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Impact of Different Yearly Rainfall Patterns on Dynamic Changes of Soil Moisture of Fixed Sand Dune in the Horqin Sandy Land

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Abstract. The in-situ monitoring method was used for studying the spatio-temporal variation of soil moisture in the growing season of different precipitation years in fixed dunes of Horqin Sandy Land. The results showed that different precipitation years have a certain influence on both seasonal variation and vertical variation of soil moisture in the fixed dunes of the study area. (1) During the normal year, the seasonal variation of soil moisture was relatively flat. During the dry year, the soil moisture gradually decreased before the rainy season and increased significantly after the rainy season. During both normal and dry years, heavy rainfall can significantly recharge the soil moisture content in all soil layers. During the wet year, the rapid recharge effect of soil moisture from heavy rainfall in the shallow layer was better than that in the deep layer. (2) During the normal and wet years, the soil moisture was at a relatively low level in May and changed little with the soil depth. In different months of other precipitation years, the soil moisture changes with soil depth all showed the trend of "first increase, then decrease, and finally slow increase". Higher soil moisture were generally in the soil layer of 30~70 cm, the soil moisture below 70 cm changed little with the soil depth and tended to be stable below 110 cm. (3) Under the influence of heavy rainfall, the vertical variation of soil moisture tended to be active in the wet year, showing three variation layers, i.e. quickly changing layer, active variable layer and sub-active variable layer. During the normal and dry years, the soil moisture showed small vertical changes, and it was divided into only two layers. For the dry year, only the surface layer showed active variation of soil moisture; for the normal year, the soil layer above 70cm showed active variation of soil moisture.

1. Introduction

Soil moisture is one of the important variables in land surface processes and plays a very important role in climate change [1]. As a key factor of soil-plant-atmosphere continuum, soil moisture is the carrier of material circulation and energy flow in the soil system, exerting significant effects on soil properties, vegetation growth and regional ecosystem [2]. Due to the importance of soil moisture to the entire earth system, its temporal and spatial variations have drawn wide attention [3]. As a key factor affecting the survival and growth of plants, soil moisture changes can not only directly determine the survival and death of plants, but also exert an indirect effect on plants by regulating the salt and heat in the soil [4-6].Soil moisture is an important ecological factor of sandy land ecosystems that determines the occurrence, evolution and productivity of sandy soil and restricts the vegetation formation and development in sandy land [7]. The dynamics of soil moisture and its spatio-temporal variability is an important part of the study on soil moisture in sandy land [8].

In order to analyse the dependence of soil moisture on precipitation, some scholars have studied the impact of different precipitation years on soil moisture dynamics. For example, Zhang Beiying et al.[9] studied and concluded that different precipitation years have a certain influence on both seasonal variation and vertical variation of soil moisture for different vegetation types in the study area. Zou Wenxiu et al. [10] studied the impact of different precipitation years on soil moisture dynamics in the black soil area. Li Fengrui et al. [11] analysed the spatio-temporal variability of soil moisture in different precipitation years in the Loess Plateau of eastern Gansu province. Qiu Yang et al. [12] used DCCA ordination to study the spatio-temporal variability of soil moisture and its relationship with environmental factors in small watersheds of Loess Hilly Region. Chen Baoqun et al.[13] discussed the soil moisture dynamics of forest lands in the heaviest rainfall year. Li Yuqin[14] discussed the soil moisture variation in the soil layer of 0-600 cm in forest land of Xi'an in different precipitation years, as well as soil moisture recovery and depletion rules in dried soil layers

The Horqin Sandy Land is located in the semi-arid farming-pastoral ecotone in northern China, with a fragile ecological environment. In recent years, population explosion, overgrazing and unreasonable land use has further exacerbated land degradation and drought in this region [15]. Sandy land ecosystems have degraded to varying degrees, biological resources have decreased drastically and land productivity has declined sharply, resulting in vegetation degradation and land desertification that severely threatened the coordinated development of ecological environment in the entire region [16]. However, there are few reports on the impact of different precipitation years on soil moisture dynamics in the region. This paper studied the seasonal variation and vertical variation of soil moisture in different precipitation years in fixed dunes of Horqin Sandy Land, with an aim to determine the effect of precipitation on soil moisture under different spatial and temporal conditions in the region, provide scientific guidance to reasonable utilization of precipitation in the region and provide scientific basis for effective use and management of soil moisture.

