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Response of Soil Moisture to Rainfall in Pine Sylvestris in the Mu Us Sandy Land

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Abstract: In order to analyze the dynamic response characteristics of soil moisture to rainfall in the Mu Us Sandy Land sand-fixing forest of Pinus sylvestris, the AV-3665R rain gauge, ECH20-5 soil moisture sensor, and deep leakage water tester are used to automatically monitor the rainfall, 0-150cm soil moisture content, and leakage below 150cm of the Pinus sylvestris sand-fixing forest in 2020-2021.The result shows: Cumulative rainfall from May to October in Pinus sylvestris sand-fixing forest significantly affected the change of soil moisture in the 0-150cm layer. Among them, rainfall from May to June has little effect on the soil layer below 100cm, and rainfall after September has a significant effect on soil moisture replenishment; Rainfall less than 40mm has no direct replenishment effect on soil layers below 100cm;Rainfall greater than 50.1mm has a replenishing effect on soil moisture in the 180cm layer, and when the initial water content of the surface layer is high, the rainfall infiltration is fast, the duration is short, and the recharge effect is large. Rainfall and initial water content of soil surface have significant effects on the process and characteristics of soil water infiltration in Pinus sylvestris sand-fixing forest after rainfall.

1. Introduction

Pinus sylvestris is one of the important sand-fixing afforestation tree species in northern my country,It is also the key tree species of the "Three Norths" shelterbelt project[1-4].It mainly absorbs water and nutrients from the soil within 50cm of the dry dune surface, the main root is generally 1-2m long, and the lateral roots are particularly developed, mostly distributed in the 10-50cm sand layer on the surface, often forming many lateral drooping roots, it can fully absorb the water in the soil, and the root system has strong plasticity and can adapt to different environmental conditions[5-7].Therefore, it has been introduced and planted in large quantities in the "Three Norths" area for sand control. After years of introduction and domestication, it has played an important role in increasing the diversity of sand-fixing plants, changing the sandy landscape, and promoting the reversal of the sandy ecological environment. Since the successful introduction of sand-fixation and afforestation in Zhanggutai Horqin Sandy Land in Liaoning

Province in 1962, with a history of nearly 60 years, since the 1980s,one of the most important reasons is the imbalance of soil moisture. In the early 1970s, the introduction of Pinus sylvestris for sand-fixing and afforestation was successful in the Mu Us Sandy Land of Yulin City, Shaanxi Province[8].It has a history of nearly 30 years and has grown well in recent years, there have been no reports of widespread declines or deaths, only some areas experienced slow growth; At present, its research mainly focuses on afforestation technology, afforestation effect, growth characteristics, water physiology, photosynthetic physiology, transpiration water consumption, soil physical and chemical properties, carbon storage, etc. However, research on soil moisture still lacks systematic and continuous observations[9].There is also a lack of continuous soil moisture data to analyze the continuous stability of P. sylvestris sand-fixation forest under rainfed conditions. At the same time, the sand-fixing forest of Pinus sylvestris in the Mu Us Sandy Land plays an important role in the "Three-North" shelter forest system. The reasons for the decline of the Pinus sylvestris sand-fixing forest in Yulin area will also become one of the research priorities in the Mu Us Sandy Land[10-14].

Desertification has become a major environmental and socio-economic problem in the world today, and threaten the survival and development of human beings[15].The Mu Us Sandy Land is one of the four major sandy land in China, with a total area of about 32,000 km2.In order to control the desertified land in the region, a large number of Pine sylvestris seedlings were introduced and planted in the Mu Us area, it is an important sandy pine introduction and planting area in China[16].Historically, the Mu Us Sandy Land used to be an excellent pasture with vast grassy beaches and clear streams, Later, due to unreasonable deforestation, overgrazing, war and climate change, etc. As a result, ground vegetation resources are gradually depleted, grasslands are degraded, sandstorms gradually invade candles, soil erosion is intensified, and the ecosystem is deteriorating, resulting in the Mu Us Sandy Land becoming an area with severe desertification development in China[17].After 1949, the ecological environment of the Mu Us Sandy Land has attracted widespread attention from people from all walks of life, the management of its sandstorm area has also been launched. Since the 1950s, through a series of comprehensive control measures, such as diverting water and pulling sand, diverting floods and silting, and building windbreak forest belts, the desertification of the Mu Us Sandy Land has been effectively controlled, and the 600km2 quicksand land has now become semi-fixed or fixed sandy land[18-22].

