Temporal and spatial characteristics of soil moisture dynamics in fixed dune of the Horqin sandy land

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Abstract. The spatio-temporal variability of soil moisture (SM) in the fixed dune was analyzed based on the long-term monitoring data of SM at a depth of 1.5m in the fixed dune of the Horqin Sandy Land from May to September (that is growing season) for the 6th consecutive year (2009–2014) and the synchronize rainfall data. The results indicated that: (1) The changes of SM with the month generally showed a “W-shaped” curve in 2009, 2010 and 2011, and higher SM appeared in July. In 2012, the SM was lower in May and higher in June, and decreased slightly in the following three months. In 2013 and 2014, the changes of SM with the month showed a continuous downward trend. (2) Except for 2013, the SM was lower in the surface layer (0~10 cm), and the SM increased first, then decreased, and finally increased with soil depth. (3) As the soil depth increases, both SD and CV of SM showed a decreasing trend. According to the SD and CV method, the vertical variation layers of SM in fixed dunes of the study area were initially divided into the fast changing layer of 0~50 cm, the active layer of 50~90 cm and the second active layer of 90~150 cm.

1. Introduction
SM is an important controlling factor of many hydrological, ecological, and biological processes, and it is usually affected by rainfall, groundwater, terrain and vegetation, etc [1]. And hence, the SM has received important attention from various related research areas [2]. Although SM accounts for only 0.001% of the total water storage on Earth, it is a key factor for the climate system [3-4]. SM in semi-arid regions is the limiting factor for the development of ecosystems, and the spatio-temporal variation rule of SM is the main reference factor for ecological construction and planning in these regions [5].

The spatio-temporal variation of SM refers to the significant differentiation and diversity of SM characteristics in different times, sites and soil layers within a certain landscape [6]. The spatio-temporal variation of SM is the result of the comprehensive effect of various factors in multiple scales, such as land use (vegetation), weather (rainfall), terrain, soil and human activities. In recent years, the study on the spatio-temporal variation of SM has become one of the research hotspots at home and abroad [7]. The temporal variation of SM decreases as soil depth increases [8]. In arid regions, the spatial variation of SM is the result of the combined effect of moisture input (rainfall) and output (evapotranspiration and leakage). Generally, the spatial distribution of SM is divided into three types, namely decreasing type, fluctuating type and increasing type, which vary with place and time [7]. For example, Qiu Yang et al. studied the SM dynamics of the Loess Plateau in China and concluded that there is a significant difference in the average SM at different soil depths, and the SM content increases significantly as soil depth increases [9]. Yang Xinmin studied the dynamics of SM in the loess hilly region of China, and
considered that the SM tends to decrease as soil depth increases [10]. Yang Yongdong’s study on SM of different vegetation types in the Loess Plateau found that the SM changes slowly in the soil profile at the early stage of vegetation growth, while the SM shows a decreasing trend in the profile at the middle stage of vegetation growth [11].

Horqin Sandy Land lies in a semiarid area of southeast Inner Mongolia. Due to the long-term influence of extensive fuelwood gathering, heavy grazing and reclamation, it has become one of the most severe desertification regions in recent years [12]. Thus, discussing the variation of SM in fixed dunes of this region can not only help us understand the temporal and spatial distribution characteristics of SM in sandy land, but also have a important effect on the next study of SM in sandy land under different environmental conditions.

2. Methods

2.1. Study area

The Horqin Sandy Land located in the agro-pastoral transitional zone between the Inner Mongolian Plateau and the Northeast Plains (120°42′ E, 42°55′ N). The climate is temperate, semiarid continental monsoonal in this area, and with an average annual precipitation of 360 mm. The annual mean temperature is about 6.4℃, and the annual mean open-pan evaporation is around 1935 mm. The annual mean wind velocity is in the range of 3.2~4.1 m·s⁻¹. The topography is characterized by dunes and interdune lowlands [13].

2.2. Data obtaining

In this research, a special fixed dune was selected, and we installed three neutron probes (CNC503DR) with equal distances to record the soil moisture (%) of eight soil layers, the lower limit of soil was 10 cm, 30 cm, 50 cm, 70 cm, 90 cm, 110 cm, 130 cm and 150 cm. The three neutron probes were installed to measure the SM, and taken the average value for analysis. From 2009 to 2014, the SM measured once every seven days and increased measurement after precipitation. For each soil layer, the total measured times was all 101. The synchronize precipitation data was received from nearby weather station.

2.3. Classification of precipitation year

We used the domestic precipitation year classification method [14] to determine the types of precipitation years: If P>0.33δ>P₁, it is dry year; if P+0.33δ<P₁, it is wet year. Where P₁ denote the current year precipitation (mm), P and δ represent the annual mean precipitation (mm) and its square error (mm), respectively.

2.4. Soil division

The commonly method was depended on CV and SD to divide the soil layer into four levels [15-16]: If SD<2, CV<0.1, it is relatively steady layer (RS); If SD: 2~3, CV: 0.1~0.2, it is second active layer (SA); If SD: 3~4, CV: 0.2~0.3, it is active layer (AL); And if SD>4, CV>0.3, it is fast changing layer (FC).

