and Nitraria sphaerocarpa. Based on daily monitoring data from soil moisture sensors and periodic measurements using the oven-drying method during the plant growing seasons of 2019–2020, we systematically analyzed daily, seasonal, and annual patterns of soil moisture in shrub and bare-ground microhabitats, and determined the effects and regulatory roles of rainfall variation and shrub interactions on the spatiotemporal dynamics of soil moisture. The results showed that Reaumuria songarica increased surface soil water content, whereas Nitraria sphaerocarpa had the opposite effect. The significance and duration of these effects were jointly regulated by rainfall amount and season of occurrence, thereby determining the multiscale dynamic patterns of soil moisture among the three microhabitats. Light rainfall in spring significantly increased soil water content in all three microhabitats, and the effect lasted for up to 32 d. By contrast, rainfall events in summer and autumn had relatively weak effects, with only moderate rainfall (15 mm) significantly increasing soil water content in the three microhabitats; however, this effect lasted for only 2 d. Small rainfall events (< 5 mm) did not produce significant moisture-increasing effects in any microhabitat. At the daily scale, soil water content did not differ significantly among the three microhabitats after a single rainfall event in spring, whereas in summer and autumn, soil water content in Reaumuria songarica shrub patches and bare ground was significantly higher than that in Nitraria sphaerocarpa shrub patches. At the seasonal scale, soil water content in Nitraria sphaerocarpa shrub patches was significantly lower than that in Reaumuria songarica shrub patches or bare ground in most seasons during the observation period. At the annual scale, soil water content in Nitraria sphaerocarpa shrub patches was significantly lower overall than that in Reaumuria songarica shrub patches, and was also significantly lower than that in bare-ground microhabitats in 2019. Analysis of key driving factors showed that shrub volume, soil bulk density, and soil hardness jointly explained 31.5% of the variation in soil moisture after a single rainfall event. In summary, the effects of dominant shrubs in the Gobi Desert on surface soil moisture exhibit significant differentiation across multiple temporal scales, and this differentiation is closely related to changes in rainfall patterns.

Full Text

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Surface Soil Moisture Pulses Beneath Two Dominant Shrubs in the Gobi Desert and Their Influencing Factors

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Abstract: In desert ecosystems, shrubs regulate the spatiotemporal dynamics of surface soil moisture through the redistribution of rainfall. However, understanding remains limited regarding the short- and long-term effects of shrub presence and species differences on the spatiotemporal variation of surface soil moisture in deserts. Accordingly, this study focused on two dominant shrubs in the Gobi Desert—red sand (*Reaumuria songarica*) and *Nitraria sphaerocarpa*—and, based on daily monitoring data from soil moisture sensors during the plant growing seasons of 2019–2020 together with periodic measurements by the oven-drying method, systematically analyzed the daily, seasonal, and interannual variation patterns of soil moisture in shrub and bare-ground microhabitats, and determined the effects and regulatory roles of rainfall variation and shrub interaction on the spatiotemporal dynamics of soil moisture. The results showed that red sand increased surface soil water content, whereas *Nitraria sphaerocarpa* had the opposite effect; the significance and duration of this effect were jointly regulated by rainfall amount and the season of occurrence, thereby determining the multi-scale dynamic pattern of soil moisture in the three microhabitats. Small rainfall events in spring (<5 mm) caused only a short-term increase of 2–3 d in soil water content under red sand and in bare ground; by contrast, extreme rainfall in autumn (>25 mm) significantly increased soil water content in all three microhabitats, and the effect lasted as long as 32 d. At the daily scale, there were no significant differences in soil water content among the three microhabitats after a single rainfall event in spring, whereas in summer and autumn the soil water content in red-sand shrubland and bare ground was significantly higher than that in *Nitraria sphaerocarpa* shrubland. At the seasonal scale, soil water content in *Nitraria sphaerocarpa* shrubland was significantly lower than that in red-sand shrubland or bare ground in most seasons during the observation period. At the annual scale, soil water content in *Nitraria sphaerocarpa* shrubland was overall significantly lower than that in red-sand shrubland and was also significantly lower than that in the bare-ground microhabitat in 2019. Analysis of key driving factors showed that shrub volume, soil bulk density, and soil hardness jointly explained 31.5% of the variation in soil moisture after a single rainfall event. In summary, the effects of dominant shrubs in the Gobi Desert on surface soil moisture exhibit significant differentiation across multiple

temporal scales, and this differentiation is closely related to changes in rainfall patterns.

Keywords: Gobi Desert; rainfall variation; shrub; soil water content; spatiotemporal dynamics

The Gobi Desert refers to a distinctive type of desert landscape formed in arid or extremely arid regions under long-term, intense wind erosion or physical weathering; it is widely distributed in open terrain and is characterized by a ground surface covered with gravel[1]. The Gobi Desert has scarce precipitation and poor soils, and its vegetation shows a pronounced patchy distribution pattern. Natural precipitation is the main water source for plant growth and animal survival in this region, and small rainfall events account for approximately 80% of all precipitation events[2]. Desert precipitation is scarce and exhibits distinct pulsed variation. Rainfall events of different magnitudes drive short- and long-term pulses in soil moisture, affecting the structure and function of desert ecosystems[3–5]. In the Gobi Desert, the groundwater table is relatively deep, and shrubs and herbs mainly use natural precipitation. The presence and species identity of shrubs can induce the redistribution of precipitation, drive spatiotemporal changes in surface soil moisture, and thereby affect plant growth and animal survival[6–9].