In this paper, the sand-fixing forest of Pinus sylvestris in the Mu Us Sandy Land is taken as the research object. The automatic monitoring system is used to continuously monitor rainfall, soil moisture content of 0-150cm, and leakage below 150cm.Systematic analysis of the response characteristics of soil moisture to rainfall in P. sylvestris sand-fixing forest and preliminary estimation of water balance, it provides a reference for the analysis of water balance, soil water carrying capacity, vegetation stability and water cycle process mechanism in Mu Us Sandy Land.

2. Materials and Methods

2.1 Overview of the Study Area

The study area is located in Baijian Township, Hengshan District, Yulin City, Shaanxi Province. It is located in the southeast of Mu Us Sandy Land (38°19’49’’N−38°20’12’’, 109°42’08’’−109°42’55’’E), 1.2 km above sea level[23-24].The region has a warm temperate semi-arid continental monsoon climate with sufficient sunlight and a large temperature difference between day and night[25] (Figure 1).The annual average temperature is 6.0−8.5 °C, and the annual average frost-free period is about 150 days, the average annual precipitation is 385 mm, the distribution of rainfall is uneven, and the average annual evaporation is 2914 mm. The main soil type in the study area is non-zonal aeolian sandy soil, its mechanical composition is dominated by sand grains, with a loose structure and low nutrient content. The main arbor species in the study area are pine sylvestris and Pinus tabuliformis. Major shrubs include Artemisia ordosica、A. gmelinii, Bidens pilosa, Agropyon oristatum and Tribulus terrestris, etc.

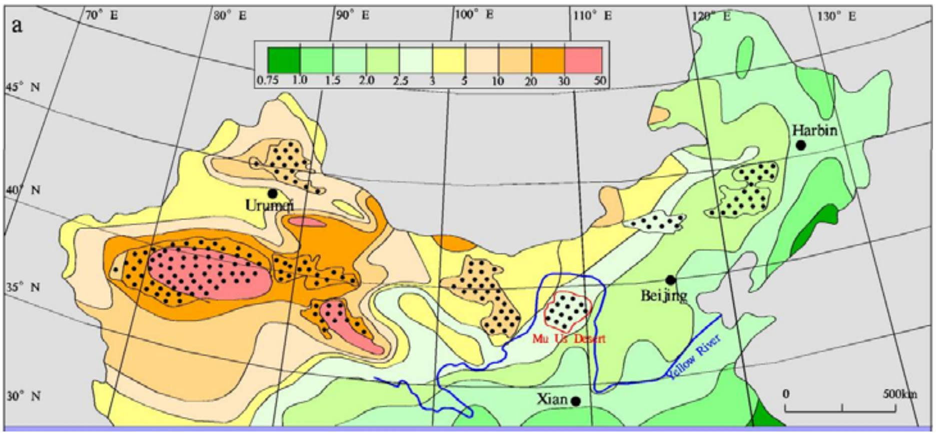

Figure 1. Geographical location of the Mu Us Desert (The base map is from references [26], with changes)