2. Materials and Methods

2.1. Study Area Description

The study area is located in the southern part of the the Horqin Sand Land in eastern Inner Mongolia, China (42°55′ N, 120°42′ E). It is one of four well-known sandy areas in northern China, which are generally thought to originate from sand and dust storms that occur frequently in the arid and semi-arid regions of northern China[17]. This area has a temperate continental semi-arid monsoonal climate. Annual precipitation is 366 mm. The average annual wind speed is 3.4 m s^{-1}. Soils are sandy, light yellow, have loose structure, and are particularly susceptible to wind erosion[18].

2.2. Data Getting

In the study area, the typical fixed dune was selected as the experimental plot, where the main vegetation type was *Artemisia halodendron* and *Caragana microphylla*. Three 2m-deep neutron probes (CNC503DR) were buried at equal distances in the plot, and the soil volumetric water content (%) of 8 soil layers (including 0~10 cm, 10~30 cm, 30~50 cm, 50~70 cm, 70~90 cm, 90~110 cm, 110~130 cm and 130~150 cm) was recorded. The soil moisture was measured by the three neutron probes each time was averaged as the soil moisture of the plot. From 2005 to 2014, the measurement was conducted once every 4~10 days and added after rainfall. The soil moisture of each soil layer was measured for 164 times. Precipitation data for the same period was obtained from the meteorological station of the nearby Naiman Desertification Research Station.

2.3. Precipitation Year Classification

The commonly-used domestic precipitation year classification standard[19] was used to classify different precipitation years. For the wet year, $Pi>P+0.33\delta$; for the dry year, $Pi<P-0.33\delta$, where Pi is the precipitation in the current year (mm), P is the mean annual precipitation (mm) and δ is the mean square error (mm) of the mean annual precipitation. According to the multi-year precipitation data of

the study area, it was calculated that the mean annual precipitation in the past 30 years (1985-2014) was 342.5mm, and the mean square error was 100.41 mm, $P+0.33\delta$=375.6mm, $P-0.33\delta$=309.3mm. The annual precipitation was 318.2 mm in 2005, which was a normal year; the annual precipitation was 201.8 mm in 2011, which was a dry year; and the annual precipitation was 430.6 mm in 2012, which was a wet year. Compared with the mean annual precipitation of different precipitation years, the precipitation distribution in 2005, 2011 and 2012 was consistent with the average precipitation in the corresponding precipitation years. Therefore, this paper took these three years as an example to study the impact of different precipitation years on soil moisture dynamics of fixed dunes. The characteristics of precipitation in these 3 years are shown in Table 1.

Table 1. Rainfall characteristics of experimental year.

Yearly rainfall pattern	Normal year	Dry year	Rainy year	Average of 30 years
Year	2005	2011	2012	(1985~2014)
Jan.	0.0	0.0	0.0	1.1
Feb.	0.7	0.2	3.4	2.0
Mar.	0.6	0.2	4.2	5.9
Apr.	5.1	3.0	17.0	13.6
May.	32.5	34.4	28.6	35.4
Jun.	136.4	33.4	87.4	63.2
Jul.	55.8	90.8	93.8	106.4
Aug.	66.8	24.8	27.8	58.7
Sep.	11.8	2.0	144.8	36.3
Oct.	8.2	7.8	17.4	13.9
Nov.	0.0	5.2	6.2	4.3
Dec.	0.3	0.0	0.0	1.6
Sum	318.2	201.8	430.6	342.5

2.4. Vertical Stratification of Soil Moisture Profile
When dividing the vertical variation layers of soil moisture profile, the vertical section of the soil was divided into four layers using the two indicators of SD and CV[20-21], i.e. the quickly changing layer (CV>0.3, SD>4), active variable layer (CV: 0.2~0.3; SD: 3~4), sub-active variable layer (CV: 0.1~0.2; SD: 2~3) and relatively steady layer (CV<0.1, SD<2). In the actual division process, the CV prevails when CV and SD cannot meet the above classification criteria at the same time[21].

3. Results and Discussion

3.1. Soil Moisture Changes with the Month
The analysis on the changes of soil moisture in different soil layers and precipitation with the month in different precipitation years (Fig. 1) showed that:

(1) From May to June, the soil moisture in different soil layers increased significantly in the normal year (Fig. 1 (A)) and wet year (Fig.1 (C)). The average soil moisture in different soil layers increased from 2.94% in May to 4.65% in June during the normal year and from 2.81% in May to 4.56% in June during the wet year. The main reason is that with the increase of rainfall, the vegetation growth was in the initial stage and the evapotranspiration was weak, resulting in significant recharge of soil moisture from precipitation. In the dry year (Fig. 1 (B)), due to the low rainfall, soil moisture decreased from 4.22% in May to 3.88% in June.