Short-term precipitation pulses can increase the growth and developmental rates of plants and animals, while interannual and seasonal variation in precipitation can also exert long-term effects on plant growth and animal population dynamics. Desert plant primary productivity and arthropod populations show long-term responses and lag effects to precipitation[10–12]. In recent years, considerable attention has been paid to the process by which shrubs redistribute precipitation. Researchers have clarified the redistributive effects of shrubs on precipitation in terms of shrub roots influencing precipitation distribution dynamics[13], the relationship between soil evaporation in shrub patches and precipitation[14], and the effects of throughfall and canopy interception on precipitation redistribution[7–9]. These studies have revealed the response, adaptation, and feedback mechanisms of shrub ecophysiology to precipitation changes under different climatic backgrounds. However, studies on the duration of soil moisture dynamics under different shrubs after rainfall and the regulatory mechanisms of their attenuation remain relatively weak. In arid and semi-arid regions,

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Driven by precipitation events, soil moisture exhibits typical pulse dynamics; this process can be divided into a brief pulse high-water period (Pulse) and a long interpulse period (Interpulse). Under light-rain events, canopy interception and surface evaporation dominate water loss, and the pulse is short-lived[9]; whereas heavy rainfall or continuous rainfall can promote water infiltration, enhance deep soil water storage, and prolong the duration of the high-water period, thereby more markedly alleviating vegetation water stress[3,7,13]. Precipitation pulses drive changes in soil moisture and temperature, regulate plant life-history processes, population dynamics, and community structure[5,15], and further affect desert animal diversity, ecological functions, and the health and stability of desert ecosystems[5,10,15–17]. Existing studies still lack systematic observations and quantitative analyses of the interactions between precipitation and shrubs and the resulting mechanisms of differentiation in microhabitat moisture dynamics. Therefore, research on the relationship between soil moisture and precipitation at different spatial and temporal scales will help deepen understanding of how precipitation pulses act on ecosystem processes.

Reaumuria songarica and *Nitraria sphaerocarpa* are two dominant shrub species in the Gobi Desert. Among them, the more drought-tolerant *R. songarica* is mainly distributed on the relatively higher terrain on both sides of gullies, whereas *N. sphaerocarpa* is concentrated along gully margins. Previous studies have found that the patchy microhabitats formed by these two shrubs can influence soil moisture and improve the soil environment; they can also enrich food resources and provide animals with refuges from predator predation and temperature stress, thereby increasing plant and animal diversity[18–19]. As "ecosystem engineers," shrubs in the Gobi Desert can also alter the surface soil environment and affect precipitation infiltration and the processes of soil moisture change at different depths[18,20]. Precipitation-induced pulses in soil moisture drive aboveground and belowground processes in desert ecosystems[3,5,17]. However, understanding remains limited regarding how rainfall variation and shrub interactions jointly drive the spatiotemporal variation of soil moisture, especially in typical desert ecosystems. The presence of desert shrubs and interspecific differences drive changes in surface soil moisture and temperature, which affect herbaceous plant distribution and the maintenance of animal diversity across body sizes. Therefore, taking the two dominant shrub species *R. songarica* and *N. sphaerocarpa* in the Gobi Desert as study objects, this paper uses continuous monitoring data of surface soil moisture in shrub and bare-land microhabitats from 2019 to 2020, fixed-site monitoring data of soil moisture after rainfall events of different magnitudes, and soil moisture monitoring data in different seasons to analyze the daily, seasonal, and annual variation patterns and influencing factors of surface soil moisture, thereby deepening understanding of the processes by which precipitation–shrub interactions affect the spatiotemporal variation of surface soil moisture in the Gobi Desert under the background of climate change.

1 Materials and Methods

1.1 Overview of the Study Area

The study area is located on the northern margin of Linze County, Zhangye City, in the middle section of the Hexi Corridor, Gansu Province. This area is a gravelly desert formed by piedmont alluviation (39°21′N, 100°07′E; 1350 m). The climate is a temperate continental arid desert climate, with a long-term mean annual precipitation of 117.0 mm and a mean annual evaporation of 2390 mm. Precipitation is mainly concentrated from July to September, accounting for about 65% of annual precipitation. The mean annual temperature is 7.6 ℃, and wind-sand activity is mainly concentrated from March to May. The soil is gray-brown desert soil; the sand content of the soil exceeds 95%, and the groundwater table is deeper than 10–12 m. Annual precipitation and annual numbers of precipitation events of different types, as well as monthly precipitation and monthly mean temperature changes in the study area during 2019–2020, are shown in Figure 1. Precipitation events of 0–5 mm occurred most frequently. Annual precipitation was relatively high in 2019 (130.9 mm), whereas annual precipitation in 2020 was close to the long-term mean annual precipitation (111.7 mm), with a mean annual temperature of 8.9 ℃. A precipitation process beginning when daily precipitation was >0.1 mm and ending when daily precipitation reached 0 mm was defined as one precipitation event. During the entire observation period from 2019 to 2020, a total of 63 precipitation events occurred. According to the precipitation-grade classification standards of the China Meteorological Administration, precipitation events at this site were classified by grade. Statistics showed that during the investigation period there were 58 light-rain events (0–10 mm), 4 moderate-rain events (10–25 mm), and 1 heavy-rain event (43.4 mm), indicating that the study area was dominated by small precipitation events of <10 mm. Among them, precipitation frequency was highest in August 2019 (29.03%), followed by May 2020 (22.58%) and August 2020 (22.57%); moderate and heavy rains occurred from June to September (Figure 1).