2.2 Research methods

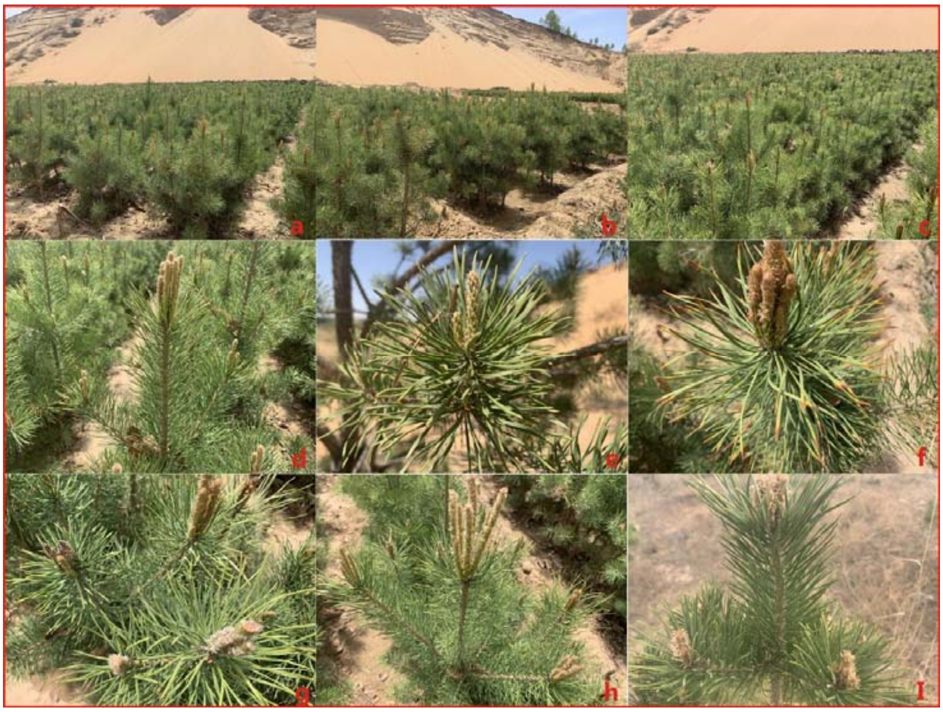

Figure 2. Pinus sylvestris in the Mu Us Desert

In September 2020, the method of fixed-point monitoring was adopted, a 28-year-old Pine sylvestris sand-fixing forest was selected in the study area (strip spacing 8m, crown width 270cm×230cm, plant height 3m;Scattered distribution of shrubs, Artemisia, etc; A small amount of physical crusting; The average soil bulk density of 0-150cm is 1.49g/cm^3, particle diameter: 0.09-0.51mm, accounting for 85.2%, and <0.09mm accounting for 12.9%(Figure 2).A soil profile of 300 cm deep was excavated in the middle of the sand-fixing forest. From bottom to top, the drainage part, metering part, current collecting part and capillary water holding part are embedded close to one side of the complete section. At this time, the upper edge of the water-holding part of the capillary is at a depth of 180cm in the soil, and the metering part will record the amount of water that leaks below 180cm. Install rain sensor on the ground; The CR200X data collector made in the United States was used to record rainfall, soil water content, and leakage data. The soil water content was recorded every 1 hour, and the rainfall and leakage were recorded every 30 minutes.

3. Results and Analysis

3.1 Characteristics of Rainfall Distribution in the Study Area

A total of 70d rainfall events occurred in the study area from May 1 to October 31, 2020.The total rainfall was 398.6mm, and the 24-hour rainfall was less than or equal to 5.5mm for 49 days, with a total rainfall of 77.32mm, accounting for 21.45% of the total rainfall. The 24-hour rainfall was between 4 and 9 mm for 8 days, with a total rainfall of 59.87 mm, accounting for 16.2% of the total rainfall.24 hours of rainfall ≥ 9mm rainfall for 15 days, total rainfall 249mm, accounting for 66.32% of total rainfall; From May 1st to October 31st, 2020, a total of 78d rainfall events occurred, with a total rainfall of 290mm,55d with 24-hour rainfall ≤5.5mm, total rainfall of 68.1mm, accounting for 21.66% of total rainfall, 16d of rainfall events with 24-hour rainfall between 4-9mm, total rainfall of 109.4mm, accounting for 36.66% of total rainfall, the rainfall in 24h is ≥12mm for 7.5d, with a total rainfall of 116.2mm, accounting for 39.66% of the total rainfall.Under the conditions of drought and water shortage, no runoff occurs even when the rainfall intensity in this area is 11.5mm/h. During the study period, the maximum rainfall intensity was 11.5mm/h, indicating that there was no surface runoff in the study area, and the rainfall redistribution of Pinus sylvestris sand-fixing forest included rainfall loss (rainfall interception, soil evaporation, plant transpiration), soil water storage and deep seepage.

Table 1. Peak value of soil volumetric water content in each layer of Pinus sylvestris over time (daily average)

soil thickness(cm)	2020.5-10		2021.5-10	
	Min/date	Max/date	Min/date	Max/date
10	3.65%/6.18	23.11%/9.8	3.45%/5.8	19.11%/7.8
30	3.95%/6.21	20.38%/9.9	2.77%/6.8	13.11%/9.8
50	4.15%/10.2	18.43%/9.11	1.23%/9.8	9.66%/9.13
80	5.65%/10.11	15.69%/9.17	2.69%/9.11	5.98%/10.8
120	6.33%/9.8	14.11%/7.8	2.82%/9.18	3.11%/10.9
150	6.74%/9.12	11.46%/7.12	3.15%/9.23	5.67%/5.8

