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Response of the soil water content of mobile dunes to precipitation patterns in Inner Mongolia, northern China☆

S.X. Yao [a,b], C.C. Zhao [b,*], T.H. Zhang [b], X.P. Liu [b]

[a] Lanzhou City University, Lanzhou 730070, China
[b] Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, 320 Donggang West Road, Lanzhou 730000, China

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ABSTRACT

We analyzed the relationship between soil water content (SWC) dynamics in mobile dunes to a depth of 100 cm and precipitation patterns from June to July 2010 in the Horqin Sand Land. The precipitation was dominated by small events of 0.1–3.0 mm, which accounted for 52% of the total events. Precipitation >20 mm had the highest intensity, accounting for 50% of the total precipitation. SWC differed significantly among the soil layers: mean SWC was greatest from 80 to 100 cm and lowest from 40 to 60 cm. SWC from 0 to 100 cm was significantly affected by relative humidity, water barometric pressure and minimum temperature, and the SWC of 0–40 cm was obviously influenced by precipitation amount and wind velocity. Precipitation <5 mm did not replenish SWC, precipitation between 5 and 20 mm provided some replenishment to SWC from 0 to 40 cm, and precipitation >20 mm increased significantly SWC from 0 to 100 cm. In addition, precipitation intensity significantly affected the infiltration rate, with higher intensity leading to deeper and faster infiltration. At longer intervals between precipitation events, SWC in each soil layer decreased continuously over time; however, SWC from 0 to 80 cm changed little within the first 3 days, and SWC from 0 to 100 cm started to decrease greatly after 5 days.

1. Introduction

Soil moisture is an important parameter of the hydrological cycle of terrestrial ecosystems (Bindlish et al., 2003; Schneider et al., 2008; Song et al., 2007), and plays a critical role in predicting and understanding various hydrologic processes, including weather changes, precipitation pattern, runoff generation, and irrigation scheduling (Puri et al., 2011). Soil moisture also is one of the most important ecological factors in sandy ecosystems, where its shows significant variation (Chen et al., 2011; Das et al., 2008; Entin et al., 2000; Mahmood et al., 2004; Wagner et al., 2003). Thus, decreasing soil water content (SWC) is a main driving force in the development of desertification (Berndtsson and Chen, 1994; Chen et al., 1996; Nash et al., 1991). Many researchers have described the responses of SWC to land use (Fu et al., 2000; Huang et al., 2009; Yao et al., 2012), terrain (Bergkamp, 1998; Berndtsson and Nodomi, 1996; Svetlitchnyi et al., 2003; Tomer and Anderson, 1995), and vegetation types (He and Zhao, 2002; van Rheenen et al., 1995; Wilson and Kleb, 1996). Researchers have also found that rainfall characteristics such as amount, frequency, and intensity affect the temporal and spatial heterogeneity of SWC (Reynolds et al., 2004; Sala et al., 1992; Wilson et al., 2004).

The Horqin Sand Land lies in a semi-arid area of eastern Inner Mongolia, in northern China. Due to the long-term influence of heavy grazing, land reclamation for agriculture, and extensive harvesting of fuelwood, this region has become one of the most severely desertified areas in China (Zuo et al., 2008). In recent years, desertification has produced distinctive mobile dune landscapes in this region. The soil water conditions and their relationship with precipitation dynamics in such dune areas have become one of the most important areas of research on land-surface processes in arid China (Wang and Takahashi, 1999). However, despite the obvious importance of these processes in determining the effectiveness of efforts to slow or reverse desertification, no studies have described the dynamics of SWC and their relationship with the precipitation patterns in dune areas. In addition, SWC data obtained during most previous research was obtained at a daily scale or longer, so little SWC data is available at an hourly scale (Miller et al., 2007).

In the present study, we used hourly SWC data to describe the temporal dynamics of SWC in five soil layers in an area of mobile dunes in the Horqin Sand Land. Using this data, we firstly examined the relationships between SWC and the precipitation patterns,

* Corresponding author. Tel.: +86 93 1496 7160.
E-mail addresses: zhao_chch1978@163.com, zhao_cc@yahoo.cn (C.C. Zhao).

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including precipitation amount, intensity and duration. And then we assessed the changes in SWC over time in response to rainfall events with its pattern characteristics.

2. Materials and methods

2.1. Study site description

The study site is located in the southern part of the Horqin Sand Land in eastern Inner Mongolia, China (42°55′N, 120°42′E, 345 m a.s.l.). The landscape in this area is characterized by sand dunes alternating with gently undulating lowland areas. The soils are sandy, light yellow and loose in structure. The main soil type is classified as an Arenosol in WRB (ISSS, ISRIC and FAO) (Deckers et al., 1998). The climate is temperate, semi-arid and continental, receiving 360 mm annual mean precipitation, with 75% of this falling in the June–September period, versus a mean annual potential evaporation of 1935 mm. The mean annual temperature is 5.8–6.4 °C, with a minimum mean monthly temperature of −12.6 to −16.8 °C in January and a maximum mean monthly temperature of 20.3–23.5 °C in July. There was little rain or snow during the late autumn–early spring period at which was coupled generally with frequent strong winds. The period from November to May was therefore considered as the major wind-erosion season (Li et al., 2005). Based on wind data (1997–2002) from the weather station of the Naiman Desertification Research Station, the annual mean wind speed ranges between 3.4 and 4.1 m s^{-1} at 2 m height, and the prevailing wind directions over the erosive season are S, SSW, SW, NNW, WNW, NW, N and NNE. The winds occur with high speeds in excess of 4 m s^{-1} at 2 m height (a threshold wind speed to initiate sand movement; Zhang et al., 2004) in most days of the erosive season. As severely wind-erosion, soil particles of mobile dunes are mainly concentrated in 2–0.1 mm and 0.1–0.05 mm (Su and Zhao, 2003).