(2) From June to August, the soil moisture in all soil layers except for 0-30cm showed a decreasing trend during the normal year. Due to the insignificant precipitation increase, temperature rise, vigorous vegetation growth, strong soil evaporation and vegetation transpiration, the soil moisture was in a state

of depletion during this period, decreasing from 4.65% in June to 4.25% in August. The soil moisture in the soil layer of 0-30cm increased slightly from precipitation recharge in July and August. During the wet year, the soil moisture in soil layers above 70 cm showed a downward trend, while the soil moisture below 70 cm increased slowly. This is because the vegetation root system in fixed dunes is mainly distributed in the soil layer above 70 cm[22]. Due to temperature rise, vegetation growth, strong evapotranspiration and lack of rainfall, the soil moisture in the shallow layer (above 70 cm) was in the state of depletion. During the dry year, the precipitation in July reached up to 90.8 mm, significantly higher than that in other months, so that the originally low soil moisture recovered significantly due to recharge from heavy rainfall. The soil moisture reached the highest level in July. Afterwards, with the enhancement of evapotranspiration and the reduction of rainfall, the soil moisture in all soil layers showed a decreasing trend, especially in the surface layer (0~10cm).

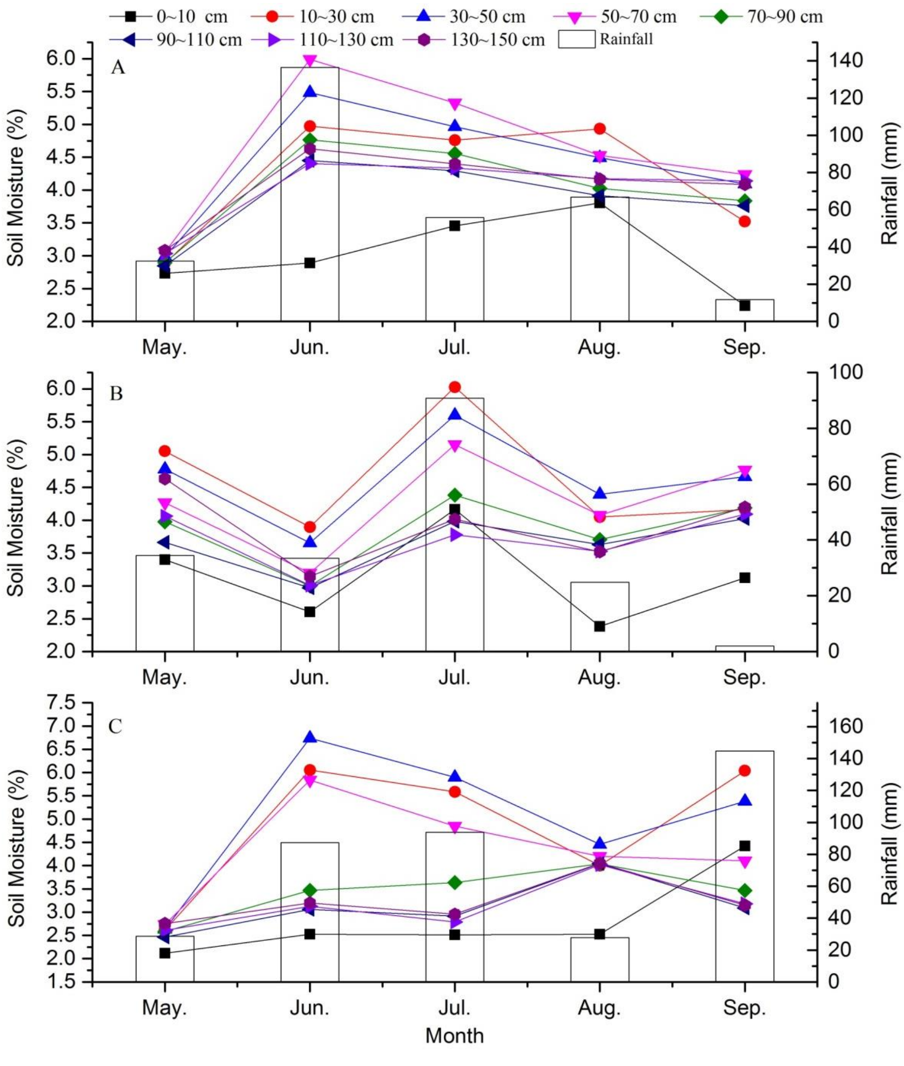

Figure 1. Monthly dynamics of soil moisture and rainfall; A, B, C denote 2005 (Normal year), 2011 (Dry year), and 2012 (Rainy year), respectively.