The study area is a Gobi Desert formed by piedmont alluviation. Vegetation cover is below 10%, showing an obvious banded or patchy distribution pattern. *R. songarica* and *N. sphaerocarpa* are the dominant vegetation-forming species in this area. *R. songarica* is more drought-tolerant than *N. sphaerocarpa*, is mainly distributed in areas with relatively higher terrain, and can form monodominant communities; *N. sphaerocarpa* is mainly distributed in lower-lying areas and grows well in areas of seasonal runoff accumulation, where it forms tall sand mounds. *R. songarica* shrubs are smaller than *N. sphaerocarpa* shrubs and flower and set fruit in autumn; *N. sphaerocarpa* flowers and sets fruit in summer and then sheds its leaves, and after rainfall increases in autumn it can flush leaves again and even flower[10]. Desert perennial herbs are dominated by *Stipa tianschanica*, *Allium mongolicum*, *Zygophyllum fabago*, and *Artemisia annua*, among others. Annual herbs are mainly composed of *Agriophyllum squarrosum*, *Halogeton glomeratus*, *Bassia dasyphylla*, *Echinops gmelinii*, *Chloris virgata*, and *Eragrostis minor*, among others. Herbaceous growth is affected by precipitation fluctuations and shows marked interannual and seasonal variation. Small and medium-sized desert mammals and reptiles inhabit *N. sphaerocarpa* shrublands; typical desert arthropods such as Arachnida and Tenebrionidae inhabit and reproduce in *N. sphaerocarpa* shrublands; and the active period of desert harvester ants occurs during the seed-maturation periods of *N. sphaerocarpa* and *R. songarica*[12,21-22].

1.2 Experimental Design and Sample Collection

Monitoring of soil water content in *R. songarica*, *N. sphaerocarpa*, and bare land was conducted at the Chinese Sci—

Figure 1. Changes in annual precipitation frequency and annual precipitation, monthly precipitation, and monthly mean temperature in the study area from 2019 to 2020.

Panel labels: (a) bubble-thorn; (b) red-sand shrub; (c) bare land; (d) HOBO meteorological station; (e) annual precipitation frequency and annual precipitation; (f) monthly precipitation and monthly mean temperature.
Legend text in (e): precipitation frequency: 0–5 mm, 5-10 mm, 10–20 mm, > 40 mm; precipitation: 0–5 mm, 5-10 mm, 10–20 mm, > 40 mm. Axes: precipitation frequency/times; precipitation/mm; year.
Legend text in (f): 2019—precipitation, temperature; 2020—precipitation, temperature. Axes: precipitation/mm; temperature/°C; month.

The work was carried out in the long-term desert ecosystem observation field of the Linze Inland River Basin Research Station of the Academy. In spring 2018, fixed monitoring plots for simulated precipitation and changes in predation intensity were established in the observation field. Centered on two shrub species, red-sand shrub and bubble-thorn, $3\,m \times 3\,m$ fixed monitoring plots were established. In this study, eight red-sand shrub plots and eight bubble-thorn plots under natural rainfall treatment were selected. In addition, eight bare-land plots between shrubs were selected as control plots, with the distance from the nearest shrub $> 5\,m$. In April 2018, a HOBO mini meteorological station (U30-NRC) was installed in the Gobi desert to monitor air temperature, precipitation, relative humidity, wind direction, wind speed, and other variables. The HOBO mini meteorological station was equipped with three soil-temperature sensors and three moisture sensors. From March to October in 2019–2020, it continuously monitored daily changes in soil water content and temperature in the 10 cm soil layer of the red-sand shrub, bubble-thorn, and bare-land microhabitats; the meteorological station recorded one value every 5 min. In spring (April 30), summer (July 30), and autumn (September 30) of 2019 and 2020, a soil auger with a diameter of 2.5 cm was used to collect soil samples from the 10 cm soil layer beneath the canopies of the two shrub species and from bare-land microhabitats. Four soil samples were collected from each microhabitat, mixed, and brought back to the laboratory; soil water content was determined by the oven-drying method (105 °C) to compare seasonal differences in soil moisture among different microhabitats. During the 2019 plant growing season, six rainfall events of different magnitudes were also selected. On the second day after rainfall, soil samples from the 10 cm soil layer beneath shrub canopies and in bare land were collected and brought back to the laboratory, where soil water content was measured by the oven-drying method to compare differences in soil moisture among microhabitats after individual rainfall events (Table 1).

Table 1. Statistical information on six different precipitation events in 2019

Precipitation event	Precipitation date	Precipitation class	Precipitation amount/mm	Precipitation intensity/(mm · h^{-1})
$R_{6.0}$	May 10	Light rain	6.0	0.25
$R_{12.6}$	June 16	Moderate rain	12.6	0.53
$R_{11.4}$	June 23	Moderate rain	11.4	0.48
$R_{1.6}$	June 28	Light rain	1.6	0.07
$R_{12.8}$	July 9	Moderate rain	12.8	0.53
$R_{3.8}$	July 23	Light rain	3.8	0.16

Note: R denotes a precipitation event, and the subscript denotes the precipitation amount; heavy rain (25–50 mm); moderate rain (10–25 mm); light rain (< 10 mm).

