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Seasonal changes in soil water repellency of different land use types in Inner Mongolia grassland

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ABSTRACT

Soil water repellency (SWR) is a physical phenomenon in which the rate of wetting is restricted and water beads are formed on the soil surface where the soil is called water-repellent soil. SWR analysis is necessary to interpret nonuniform wetting and preferential flow for site-specific ecosystems. This study aims to investigate the effects of soil water conditions and land use types on SWR in *Leymus chinensis* steppe soil in Xilinhot, Inner Mongolia, China. The main objective is to determine how SWR in soils in Inner Mongolia is influenced by different grassland utilization types, including no grazing since 1979 and 1999, winter grazing, and continuous grazing, by using water drop penetration time (WDPT). Results show that a slightly hydrophobic or hydrophilic soil behavior was often observed, and SWR was most evident in the months with the highest evaporation despite heavy rainfall. Changes in SWR in different seasons were affected by grazing intensity. The highest number of hydrophobic soil samples was found in the continuous grazing sites, followed by that in the winter grazing sites. Few hydrophobic soil samples were detected in the ungrazed sites since 1979, and the lowest number of samples was observed in the ungrazed sites since 1999. The SWR of different particle size classes decreased with increasing particle size. Therefore, SWR was significantly correlated with soil particle size class at 0–0.05 and 0.05–0.1 mm. These results emphasized the need to consider SWR in soil utilization because grazing intensity affects the soil repellent properties in steppe soil and provided a basis for the development of grassland management.

1. Introduction

Soil water repellency (SWR) is a physical phenomenon in which the rate of wetting is restricted and water beads form on the soil surface where the soil is called water-repellent soil (Anderson, 1986). The soil in this state is called water repellent soil (Yang et al., 1996). SWR causes precipitation or irrigation water to flow along preferential flow paths into the soil, leading to the uneven distribution of soil moisture, seriously affecting the emergence rate of seeds and eventually resulting in the reduction of crop production (Dekker and Ritsema, 1994; Yang et al., 2003). Moreover, SWR enables water to carry solutes along preferential flow paths to reach groundwater rapidly, increasing groundwater contamination risk and causing a series of environmental problems (Carrillo et al., 2000; Liu et al., 2016a). In addition, SWR reduces water infiltration and when a part of the surface soil remains dry it may lead to erosion in rainy seasons (Witter et al., 1991). Water is the main limiting factor of grassland productivity in semi-arid areas. The effects of grazing intensity on soil physical and mechanical properties, such as soil water content (SWC), hydraulic conductivity (K), water drop penetration time (WDPT), soil organic carbon (SOC) concentration, bulk density (BD), and soil texture, in the *Leymus chinensis* steppe in Inner Mongolia, China have been reported (Zhao et al., 2007). Studies on the water-repellent properties of steppe soils will help examine the influence of grazing intensity on soil water cycle and utilization in grassland, thereby providing a scientific basis for the development of reasonable grassland management measures.

Studies on SWR in grasslands mainly include the analysis of basic grass characteristics, influencing factors on SWR, and strategies to decrease or prevent SWR in practice. Dekker and Jungerius (1990) and Dekker and Ritsema (2000) investigated the SWR characteristics of sand dune grass that has not been cultivated for at least a few decades in the southwest of the Netherlands. They considered the critical soil moisture content and explained the relationship between SWR and soil water content. Their results revealed no relationship between organic matter content and SWR. Newton et al. (2003) evaluated the rangelands located in the Western North Island of New Zealand and found that the increase in soil organic matter (SOM) contents remarkably strengthened SWR in fields, but SWR decreased as the amount of carbon dioxide

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in air increased (Liu et al., 2016b). SWR is affected by land use types, vegetation distribution and soil moisture content, soil texture, soil organic matter, and other physicochemical properties (Keizer et al., 2007; Mataix-Solera et al., 2013). SWR also exhibits strong temporal and spatial variability (Czachor et al., 2010), which is especially obvious in different land use types. For example, the soil properties of orchards and cultivated lands differ significantly from other land use types (Sharpley and Menzel, 1987). Soil erosion not only leads to nutrient loss and reduced soil productivity but also induces nutrient transport through the surface runoff into the water body, thereby causing water pollution and eutrophication, which is a non-point source pollution factor that limits agricultural activities (Gomi et al., 2008). The effects of water repellency on soil erosion are affected by their spatiotemporal changes (Jordan et al., 2008), and previous studies only revealed the characteristics of SWR for single land use (Lemmnitz et al., 2008; Benito et al., 2003). However, the spatial distribution of SWR under different land uses (Harper and Gilkes, 1994) and its influencing factors have not been considered.