(3) From August to September, the soil moisture has different variation rules in different precipitation years. The soil moisture in different soil layers showed a downward trend in the normal year and a slight increase in the dry year. In the wet year, the soil moisture content varied significantly among different soil layers, showing an increasing trend above 50 cm and a decreasing trend below 50cm. This was mainly affected by the heavy rainfall (144.8mm) in September. The rapid recharge effect of soil moisture from heavy rainfall in the shallow layer (above 50cm) was significantly better than that in the deep layer (below 50cm).

3.2. Vertical Variation of Soil Moisture Profile

The vertical variation of soil moisture is mainly affected by the interaction among rainfall, soil evaporation and vegetation water consumption[23]. The change of soil moisture with soil depth in the growing season (May-September) of different precipitation years (Fig. 2) showed that, (1) During the normal year (Fig. 2 (A)), the soil moisture was at a low level in May and showed no obvious change with the soil depth, because the low rainfall and weak evapotranspiration in May led to low soil moisture and its little change with soil depth. The soil moisture reached the peak at the soil depth of 30cm in August, peak at the soil depth of 70cm in June, July and September, and then gradually decreased with the increase in the soil depth until reaching 110cm and below, where the soil moisture increased slowly and tended to be stable. (2) During the dry year (Fig. 2 (B)), the soil moisture was at a low level in June and at a high level in July, and the soil moisture generally reached the peak at the soil depth of 30cm, and then gradually decreased with the increase in the soil depth until reaching 110cm and below, where the soil moisture slowly increased. (3) During the wet year (Fig. 2 (C)), the soil moisture was at a low level in May and showed no obvious change with the soil depth. The soil moisture reached the peak at the soil depth of 30cm in September, peak at the soil depth of 50cm from June to August, and then gradually decreased with the increase in the soil depth until reaching 110cm and below, where the soil moisture slowly increased. It indicates that under the combined influence of rainfall and evapotranspiration after May, the soil moisture in different precipitation years varied greatly with soil depth.

In general, during the normal and wet years, the soil moisture was at a relatively low level in May and changed little with the soil depth. In different months of other precipitation years, the soil moisture changes with soil depth all showed the trend of “first increase, then decrease, and finally slow increase”. In different months, higher soil moisture were generally in the soil layer of 30~70 cm, the soil moisture below 70 cm changed little with the soil depth and tended to be stable below 110 cm. It shows that the soil moisture changes with the month is quite complex, which is not only affected by environmental factors such as precipitation and temperature, but also closely related to vegetation water consumption characteristics and vegetation growth status.

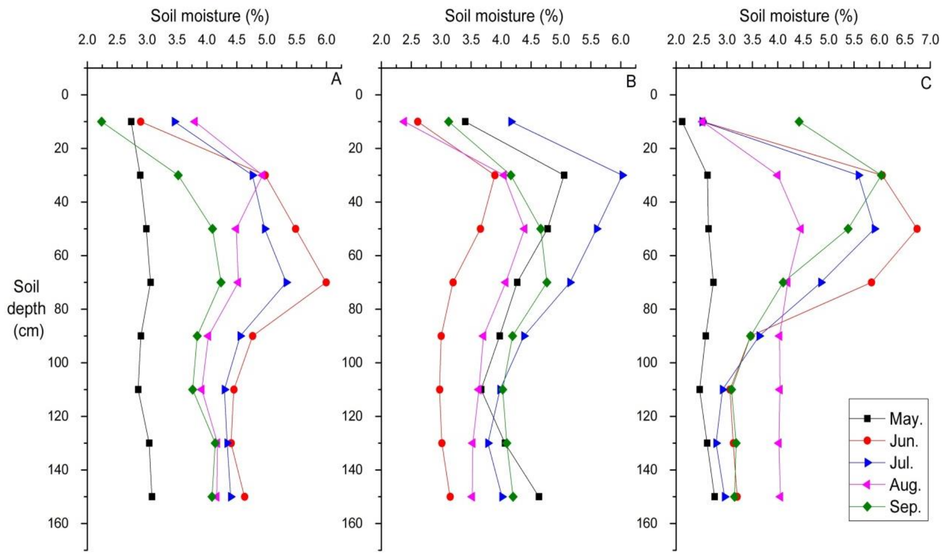

Figure 2. Vertical dynamics of soil moisture at different months; A, B, C denote 2005 (Normal year), 2011 (Dry year), and 2012 (Rainy year), respectively.