In autumn 2020, soil moisture, shrub height, and east–west and north–south crown widths of red-sand shrub and bubble-thorn were measured, and herbaceous cover and species were counted with the shrub and bare-land monitoring points as the centers. In each quadrat, two soil samples (0–10 cm) were collected using the cutting-ring method and mixed to obtain one composite soil sample. Of the collected soil samples, one quarter was used to determine the soil water content of shrub and bare-land soils by the oven-drying method and to monitor the 0–10 cm soil bulk density of the plots; the remaining three quarters were placed indoors and air-dried under natural conditions to constant weight. After sieving to remove stones, grass roots, leaves, and other impurities, the contents of coarse sand ($\geq$ 0.25 mm), fine sand (0.05–0.25 mm), and clay–silt particles ($\leq$ 0.05 mm) in the soil were determined by the dry-sieving method [23]. Using soil

Tab. 2 Vegetation and soil environment characteristics of *Reaumuria songarica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats

<table>
<tr><th>Characteristic</th><th>Reaumuria songarica</th><th>Nitraria sphaerocarpa</th><th>Bare ground</th></tr>
<tr><td>Shrub height/cm</td><td colspan="3">30.25$±7.13a|39.75± [illegible] cm^{- 3})|1.53±0.14a|1.60±0.08a|1.55±0.11a||Soilclayandsiltcontent/±1.17a| [illegible]</td></tr>
</table>

Note: Different lowercase letters indicate differences among different microhabitats.

A hardness meter was used to determine soil hardness in the shrub and bare-ground monitoring plots. In each plot, hardness values were measured in four directions around the shrub, and the mean value was taken to represent the soil hardness of that microhabitat (Table 2).

1.3 Data processing

Soil moisture content data for *Reaumuria songarica*, *Nitraria sphaerocarpa*, and bare ground, continuously monitored by sensors at the HOBO meteorological station from March to October in 2019–2020, were summarized by day. According to the dates on which rainfall occurred, the number of days over which soil moisture exhibited pulse increases after rainfall events of different magnitudes in the three microhabitats was calculated. After a rainfall event occurred, soil moisture entered a rapid increase phase (pulse periods); as time elapsed, soil moisture began to decline again and approached the soil moisture content before rainfall, i.e., the non-increase phase (interpulse periods). Referring to relevant literature

$$3, 24$$

, the time at which soil moisture after rainfall approached the pre-rainfall level was taken as the cutoff time, and the number of days of pulse increase in soil moisture after rainfall events of different magnitudes was calculated.

Three-way analysis of variance was used to determine the effects of year, season, and microhabitat type on soil moisture content in the *Reaumuria songarica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats during 2019–2020, and to compare differences in soil moisture content among the three microhabitats in different years and seasons. Statistical analyses were conducted using SPSS 21.0. Two-way analysis of variance was used to analyze the effects of rainfall events and microhabitat type on soil moisture content after rainfall, and to compare differences in soil moisture content between shrub and bare-ground microhabitats after different rainfall events, together with tests of significance for these differences ($\alpha = 0.05$). In addition, differences in soil moisture content among *Reaumuria songarica*, *Nitraria sphaerocarpa*, and bare ground from March to October in 2019–2020 were calculated. Spearman correlation analysis was used to determine the relationships between vegetation and soil physical environmental factors in shrub and bare-ground microhabitats and soil moisture content after rainfall. Redundancy analysis (RDA) was used to analyze the contribution rates of vegetation and soil physical environmental factors after rainfall to their effects on microhabitats. Statistical analyses were conducted using the general ordination software CANOCO 5.0.

2 Results and analysis

2.1 Pulse changes in soil moisture content in the three microhabitats

There were extremely significant differences in surface soil moisture content between shrub and bare-ground microhabitats ($P < 0.01$). Surface soil moisture content in the *Reaumuria songarica* microhabitat was significantly higher than that in the *Nitraria sphaerocarpa* and bare-ground microhabitats ($P < 0.05$). Compared with the *Reaumuria songarica* microhabitat, the annual mean soil moisture content in the *Nitraria sphaerocarpa* and bare-ground microhabitats decreased significantly by 38.03% and 34.29%, respectively. The difference in surface soil moisture content between the *Nitraria sphaerocarpa* and bare-ground microhabitats was not significant ($P > 0.05$) (Fig. 2). Differences in soil moisture content among microhabitats showed significant seasonal differentiation with rainfall events. In spring (March–May), after heavy rainfall, the pulse duration of surface soil moisture was long, about 13 d; after small rainfall events, the soil moisture pulse duration was short, about 3 d, among which

Fig. 2 Dynamic changes in precipitation and topsoil moisture content across *Reaumuria soongorica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats in the study area from March to October in 2019–2020

In the *Nitraria sphaerocarpa* microhabitat, the duration of increased soil moisture content was the longest. In summer (June–August), the number of rainfall events increased; after light and heavy rainfall, the pulse duration of topsoil moisture was generally similar, at approximately 2–6 d, with the shortest duration of increased soil moisture occurring in the *N. sphaerocarpa* microhabitat. In autumn (September–October), rainfall decreased. After an extreme rainfall event (43.6 mm), the pulse duration of topsoil moisture was the longest, approximately 32 d; among the microhabitats, the duration of increased soil moisture in the *Reaumuria songarica* and *N. sphaerocarpa* microhabitats was prolonged by 3 d. Differences in soil moisture content among the microhabitats weakened in spring and autumn. In spring, when rainfall was 42.1 mm, the soil moisture content in the *R. songarica* microhabitat was 152.43% and 150.22% of that in the *N. sphaerocarpa* and bare-ground microhabitats, respectively. In autumn, when rainfall was 75.8 mm, the soil moisture content in the *R. songarica* microhabitat was 136.37% and 144.78% of that in the *N. sphaerocarpa* and bare-ground microhabitats, respectively. In summer, differences in soil moisture content among the microhabitats increased; when rainfall was 118.4 mm, the soil moisture content in the *R. songarica* microhabitat was 184.60% and 167.00% of that in the *N. sphaerocarpa* and bare-ground microhabitats, respectively (Fig. 2). After heavy rainfall occurred, the soil moisture content beneath *N. sphaerocarpa* shrubs was temporarily higher than that of bare ground, and sometimes even higher than that beneath *R. songarica* shrubs.