2.5. Data analysis

The statistical characteristics of SM in each month and each soil layer was obtained by Micro-Excel, and the graph that shows the dynamic of SM with month and soil depth was compiled by the Micro-Origin 8.0 software.

3. Results and discussion

3.1. Precipitation characteristics

During the experimental period, the statistical characteristics of precipitation in the study area (Table 1) showed that, in the past 6 years (2009~2014), the mean annual precipitation of the study area was 280.7 mm, with the mean square error of 78.12 mm, P+0.33 δ =306.48 mm, P-0.33 δ =254.92 mm. According
to the classification standard for precipitation years [14], the rainfall was the highest (>306.48 mm) in 2012; at the lower levels (<254.92 mm) in 2009, 2011 and 2013, which were dry years; and at normal levels in 2010 and 2014, which were normal years. The annual rainfall was mainly implanted from May to September, more than 70% of the annual rainfall implanted in this period and even reaching up to 92.8% in 2014. In the meantime, the mean rainfall of different months was the highest (82.5%) in July and the lowest in January. The rainfall was scarce in January, February, November and December, and the total rainfall in the four months accounted for no more than 3% of the annual rainfall. The monthly rainfall was the highest in September 2012 at 144.8 mm, which exceeded half of the annual rainfall in all years except 2012 and accounted for 33.6% of the annual rainfall in that year.

Table 1. Rainfall characteristics of experimental year (2009~2014).

| Year | 2009  | 2010  | 2011  | 2012  | 2013  | 2014  | Mean  |
|------|-------|-------|-------|-------|-------|-------|-------|
| Jan. | 0.0   | 0.0   | 0.0   | 0.0   | 0.0   | 0.0   | 0.0   |
| Feb. | 3.5   | 0.0   | 0.2   | 3.4   | 2.0   | 0.0   | 1.5   |
| Mar  | 0.0   | 5.4   | 0.2   | 4.2   | 3.8   | 11.8  | 4.2   |
| Apr  | 64.4  | 11.2  | 3.0   | 17.0  | 30.0  | 2.2   | 21.3  |
| May  | 23.2  | 51.0  | 34.4  | 28.6  | 10.0  | 79.0  | 37.7  |
| Jun  | 54.4  | 13.4  | 33.4  | 87.4  | 36.0  | 69.2  | 49.0  |
| Jul  | 86.6  | 82.0  | 90.8  | 85.2  | 56.8  | 82.5  |       |
| Aug  | 9.8   | 26.8  | 24.8  | 27.8  | 59.2  | 7.8   | 26.0  |
| Sep  | 4.4   | 29.2  | 2.0   | 144.8 | 7.6   | 36.8  | 37.5  |
| Oct  | 1.6   | 58.2  | 7.8   | 17.4  | 17.4  | 5.2   | 17.9  |
| Nov  | 1.7   | 1.8   | 5.2   | 6.2   | 0.4   | 0.2   | 2.6   |
| Dec  | 2.2   | 0.4   | 0.0   | 0.0   | 0.0   | 0.0   | 0.4   |
| Sum  | 251.8 | 279.4 | 201.8 | 430.6 | 251.6 | 269.0 | 280.7 |

Yearly rainfall pattern: Dry year, Normal year, Dry year, Rainy year, Dry year, Normal year

3.2. SM changes with month
The changes of the average SM in different soil layers with the month from 2009 to 2014 (Figure. 1) illustrated that, the varies of SM with the month generally showed a “W-shaped” curve in 2009, 2010 and 2011. Higher SM appeared in July and higher rainfall also occurred in July of these three years, indicating that heavy rainfall can greatly replenish SM at the middle stage of vegetation growth. In these three years, the SM was relatively lower in June and August. In 2012, the SM was lower in May and higher in June, and decreased slightly in the following three months, to the extent that the heavy rainfall (144.8 mm) in September failed to significantly increase the SM content. It shows that the recharge effect of heavy rainfall on SM at the later stage of vegetation growth is not as obvious as that at the middle stage of vegetation growth. In 2013, although higher rainfall also appeared in July (85.2 mm), the changes of SM with the month didn’t show a “W-shaped” curve like that in the previous three years, but showed a continuous decline. In 2014, the highest rainfall (79 mm) occurred in May, when the SM was not the highest in all months. This is because May belongs to the early stage for vegetation growth in the study area, and the initial SM was at a low level. Combined with strong soil evaporation, the SM was not effectively recharged from heavy rainfall. The SM continued to decline since June, which was similar to that in 2013.
3.3. SM changes with soil depth

The varies of SM along with soil depth (Figure. 2) displayed that, except for 2013, the average SM in each month of the growing season was lower in the surface layer (0~10 cm), mainly because the strong evaporation of the surface soil results in lower SM. On the whole, the SM increased first, then decreased, and finally increased with soil depth. Higher SM occurred in the soil layer of 10~30 cm from 2009 to 2011 and 30~50 cm in 2012 and 2014, and then decreased to the second low content in 90-110 cm, followed by an increasing trend again. In 2013, the SM basically continued to increase as the soil depth increased, which was different from that of the other five years. In the analysis of SM changes with the month, there was also a great difference between 2013 and other years. The reason remains to be further explored.