3.2 Dynamic Response of Soil Volumetric Water Content to Rainfall

During the test period, the minimum and maximum values of the time change of soil volumetric water content in each layer of Pinus sylvestris sand-fixing forest are shown in Table 1.The variance analysis shows that the difference between the minimum and maximum soil volume water content in each layer in 2020 and 2021 is significant, it shows that rainfall has a significant effect on soil moisture in the 0-150cm layer. Figure 2 shows the dynamic changes of soil volumetric water content in each layer of Pinus sylvestris sand-fixing forest with time during the experiment. It can be seen from the figure that from May to October 2020, the soil volumetric water content of the 10cm and 20cm layers fluctuated frequently. Each fluctuation peak corresponds to the rainfall time. Among them, a total of 15d rainfall events occurred from May 1 to May 15, 2020.The total rainfall is 30.2mm (the maximum one-day rainfall is 8.9mm), and the soil volumetric water content only fluctuates at a depth of 10cm.The variation range is 3.16%~11.87%, and the maximum value appears 2d after the rainfall of 8.9mm;During this period, the soil water content of the 20cm layer showed a continuous downward trend, with a decrease of 3.12%;The volumetric water content of the 50cm, 80cm, 120cm, and 150cm soil layers is basically stable; from June 18 to October 31, 2020, it rained for 55 days, the total rainfall is 340mm, and the soil volumetric water content of each layer above 150cm fluctuates. Among them, the 10cm and 20cm layers fluctuated frequently, 5 times at 50cm, 4 times at 80cm, 3 times at 120cm, and 2 times at 150cm, all of which occurred after the corresponding rainfall; Among them, the fluctuations of 120cm and 150cm are basically consistent with the rainfall time, but its fluctuations are the result of a combination of previous rainfall accumulations.

It can also be seen from Table 1 that from May to October 2020, the soil volumetric water content in the 10cm and 20cm layers fluctuated frequently, and the peak value of each fluctuation also corresponds to the rainfall time. Among them, a total of 16d rainfall events occurred from May 1 to June 28, 2020, with a total rainfall of 44.3mm (the maximum one-day rainfall was 12.1mm),only 12cm depth soil volumetric water content fluctuated, with a variation range of 3.87-15.45%, and the maximum value appeared 1 day after 11.2mm rainfall; During this period, the soil volumetric water content of the 30cm, 60cm, 80cm and 150cm layers showed a continuous downward trend, the declines were 5.21%, 1.52%, 1.45%, 1.45%, and 2.08%, of which the 30cm layer had the largest decline; From June 29 to October 31, 2020, it rained for 64 days, with a total rainfall of 264 mm. The soil volumetric water content of each layer above 80 cm fluctuated. Among them, the 10cm and 30cm layers fluctuated frequently, and the 60cm and 80cm layers only fluctuated once after the 35mm rainfall event on September 22 at the end of the growing season. The soil moisture content of the 150cm and 180cm layers showed a weak and continuous downward trend, and rainfall did not significantly affect the soil moisture during the period. The above results show that the soil moisture at a depth of 10cm and 30cm in the Pinus sylvestris sand-fixing forest is severely affected by rainfall, it is also the soil layer most affected by evapotranspiration; At the beginning of the rainy season, moisture affects deeper soil layers and requires longer infiltration, and in May-June rainfall basically does not affect the 150cm, 180cm soil moisture changes, water supply and consumption are maintained in a relatively balanced state. At the same time, from the perspective of soil moisture fluctuations, there was a relatively large rainfall event in September at the end of the growth season of Pinus sylvestris sand-fixing forest (the cumulative rainfall was 86.5mm from September 15 to 17, 2019, and the cumulative rainfall from September 22 to 25, 2020 was 46.32mm).It has a significant effect on water supply in the 0-150cm soil layer. It is essential to maintain soil water balance in Pinus sylvestris sand-fixing forest; However, the heavy rainfall in September 2020 did not significantly affect the soil moisture below 150cm. Combined with the changes in soil moisture at 150cm and 180cm after the rainfall, it shows that the rainfall of 47.36mm has no direct replenishment effect on the soil layer below 180cm of Pinus sylvestris sand-fixing forest.