2.2. Meteorological data

All meteorological data during the study period, including hourly precipitation data, daily maximum temperature, minimum temperature, relative humidity, net radiation, water barometric pressure and wind velocity were obtained from an automatic meteorological station less than 60 m from the study site.

2.3. SWC and precipitation data

All the SWC data were collected from the water cycle research field at the Naiman Desertification Research Station. This site consisted of 23 concrete basins, each 2 × 2 × 2 m^3, that were constructed in the summer of 2009. Three of the basins were filled with sandy soil from mobile dunes near to the station. In each basin, we installed five soil moisture Minitrase (6050X3K1, ICT, USA) to automatically measure the volumetric soil water content (SWC, %) in five soil layers to a depth of 100 cm, at 20-cm intervals. The SWC data was recorded hourly starting in the spring of 2010. The dataset used in this paper extended from 24:00 on 4 June 2010 to 07:00 on 24 July 2010. No data was recorded during the maintenance period for the instruments (from 08:00 to 18:00 on 17 July). Because of instrument malfunctions, there was also no data for the soil layer from 40 to 60 cm from 01:00 on 13 July to 18:00 on 17 July. The sample size was 1070 records for the layer from 40 to 60 cm and 1173 for the other soil layers. The SWC data of each soil layer was the average of three basins.

2.4. Soil properties

For each basin, three undisturbed soil samples from 20, 40, 60, 80 and 100 cm were taken using a cylindrical metal core with a volume of 100 cm^3. Soil bulk density was firstly measured using the volume–mass relationship, and a same soil sample nearby was then to determine other basic soil properties. Soil organic matter content was determined using the $K_2Cr_2O_7$–H_2SO_4 wet oxidation method. Soil particle size distribution was determined by the dry sieving method. As the Horqin Sand Land is a severely wind-eroded region, Soil particles are mainly concentrated in 0.25–0.1 and 0.1–0.05 mm (Su and Zhao, 2003). So, soil particle size fraction in this study was divided into three groups: coarse sand (2–0.1 mm), fine-sand (0.1–0.05 mm) and clay and silt (<0.05 mm). Soil saturated hydraulic conductivity (Ksat) of each soil layer was determined in situ using a Guelph Prememeater (2008KI, Santa Barbara, CA93105, USA). The data for bulk density, organic matter content, soil saturated hydraulic conductivity and distribution of particle size fractions were averages of the three replicates for each basin (Table 1).

2.5. Data analysis

The primary statistical analysis was performed using version 11.5 of the SPSS software (SPSS Inc., Chicago, IL, USA), and differences in SWC between the five soil layers was tested for significance using one-way ANOVA. When the ANOVA results revealed significant differences, we used the Post Hoc Tests to identify significant differences between pairs of values, *P*-values of 0.05 were considered as a significant.

3. Results

3.1. Precipitation patterns

From 24:00 on 4 June 2010 to 07:00 on 24 July 2010, 23 precipitation events were recorded, and amounted to 109.4 mm in total. Among the 23 events, the minimum precipitation was 0.2 mm and the maximum was 34.4 mm. Most of the precipitation comprised small precipitation event, with <3.0 mm of precipitation (Fig. 1), and the events with >6.0 mm were a few. We classified the amount of precipitation into five levels: 0.1 to 3.0, 3.1 to 6.0, 6.1 to 10.0, and 10.1 to 20.0 and >20.0 mm. The number of precipitation events was 12 for event with 0.1–3.0 mm, accounting for 52% of all precipitation events; in addition, there were 7 events with 3.1–

Table 1
Soil physical and chemical properties at the five soil depths in mobile dune.

Soil depth (cm)	Bulk density (g cm^{-3})	Total porosity (%)	Organic matter content (%)	Soil saturated hydraulic conductivity (mm/min)	Soil particle size distribution (%)		
					2–0.1 mm	0.1–0.05 mm	<0.05 mm
0–20	1.51	43.16	0.47	5.32	97.41	2.20	0.06
20–40	1.50	43.22	0.40	6.53	97.45	2.14	0.07
40–60	1.51	43.01	0.47	5.19	97.28	2.24	0.07
60–80	1.51	43.02	0.36	7.52	97.12	2.43	0.08
80–100	1.53	42.37	0.42	4.90	96.91	2.43	0.08
Mean	1.51	42.96	0.42	5.89	97.23	2.29	0.07