Figure 1. Variation of SM and rainfall with month.
A, B, C, D, E, F denote the year of 2009, 2010, 2011, 2012, 2013 and 2014, respectively.
3.4. SM changes with soil layer
The statistical results of SD and CV of SM in each soil layer from 2009 to 2014 (Table 2) showed that, the SD of SM was relatively small, not exceeding 2.5. As the soil depth increases, both SD and CV showed a decreasing trend, which indicates that the variability of SM decreases with the increase of soil depth.

We divided the soil layer into four levels depending on the CV and SD of SM [15-16], the result indicated that, in 2009, 0~30 cm was FC, and the soil layer >30 cm was AL; In 2010, 0~70 cm was FC, 70~90cm was AL, and the soil layer >90 cm was SA; In 2011, only 0~10 cm was AL, and the soil layer >10 cm was SA; In 2012, 0~50 cm was FC, 50~70 cm was AL, and the soil layer >70 cm was SA; In 2013, 0~10 cm was FC, 10~110 cm was AL, and the soil layer >110 cm was SA; And in 2014, 0~50 cm was FC, 50~70 cm was AL, 70~90 cm was SA, and the soil layer >90 cm was RS. Based on the above analysis results, the vertical variation layers of SM in fixed dunes can be generally divided into
the fast changing layer of 0–50 cm, the active layer of 50–90 cm and the second active layer of 90–150 cm.

Table 2. Vertical division of SM.

| Year | Soil depth (cm) | 0–10 | 10–30 | 30–50 | 50–70 | 70–90 | 90–110 | 110–130 | 130–150 |
|------|-----------------|------|-------|-------|-------|-------|--------|---------|---------|
|      | SD              | 1.12 | 1.36  | 1.10  | 0.87  | 0.77  | 0.77   | 0.80    | 0.79    |
| 2009 | CV              | 0.39 | 0.32  | 0.26  | 0.23  | 0.23  | 0.24   | 0.22    |         |
|      | Layers          | FC   | FC    | AL    | AL    | AL    | AL     | AL      | AL      |
|      | SD              | 1.20 | 1.66  | 1.74  | 1.67  | 1.12  | 0.85   | 0.70    | 0.66    |
| 2010 | CV              | 0.33 | 0.31  | 0.32  | 0.32  | 0.24  | 0.19   | 0.16    | 0.14    |
|      | Layers          | FC   | FC    | FC    | AL    | SA    | SA     | SA      | SA      |
|      | SD              | 0.70 | 0.90  | 0.70  | 0.74  | 0.54  | 0.42   | 0.45    | 0.58    |
| 2011 | CV              | 0.22 | 0.19  | 0.15  | 0.17  | 0.14  | 0.12   | 0.12    | 0.15    |
|      | Layers          | AL   | SA    | SA    | SA    | SA    | SA     | SA      | SA      |
|      | SD              | 0.91 | 1.51  | 1.57  | 1.14  | 0.53  | 0.58   | 0.54    | 0.50    |
| 2012 | CV              | 0.32 | 0.31  | 0.31  | 0.26  | 0.15  | 0.19   | 0.17    | 0.15    |
|      | Layers          | FC   | FC    | FC    | AL    | SA    | SA     | SA      | SA      |
|      | SD              | 1.08 | 0.65  | 0.68  | 0.64  | 0.73  | 0.75   | 0.68    | 0.43    |
| 2013 | CV              | 0.47 | 0.22  | 0.21  | 0.21  | 0.21  | 0.21   | 0.19    | 0.12    |
|      | Layers          | FC   | AL    | AL    | AL    | AL    | AL     | SA      | SA      |
|      | SD              | 2.40 | 1.08  | 1.20  | 0.99  | 0.39  | 0.14   | 0.08    | 0.15    |
| 2014 | CV              | 0.31 | 0.35  | 0.30  | 0.26  | 0.13  | 0.05   | 0.03    | 0.05    |
|      | Layers          | FC   | FC    | AL    | SA    | RS    | RS     | RS      |         |

4. Conclusions
(1) The changes of SM with the month generally differently at different month, which showed a “W-shaped” curve in 2009, 2010 and 2011, a continuous downward trend in 2013 and 2014, and it was lower in May and higher in June, and decreased slightly in the following three months in 2012.
(2) Except for 2013, the SM was lower in the surface layer (0–10 cm), and the SM increased first, then decreased, and finally increased with soil depth.
(3) As the soil depth increases, both SD and CV of SM showed a decreasing trend. The vertical variation layers of SM in fixed dunes of the study area were initially divided into the fast changing layer of 0–50 cm, the active layer of 50–90 cm and the second active layer of 90–150 cm.

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