3.3 Dynamic Response of Soil Water Storage to Rainfall

Figure 2 is the dynamic change diagram of soil water storage capacity in 0-180cm soil of Pinus sylvestris sand-fixing forest during the test period. It can be seen that the fluctuations of water storage correspond to rainfall events. On the whole, the water storage in June-October after the rainfall in 2019 was higher than that in May, and only in July and October in 2020 was higher than that in May. During the test period, the water storage of Pinus sylvestris sand-fixing forest in 2019 decreased by 2.89mm,among them, at the beginning of the growing season (May 1-31), the water storage capacity of 0-180cm decreased by 2.54mm, and the rainfall of 21.54mm during the period did not directly replenish soil moisture; In the middle of the growing season (June 1-August 31), the water storage capacity of 0-180cm increased by 40.68mm, and 0.87mm leaked to below 180cm), the 254mm rainfall during the period has a direct replenishment effect on soil moisture; At the end of the growing season (September 1st to October 21st), the water storage capacity of 0-180cm decreased by 35.74mm, and the rainfall of 108mm during the period had no direct replenishment effect on soil moisture. During the test period, the water storage capacity in 2020 decreased by 8.65mm, of which, the water storage capacity of 0-180cm at the beginning of the growing season (May 1-31) decreased by 51.23mm,the 8.2mm rainfall during the period did not directly replenish soil moisture; In the middle of the growing season (June 1-August 31), the water storage capacity of 0-180cm increased by 3.97mm,the rainfall of 179.2mm during the period has a direct replenishment effect on soil moisture; At the end of the growing season (September 1st to October 31st), the water storage capacity of 0-180cm increased by 45.21mm, and the rainfall of 110.2mm during this period had a direct replenishment effect on soil moisture. The above results show that the rainfall in the early growing season of Pinus sylvestris sand-fixing forest cannot meet the water loss, need to consume water already stored in the soil; The rainfall in the middle of the growing season can meet the loss of water, and some rainfall is stored in the soil; There were differences in the response of soil water storage to rainfall at the end of the growing season.

3.4 Dynamic Process of 0-8cm Surface Soil Moisture after Typical Rainfall Events

It can be seen from Table 1 that the decreasing trend of soil volumetric water content in the 0-8cm layer after the rainfall event of Pinus sylvestris sand-fixing forest is less than 8.2mm is basically the same. The soil volume water content and the days after rainfall decreased exponentially (R2>0.87).4.54mm, 7.56mm, 6.54mm after rainfall, the soil volume water content of 0-8cm layer is 5.24%, 9.87%, 7.08% respectively; On the 1st day after the rain, it decreased by 2.24%, 2.87% and 2.08% respectively; On the second day after the rain, the decrease was 0.24%, 2.87% and 0.08% respectively; On the 3rd day after the rain, the decrease was 0.24%, 0.87% and 1.08% respectively;On the 4th day after the rain, it decreased by 0.24%, 0.87% and 1.18% respectively. The above results show that the water loss of the 0-8 cm topsoil is the largest on the first day after rainfall, it accounted for more than 1/3 of the total loss 4 days after rainfall, accounting for 55.24%, 32.87% and 51.08% of the total loss, respectively.