2.2 Comparison of soil moisture content among the three microhabitats after rainfall

The effects of shrub and bare-ground microhabitats and rainfall events on soil moisture content after rainfall were both highly significant ($F = 7.32,\ P < 0.01$; $F = 42.27,\ P < 0.01$). The interaction between rainfall event and microhabitat also had a significant effect on soil moisture content ($F = 1.91,\ P = 0.044$). Differences in soil moisture content between shrub and bare-ground microhabitats varied with rainfall amount among rainfall events. Except after the light rainfall event in May (6 mm), when differences in topsoil moisture content among shrub and bare-ground microhabitats were not significant ($P > 0.05$), significant differences in topsoil moisture content among the three microhabitats occurred after the other five rainfall events ($P < 0.05$) (Fig. 3). After the 6 mm rainfall in May, the soil moisture content of bare ground was higher than that of *R. songarica* and *N. sphaerocarpa*, but the differences among them were not significant (Fig. 3). After the five light and moderate rainfall events that occurred in June and July, soil moisture content in the *R. songarica* and bare-ground microhabitats was significantly higher than that in the *N. sphaerocarpa* microhabitat. After these five rainfall events, soil moisture content in the *R. songarica* and bare-ground microhabitats varied to some extent, but the difference between the two was not significant. After the three rainfall events in June (12.6 mm, 11.4 mm, and 1.6 mm), soil moisture content in *N. sphaerocarpa* was 24.30%–38.79% lower than that in *R. songarica* and bare ground (24.30%, 31.57% and 28.65%, 29.18%, as well as 38.79%, 29.89%); after the two rainfall events in July (12.8 mm and 3.8 mm), soil moisture content in *N. sphaerocarpa* was 30.70%–39.82% lower than that in *R. songarica* and bare ground (33.15%, 30.70% and 39.82%, 37.08%) (Fig. 3). Thus, as rainfall amount decreased, the differences in soil moisture content between the *R. songarica* and bare-ground microhabitats and the *N. sphaerocarpa* microhabitat gradually increased.

Figure 3 in-figure labels: Legend: *Reaumuria songarica*; *Nitraria sphaerocarpa*; bare ground. Y-axis: Soil moisture content/%; X-axis: Rainfall event. Events: $R_{6.0}$, $R_{12.6}$, $R_{11.4}$, $R_{1.6}$, $R_{12.8}$, $R_{3.8}$.

Note: Different lowercase letters indicate differences in topsoil moisture content among different microhabitats; different uppercase letters indicate differences in topsoil moisture content among different rainfall events. R represents a rainfall event, and the subscript indicates rainfall amount; heavy rain (25–50 mm); moderate rain (10–25 mm); light rain (<10 mm). The same applies below.

Fig. 3 Comparison of topsoil moisture content at *Reaumuria songarica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats after six rainfall events

2.3 Interannual and seasonal changes in soil moisture content in the three microhabitats

Soil moisture content differed highly significantly among shrub and bare-ground microhabitats, among seasons, and among years ($F = 15.70,\ P < 0.01;\ F = 273.63,\ P < 0.01;\ F = 20.04,\ P < 0.01$). The two-way interactions of year and season with microhabitat had no significant effect on soil moisture content ($F = 0.83,\ P = 0.439;\ F = 1.27,\ P = 0.284$). The two-way interaction between year and season had a highly significant effect on soil moisture content ($F = 175.49,\ P < 0.01$), and the three-way interaction among year, season, and microhabitat also had a significant effect on soil moisture content ($F = 2.93,\ P = 0.021$). Soil moisture content differed significantly among the *R. songarica*, *N. sphaerocarpa*, and bare-ground microhabitats, and these differences varied with season and year. In 2019, soil moisture content beneath *N. sphaerocarpa* shrubs was significantly lower than that beneath *R. songarica* shrubs and in bare ground by 40.68% and 39.78%, respectively. In 2020, only the soil moisture content beneath *N. sphaerocarpa* shrubs was significantly lower than that beneath *R. songarica* shrubs, by 24.26%; the difference in soil moisture content between the bare-ground microhabitat and *N. sphaerocarpa* shrubs was not significant (Fig. 4). In spring and summer of 2019, soil moisture content beneath *N. sphaerocarpa* shrubs was significantly lower than that beneath *R. songarica* shrubs and in bare ground by 46.49%, 50.21% and 48.31%, 33.22%, respectively; in autumn, only the soil moisture content beneath *N. sphaerocarpa* shrubs was significantly lower than that in the bare-ground microhabitat, by 36.64%. In spring 2020, differences in soil moisture content among the three microhabitats were not significant. In summer, soil moisture content beneath *R. songarica* shrubs was significantly lower than that in bare ground by 34.10%, while soil moisture content beneath *N. sphaerocarpa* shrubs was significantly lower than that beneath *R. songarica* shrubs by 45.29%. In autumn, soil moisture content increased substantially; soil moisture content beneath *N. sphaerocarpa* shrubs was significantly lower than that beneath *R. songarica* shrubs by 24.91%, whereas differences in soil moisture content between bare ground and the *R. songarica* and *N. sphaerocarpa* shrublands were not significant (Fig. 4).

Fig. 4 Comparison of topsoil moisture content in the *Reaumuria soongorica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats in spring, summer, and autumn of 2019 and 2020

In-figure labels: legend—*Reaumuria soongorica*, *Nitraria sphaerocarpa*, bare ground; y-axis—soil moisture content/%; x-axis—spring, summer, autumn in 2019 and 2020.

Note: Different lowercase letters indicate significant differences in topsoil moisture content among microhabitats; different uppercase letters indicate significant differences in topsoil moisture content among seasons; ** indicates a significant difference in topsoil moisture content between years.