3.3. Vertical Variation of Soil Moisture Profile

The statistical characteristics of soil moisture in different soil layers during different precipitation years (Table 2) showed that the average soil moisture was at a higher level of 4.05% in the wet year, followed by 4.02% in the normal year, and at a lower level of 3.97% in the dry year, but there was no significant difference among these three years. The SD and CV of soil moisture in different soil layers were larger in the wet year, followed by the normal year, and smaller in the dry year, which was consistent with the level of soil moisture content, indicating that the higher the soil moisture content is, the greater its variability is. During the normal and wet years, the soil moisture in the soil layer above 70 cm showed strong variability (CV>0.2), while soil moisture in the soil layer below 70 cm showed weak variability (CV<0.2). However, during the dry year, only soil moisture in the soil layer of 0~10 cm showed strong variability (CV>0.2), while the soil moisture in other soil layers (below 10 cm) showed weak variability (CV<0.2).

Table 2. Vertical variation of soil moisture

Year	Soil depth (cm)	Mean(%)	S.D.	C.V	Layers
2005 (Normal year)	0~10	3.02	0.61	0.20	active layer
	10~30	4.21	0.95	0.23	active layer
	30~50	4.40	0.95	0.22	active layer
	50~70	4.63	1.12	0.24	active layer
	70~90	4.02	0.73	0.18	second active layer
	90~110	3.85	0.63	0.16	second active layer
	110~130	4.02	0.56	0.14	second active layer
	130~150	4.07	0.59	0.15	second active layer
	Mean	4.03	0.77	0.19	/
2011 (Dry year)	0~10	3.14	0.70	0.22	active layer
	10~30	4.64	0.90	0.19	second active layer
	30~50	4.62	0.70	0.15	second active layer
	50~70	4.29	0.74	0.17	second active layer
	70~90	3.85	0.54	0.14	second active layer
	90~110	3.65	0.42	0.12	second active layer
	110~130	3.69	0.45	0.12	second active layer
	130~150	3.90	0.58	0.15	second active layer
	Mean	3.97	0.63	0.16	/
2012 (Rainy year)	0~10	3.20	0.91	0.32	fast—changing layer
	10~30	4.98	1.51	0.31	fast—changing layer
	30~50	5.32	1.57	0.31	fast—changing layer
	50~70	4.75	1.14	0.26	active layer
	70~90	3.72	0.53	0.15	second active layer
	90~110	3.31	0.58	0.19	second active layer
	110~130	3.45	0.54	0.17	second active layer
	130~150	3.62	0.50	0.15	second active layer
	Mean	4.05	0.91	0.23	/

The vertical variation layers of soil moisture profile were divided in different precipitation years according to the SD and CV method[20-21]. During the normal year, the soil layer of 0~70cm was active variable layer, while the soil layer below 70cm was sub-active variable layer. During the dry year, only the soil layer of 0~10cm was active variable layer, while the soil layer below 10cm was sub-active variable layer. During the wet year, the soil layer of 0~50cm was quickly changing layer, the soil layer of 50~70cm was active variable layer, and the soil layer below 70cm was sub-active variable layer. This indicates that under the influence of heavy rainfall, the vertical variation of soil moisture tends to be active in the wet year, showing three variation layers, i.e. quickly changing layer, active variable layer and sub-active variable layer. During the normal and dry years, the soil moisture showed small vertical changes, and it was divided into only two layers. For the dry year, only the surface layer (0~10cm) showed active variation of soil moisture; for the normal year, the soil layer above 70cm showed active variation of soil moisture. This shows that different precipitation years have a significant influence on vertical stratification of soil moisture profile, and the influence degrees in wet and dry years are significantly higher than that in the normal year. Moreover, compared with the dry year, the active variable layer of soil moisture in wet and normal years obviously moved down in the soil.

4. Conclusions

(1) During the normal year, the seasonal variation of soil moisture was relatively flat. During the dry year, the soil moisture gradually decreased before the rainy season and increased significantly after the rainy season. During the wet year, the rapid recharge effect of soil moisture from heavy rainfall in the shallow layer (above 50cm) was significantly better than that in the deep layer (below 50cm).

(2) In different months (except for May), the soil moisture changes with soil depth showed the trend of “first increase, then decrease, and finally slow increase”. Higher soil moisture were generally in the soil layer of 30~70 cm, the soil moisture below 70 cm changed little with the soil depth and tended to be stable below 110 cm.

(3) During the wet year, the vertical variation of soil moisture tends to be active, showing three layers, i.e. quickly changing layer (0~50cm), active variable layer (50~70cm) and sub-active variable layer (below 70cm). During the normal and dry years, the soil moisture showed small vertical changes. For the dry year, only the surface layer (0~10cm) showed active variation of soil moisture; for the normal year, the soil layer above 70cm showed active variation of soil moisture.

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