3.5 Characteristics of Soil Moisture Infiltration after Typical Rainfall Events

From the peak value of soil volumetric water content in 10cm and 20cm layers in 2020 during the test period (Table 1),The lowest value of soil volumetric water content of 10cm and 20cm both appeared before June 19,The maximum values all appeared on September 13, and on June 20, the surface soil moisture of 0-20 cm was maintained at a relatively low level (5.42%).On September 16, the soil moisture of 10 cm and 20 cm of the surface layer was maintained at a relatively high level (9.21%).It can be seen from Table 1 that after June 20 and September 16, the soil layers of 0-20 cm fluctuated. Therefore, typical rainfall events of 54.2 mm in a single field after June 13, 2019 and 87.2 mm in a single field after September 20, 2019 were selected to analyze the variation characteristics of rainfall infiltration under different initial water contents. The maximum water content observed during the test remains unchanged for less than 2 hours at most, it shows that at most the saturated water content is reached instantaneously, and the rainfall infiltration process during the test is all under unsaturated conditions. It can be seen from Table 1 that when the initial water content of 0-20cm is low, from 10:00 (1h) on June 20th to after 23:00 (330h) on July 3rd,The wetting front reached the 180cm soil layer, which lasted 330h, and accumulated rainfall of 69.2mm during the period; Judging from the rainfall and time required for the wetting front to reach each layer of soil,52.1mm single rainfall (rain intensity 0.74mm/h) infiltration depth is below 80cm,the accumulated rainfall of 15.87mm reached the 180cm soil layer at the 330h wet front. However, it can be seen from Table 1 that the five rainfalls before July 2 (accumulation 13.58mm, maximum rainfall 7.54mm) only affected the change of soil water content above 20cm.It does not affect the change of soil moisture below 50cm, and has no direct replenishment effect on deep soil moisture. It shows that the wet front of 62.11mm can reach 180cm soil layer 330h after the start of a single rainfall. When the initial water content of 0-20cm is relatively high, from 10:00 (1h) on September 13th to 0:00 (80h) on September 20th,the wetting front reached the 180cm soil layer, which lasted 80h, and the accumulated rainfall during the period was 85.2mm;Judging from the rainfall and time required for the wetting front to reach each layer of soil, the infiltration depth of a single rainfall of 85.2mm (rainfall intensity of 1.54mm/h) is below 180cm,it can affect the change of soil moisture below 180cm, indicating that the wetting front can reach the 180cm soil layer 80h after the start of a single rainfall of 85.2mm.Judging from the wetting front time and rainfall time, the time is short when the water content of the 0-20cm soil layer is high. In addition, the greater the cumulative rainfall and the greater the rainfall intensity, the shorter the arrival time of the wetting front in each layer, and the greater the peak water content after rainfall. The comprehensive analysis shows that the rainfall events larger than 52.3mm can replenish soil moisture in the P. sylvestris sand-fixing forest. And when the initial water content of the surface is high, the infiltration after rainfall is faster, the duration is shorter, and the recharge of soil water is better.

3.6 Soil Moisture Subsidence Process after Typical Rainfall Events

During the test period from September 16 to 20, 2020, the soil moisture subsidence process within 8 days after a single cumulative rainfall event of 85.2 mm is shown in Table 1.During this period, only 1.54mm of rainfall occurred on September 20, and there were no rainfall events for the next 8 days. It can be seen from Figure 1 that the soil moisture in the Pinus sylvestris sand-fixing forest showed the characteristics of evapotranspiration-type moisture subsidence after rainfall (the wet front reached 180 cm due to rainfall on September 20, and there was a time lag),0-20cm is the soil moisture subsidence layer, and 20-80cm is the soil moisture replenishment layer; And after August, the Pinus sylvestris sand-fixing forest entered the final growth stage, and the subsidence of 0-20cm soil moisture mainly contributed to evaporation or infiltration recharge. Combined with the dynamic changes of soil moisture in Pinus sylvestris sand-fixing forest (Fig. 1),the analysis shows that in the growing season, the P. sylvestris sand-fixing forest will change from the evapotranspiration type to the evapotranspiration type. That is, the consumption of soil moisture is mainly used for plant transpiration and soil evaporation, and 0-80cm is the main subsidence layer of soil moisture.

4. Conclusion

(1)During the test period, the accumulated rainfall in 2020 and 2021 significantly ($P<0.02$) affected the change of soil moisture in the 0-180cm soil moisture of P. sylvestris sand-fixing forest; Among them, the rainfall from May to June has little effect on the soil layer below 180cm, and the supply and consumption of water are maintained in a relatively balanced state. Rainfall after September has a significant effect on soil water recharge.

(2)After a typical rainfall event (<8.2 mm, no continuous rainfall), the soil volumetric water content of 0-10 cm surface layer of Pinus sylvestris sand-fixing forest decreased exponentially with the number of days after rainfall ($R2>0.91$).And the soil moisture loss was the largest on the first day after the rainfall, accounting for more than 1/3 of the total loss on the 4th day after the rainfall.

(3)Rainfall less than 48.3mm has no direct replenishment effect on the soil layer below 120cm of Pinus sylvestris sand-fixing forest; Rainfall of more than 50.3mm has a replenishing effect on the soil moisture of the 180cm layer of the Pinus sylvestris sand-fixing forest, and when the initial water content of the surface layer is high, the infiltration after rainfall is fast and the duration is short. Rainfall and initial water content of soil surface have significant effects on the process and characteristics of soil water infiltration in Pinus sylvestris sand-fixing forest after rainfall.

(4) The 200-year rainfall of 350.1 mm during the test period could maintain the soil water balance in the Pinus sylvestris sand-fixing forest. But 2021, with less rainfall (274mm of rain), has begun to show a water deficit. When encountering extreme drought years or years of continuous lack of water, or when there is no large rainfall in September, the sand-fixing forest of Pinus sylvestris is likely to suffer from severe water deficit.

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