Fig. 5 Relationships between topsoil moisture content and vegetation and soil environmental factors under the *Reaumuria soongorica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats across six precipitation events ($n = 48$)

In-figure labels: shrub height, shrub crown width, shrub volume, soil clay + silt particles, soil fine sand, soil coarse sand, soil hardness, soil bulk density, $R_{6\cdot0}$, $R_{12\cdot6}$, $R_{11\cdot4}$, $R_{1\cdot6}$, $R_{12\cdot8}$, $R_{3\cdot8}$; color bar—correlation coefficient.

Note: Blue indicates positive correlation, and the darker the color, the stronger the positive correlation; red indicates negative correlation, and the darker the color, the stronger the negative correlation. * indicates $P < 0.05$; ** indicates $P < 0.01$.

2.4 Effects of vegetation and soil physical properties on soil moisture content

As shown in Fig. 5, vegetation characteristics of the shrub and bare-ground microhabitats—shrub height, crown width, and volume—as well as soil physicochemical properties, including soil hardness and soil bulk density, were significantly correlated with soil moisture content after rainfall ($P < 0.05$). After the light rainfall event in May, shrub height was significantly negatively correlated with post-rainfall soil moisture content ($P < 0.05$). After the light and moderate rainfall events in June and July, shrub crown width and shrub volume in the shrub and bare-ground microhabitats were extremely significantly negatively correlated with post-rainfall soil moisture content ($P < 0.01$), and soil bulk density was significantly negatively correlated with post-rainfall soil moisture content ($P < 0.05$). Soil hardness in the shrub and bare-ground microhabitats was significantly positively correlated only with soil moisture content after the light rainfall event in June ($P < 0.05$). Thus, as rainfall amount increased, the correlations between vegetation and soil physical properties in the shrub and bare-ground microhabitats and post-rainfall soil moisture content became significant.

As shown in Fig. 6, vegetation and soil physical factors cumulatively explained 39.3% of the variation in the soil environment, and the ordination results well reflected the relationships between post-rainfall soil moisture content in different microhabitats and changes in vegetation and soil environmental factors. The results of variance partitioning showed that shrub volume and soil bulk density explained 21.5% and 6.3% of the variation in the soil environment, respectively ($F = 12.6$, $P = 0.002$; $F = 3.9$, $P = 0.004$), while soil hardness explained 3.7% of the variation in the soil environment ($F = 2.4$, $P = 0.040$). The RDA results showed that shrub volume, soil bulk density, and soil hardness were key environmental factors affecting vegetation and soil environmental changes after rainfall, together explaining 31.5% of the variation in the soil environment (Table 3). Ordination axis 1 mainly reflected changes in shrub volume and soil bulk density, indicating certain differences in soil environmental changes between the *Nitraria sphaerocarpa* microhabitat and the *Reaumuria soongorica* and bare-ground microhabitats; ordination axis 2 mainly reflected changes in soil hardness and shrub height. The distributions of the different microhabitats (*Reaumuria soongorica*, bare ground, and *Nitraria sphaerocarpa*) on the ordination diagram differed, indicating that the relationships between post-rainfall soil moisture content and vegetation and soil environmental variables had distinct characteristics among microhabitats.

3 Discussion

Soil moisture is a key factor limiting vegetation growth and development in desert ecosystems, and its magnitude and temporal distribution determine vegetation developmental processes and growth patterns[25–26]. In recent years, some studies have also found that precipitation events of different magnitudes affect short- and long-term pulse dynamics of soil moisture beneath shrubs in Gobi deserts, while also stimulating various biochemical processes, such as denitrification–decomposition processes[27], and plant physiological activities, such as nutrient uptake, respiration, and growth[28]. Previous studies have found that precipitation events can induce moisture pulses in the topsoil lasting from several hours to several days, with their duration depending on the magnitude of the precipitation event and the air vapor pressure deficit[29]. Discontinuous soil moisture conditions directly control belowground water processes in arid and semi-arid ecosystems[30]. Collins et al.[31], in a study of Chihuahuan Desert grassland, found that light rainfall events increased the belowground

[Figure 6]

Note: R denotes a rainfall event, and the subscript denotes rainfall amount; SH1 is soil hardness; SBD is soil bulk density; FSC is fine sand; CSC is coarse sand; SH2 is shrub height; CW is shrub crown width; SV is shrub volume.

Fig. 6 Two-dimensional RDA ordination diagram illustrating the relationships between topsoil moisture content following six rainfall events and vegetation and soil factors across the *Reaumuria soongorica*, *Nitraria sphaerocarpa*, and bare-ground microhabitats

Table 3 Relative contributions of vegetation and soil environmental factors to microhabitat soil moisture variation after six rainfall events, determined by RDA

Tab. 3 Quantification of the relative contributions of vegetation and soil environmental factors to topsoil moisture variation after six rainfall events using RDA

Variable	Explanation rate/%	Contribution rate/%	F	P
Shrub volume/m^3	21.5	54.8	12.6	**0.002**

Variable	Explanation rate/%	Contribution rate/%	F	P
Soil bulk density/$(g \cdot cm^{-3})$	6.3	16.1	3.9	**0.004**
Shrub crown width/cm	2.1	5.2	1.3	0.278
Soil hardness/mm	3.7	9.4	2.4	**0.040**
Shrub height/cm	3.0	7.6	2.0	0.092
Soil fine sand content/%	2.0	5.0	1.3	0.246
Soil coarse sand content/%	0.7	1.9	0.5	0.770
Total	39.3	100		

Note: Bold values indicate significant differences ($P < 0.05$).

productivity. Although small rainfall events deliver little water in a single event, they can moisten the surface soil more frequently, stimulating sustained root growth and water input. Zhang et al. [32] collected and analyzed 40 studies of runoff plots from across China, finding that rainfall amount determines the roles of soil erosion and vegetation protection in soil and water conservation; this is similar to the results of the present study.

This study also found that, after rainfall occurs, soil moisture in the Gobi desert exhibits pulsed changes, and these changes are clearly affected by rainfall amount, season, and interannual variation. Differences in moisture content among microhabitats showed significant seasonal differentiation with rainfall events—the differences were smallest in spring and largest in summer and autumn. After small spring rainfall events, the duration of soil moisture pulses was short; among them, the *Nitraria sphaerocarpa* microhabitat had the longest period of increased soil moisture content. This may be because *N. sphaerocarpa* grows relatively slowly in spring and has weaker transpiration, consuming less soil water and thereby allowing soil moisture fluctuations to persist for a longer time [3, 7, 9]. After summer rainfall, shrub and bare-ground microhabitats had the shortest soil moisture pulse duration. It is inferred that higher summer temperatures and enhanced transpiration rapidly consume soil water, leading to shortened soil moisture pulse duration [9]. The study found that in summer the difference in soil moisture content between *Reaumuria soongorica* shrub patches and the *N. sphaerocarpa* and bare-ground microhabitats increased, indicating that under hot and rainy summer conditions, *R. soongorica*, relying on its own physiological and ecological adaptability, can more effectively use precipitation to replenish soil moisture and reduce water loss [5, 25, 33]. Zhou Hai et al. [6] also showed that pulsed changes in desert surface soil moisture are regulated by rainfall amount and season, reflecting the combined influence of precipitation patterns and vegetation type on dynamic changes in soil moisture. This study further found that after extreme autumn rainfall, the pulse duration of surface soil moisture was the longest, and the period of increased soil moisture in shrub microhabitats was prolonged. This may be because temperatures decline in autumn, vegetation transpiration weakens, and the soil evaporation rate decreases, allowing soil moisture after rainfall to remain relatively stable for a longer period. Han Wenjun et al. [34] also found similar conclusions in the Alxa desert region; this may be attributable to the favorable sandy characteristics of desert soils, with shrub canopy interception and soil water retention acting together to prolong the residence time of surface water [20, 33]. At the interannual scale, soil moisture content under *R. soongorica* and on bare ground was significantly higher than under *N. sphaerocarpa*, indicating that long-term climate change may intensify microhabitat water differentiation by altering the seasonal distribution of precipitation—for example, spring aridification. This is consistent with the research trend reported by Hao Lu et al. [35] on the earlier onset of shrub regreening in the Alxa desert region. The rainfall pattern of "more light rain and less heavy rain" in the Gobi desert will have important effects on surface soil moisture and future local vegetation succession [36].

The presence of desert shrubs can accumulate litter and soil and increase soil nutrient content. Numerous studies have confirmed that shrubs have a "fertile island" effect, but this effect varies with shrub species [37–39]. Previous studies have also found that microhabitats shaped by shrubs in the Gobi desert not only accumulate seeds and litter and increase soil fertility, but also increase the abundance and diversity of surface arthropods [12, 18, 40]. This study found that the presence of the two dominant shrubs, *R. soongorica* and *N. sphaerocarpa*, in the Gobi desert had significant effects on the spatial distribution of surface soil moisture, and that these effects varied with shrub species.

···changed. Differences in soil moisture between shrub and bare-ground microhabitats decreased as the time after rainfall increased. Compared with bare ground, *Reaumuria soongorica* increased surface soil moisture; after rainfall in summer and autumn, surface soil moisture beneath *R. soongorica* shrubs could rise substantially. Ma et al.[41] also found in the Alxa desert steppe that, owing to its distinctive root structure and physiological traits, *R. soongorica* enhanced its capacity to absorb and retain deep soil water. Its well-developed root system can penetrate deeply into the soil to acquire more water, and root exudates can also improve soil structure and increase soil water-holding capacity, thereby enabling the *R. soongorica* microhabitat to accumulate more surface soil moisture[39]. Meanwhile, soil water content beneath *Nitraria sphaerocarpa* shrubs was lower than that in the *R. soongorica* shrub and bare-ground microhabitats; this difference was especially evident after rainfall. This is similar to the conclusions of Zhao Wenyue et al.[9] regarding rainfall redistribution by *N. sphaerocarpa* shrubs at the margins of an oasis in northwestern China. Compared with other vegetation in arid regions, *N. sphaerocarpa* shrubs have a stronger interception and adsorption capacity; most intercepted rainwater is consumed by evaporation, reducing rainfall infiltration and resulting in low soil water content[42–43]. However, after heavy rainfall, soil water content beneath *N. sphaerocarpa* shrubs may, for a short period, be higher than that of bare ground and also higher than that of *R. soongorica*. This may be because the canopy of *N. sphaerocarpa* shrubs rapidly becomes saturated during heavy rainfall, allowing simultaneous use of shallow infiltration and deep stored water, and it may also be related to the coarser soil texture under *N. sphaerocarpa*[7,9,43]. Because bare ground lacks vegetation cover, surface runoff and evaporative losses are more pronounced after heavy rainfall. Vegetation characteristics and soil physical factors in shrub and bare-ground microhabitats were significantly associated with differences in soil water content after rainfall; they not only directly regulate soil structure, but also indirectly dominate moisture changes in the two microhabitats by influencing nutrient cycling and energy-exchange processes[38]. The results of this study indicate that vegetation traits of shrub and bare-ground microhabitats (shrub height, crown width, and volume) and soil physical properties (soil hardness and soil bulk density) were significantly correlated with soil water content after rainfall, suggesting that shrub vegetation traits and soil physical properties act synergistically to enhance water-retention capacity. These findings are consistent with the study by Zhou Bingqian et al.[44] on the canopy–soil synergistic effect of tamarisk, indicating that shrub canopy interception capacity and stemflow collection channels can effectively concentrate precipitation toward the root zone, forming local "water-enriched zones" and further increasing the residence time of surface moisture[9,20]. The study found that soil hardness in shrub and bare-ground microhabitats was significantly correlated with soil water content after light rainfall, revealing the inhibitory effect of surface crusts under vegetation cover on infiltration. In addition, shrub volume, soil bulk density, and soil hardness are key environmental factors affecting changes in the vegetation and soil environment after rainfall; together they influence the dynamic balance between vegetation and soil and play a key role in ecosystem stability and functioning. This result is consistent with the findings of Xiao Honglang et al.[45], who showed that vegetation–soil systems developed in a coordinated manner during the fixation of shifting sand, highlighting the driving role of vegetation community structure in soil evolution. In summary, the vegetation characteristics and soil physical properties of shrub and bare-ground microhabitats in desert regions differentially regulate soil-moisture dynamics after rainfall, confirming the synergistic effect of the vegetation–soil system and its key significance for water retention in desert ecosystems.

4 Conclusion

The presence of shrubs and differences among shrub species significantly altered surface soil water content in the Gobi desert. However, this influence exhibited clear diurnal, seasonal, and interannual variability and was closely related to changes in rainfall patterns:

(1) Soil water content beneath *Nitraria sphaerocarpa* shrubs was generally lower than beneath *Reaumuria soongorica* shrubs and on bare ground. Rainfall amount and the season in which rainfall occurred jointly determined the degree and pattern of the effects of these two shrub species on soil water content, thereby influencing seasonal and interannual dynamics of soil moisture.

(2) At the daily scale, after a single rainfall event in spring, soil water content did not differ significantly among microhabitats; in summer and autumn, however, soil water content beneath *R. soongorica* shrubs and on bare ground was significantly higher than beneath *N. sphaerocarpa* shrubs.

(3) At the seasonal scale, except in spring 2020, soil water content beneath *N. sphaerocarpa* shrubs was significantly lower than beneath *R. soongorica* shrubs or on bare ground in most seasons during the observation period.

(4) At the annual scale, soil water content beneath *N. sphaerocarpa* shrubs was significantly lower overall than beneath *R. soongorica* shrubs, and in 2019 it was also significantly lower than on bare ground.

(5) RDA analysis showed that shrub volume, soil bulk density, and soil hardness were the main environmental factors regulating changes in soil moisture after rainfall across the three microhabitats, together explaining 31.5% of the variation.

In conclusion, shrub presence and shrub species are key factors driving surface soil-moisture dynamics in Gobi desert ecosystems. Their interaction with rainfall jointly determines the spatiotemporal pattern of soil moisture and profoundly affects desert plant growth and soil-development processes.

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Topsoil moisture fluctuation and its influencing factors under two dominant shrubs in the Gobi Desert

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Abstract: In desert ecosystems, shrubs function as "ecosystem engineers" by redistributing rainfall and shaping topsoil moisture patterns. However, how shrub presence and species identity regulate the spatiotemporal dynamics of topsoil moisture over short and long terms remains a key unanswered question. To address this gap, we investigated two dominant desert shrubs—*Reaumuria songarica* (*R. songarica*) and *Nitraria sphaerocarpa* (*N. sphaerocarpa*)—during the 2019-2020 growing seasons. By combining daily soil moisture monitoring with periodic gravimetric measurements, we analyzed daily, seasonal, and inter-annual variations in topsoil moisture dynamics in shrub (*R. songarica* and *N. sphaerocarpa*) and bare ground microhabitats to elucidate the effects of rainfall variability and shrub interactions on the spatiotemporal patterns. The results indicated that *R. songarica* and *N. sphaerocarpa* microhabitats increased and decreased topsoil moisture, respectively. The magnitude and duration of these effects were regulated by rainfall amount and season, thereby shaping the multiscale dynamic patterns of soil moisture across the three microhabitats. Small rainfall events (<5 mm) in spring induced only a brief (2-3 days) increase in topsoil moisture under *R. songarica* and bare ground microhabitats. Meanwhile, extreme rainfall events (>25 mm) in autumn markedly increased topsoil moisture across all three microhabitats, with effects lasting up to 32 days. The results revealed scale-dependent patterns in topsoil moisture dynamics. At the daily scale, topsoil moisture under *R. songarica* and bare ground microhabitats was substantially higher than that under *N. sphaerocarpa* microhabitats after summer and autumn rainfall events, but not after spring rain events. At the seasonal scale, topsoil moisture under *N. sphaerocarpa* microhabitats was generally lower than that under the other microhabitats. At the interannual scale, topsoil moisture under *N. sphaerocarpa* microhabitats was consistently lower than that under *R. songarica* microhabitats and considerably lower than that under bare ground microhabitats in 2019. Key factor analysis based on RDA indicated that the shrub volume, soil bulk density, and soil hardness collectively explained 31.5% of the variation in postrainfall topsoil moisture across the three microhabitats. In conclusion, the influence of dominant shrubs on topsoil moisture operates across multiple temporal scales, a process governed by the interplay between shrub presence and rainfall variability.

Keywords: Gobi Desert; rainfall regime changes; shrubs; topsoil moisture; spatiotemporal dynamics

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