Grassland is the main land use type in northern China and in the semi-arid areas of Eurasia. Grassland degradation resulted in grassland productivity decline and ecosystem deterioration because of improper management and overgrazing (Tong et al., 2004). Uneven soil wetting and limited water retention in these soils caused poor crop and pasture establishment, resulting in increased susceptibility to wind and water erosion (Tate et al., 1989). Reduced tillage practices have been enthusiastically adopted by farmers in southern Australia, which is associated largely by well-documented reductions in soil erosion (Flower et al., 2008). The benefits of no-tillage include high soil carbon contents (Bachmann et al., 2008), which led to remarkable water and nutrient holding capacity of many soil types (Lal and Kimble, 1997). The impact of reduced tillage and no-tillage practices on SWR in fields has been examined (Blanco-Canqui and Lal, 2009; González-Peñaloza et al., 2012; Roper et al., 2013; Ward et al., 2015) but has yet to be investigated in grasslands.

In this research, the influence of different grassland uses in China on the original physical soil and its chemical and biological characteristics was investigated. This study also briefly described the benefit of water retention characteristic, water infiltration and redistribution in grassland soils, and soil water movement patterns that are closely related to SWR properties. The main objectives of this study are as follows: (1) to evaluate the SWR of grassland soil in Inner Mongolia under different land use types through a field experiment; (2) to examine the characteristics of the SWR of different land use types under different seasons; and (3) to investigate the effects of different particle sizes under different land use types on SWR.

2. Methods

2.1. Study area

The study area is located in the Inner Mongolia grassland ecosystem in Baiyinxile pasture station in Xilinhot, Inner Mongolia. The geographical coordinates of the study area are 43° 32′ 45″ − 43° 33′ 10″ N and 116° 40′ 30″ − 116° 40′ 50″ E (Fig. 1), located on the south bank of the Xi lin River in the hilly area. The area is formed on the basalt platform gentle hilly valley, at an elevation of 1200–1250 m, a relative hill height of 20–30 m, and with a round top and long valley slope of less than 5°, bordering on flat valley (http://ngcc.sbsm.gov.cn/). The study area has a temperate semi-arid grassland climate (Wang et al., 2010), the annual average temperature is 0.57 °C, the coldest month is January with an average temperature of − 21.4 °C, the hottest month is July with an average temperature of 18.5 °C, and an extreme minimum temperature of − 30.6 °C (http://www.zhongguotianqi.com.cn). The annual average rainfall is approximately 350 mm, and the precipitation is mainly concentrated in July to September, with a high rainfall interannual variation coefficient of more than 30%. The highest precipitation for the year is 645 mm, the lowest precipitation is 182 mm, and the potential mean annual evapotranspiration is 1600–1800 mm (http://www.nmgtj.gov.cn/nmgttj/index.htm). The plant growth period is from May to September of each year (Wang et al., 2009). By the end of September, the temperature suddenly drops with the rapid death of grass plants in the short growing season (Wang et al., 2013).

The area is typical temperate grassland. The *Leymus chinensis* community and the *Stipa grandis* community are the most widely distributed plant community in the area, and they are extensively present in the Eurasia temperate grassland. *Leymus chinensis* is the dominant species in the grassland, followed by *S. gradis*, *Agropyron cristatum*, and *Cleistogenes squarrosa*. *L. chinensis* contributes to 80% of the total biomass of the community. The *S. grandis* community, consisting of *S. grandis*, *Koeleria cristata*, *A. cristatum*, and *C. squarrosa*, has a significant advantage that accounts for 85% of the total biomass with a grass group height of 50–60 cm and coverage from 30 to 40% to 60–70% in the rainy season with the remaining bare soil. The surface layer of the bare soil is covered with thin litter.

Chestnut soil is the main soil in this area, which was characterized by the significant accumulation of organic matter and calcium carbonate in the upper part of the soil of the chestnut humus layer, the middle part of the gray calcareous layer, and the lower part of the weathered parent layer. The humus layer thickness was generally in the range of 30–45 cm, and had an organic matter content of 2.0-4.0%. The texture mostly consists of sand and silt. The clay minerals are mainly montmorillonite and hydromica. The dynamic change of grassland soil moisture in a year is divided into four periods. From March to early April with the melting of snow and ice and the dissolution of permafrost, the soil has a short wetting period. From the beginning of April to the end of June, the probability of precipitation is small and the soil experiences a dry period with the rising temperature and frequent winds. By the end of June, the soil moisture fluctuates because of the strong evaporation and rising temperature. From the beginning of September to the end of the freezing month (December), the soil moisture content is constant low because of the low temperature and evaporation (Chen and Wang, 2003).

2.2. Sampling sites

Before 1979, the whole experimental area was lightly grazed, with 70–90% of sheep livestock and 10–30% of goats. The test included four fence plots (Fig. 1). Sample site A has fencing and has been ungrazed since 1979; this site has an area of 24 ha, grassland native vegetation, high grass group, lush growth, and a large material coverage of approximately 3–5 cm thickness on the surface. Sample site B has fencing and has been un grazed since 1999; it has an area of 35 ha, which is basically for native vegetation, high grass group, lush growth, and a large continuous coverage. Sample site C is an area of 40 ha, and the grazing intensity is 0.5 sheep unit/(ha a). Sample site D is an area of 250 ha, and the grazing intensity is 2.0 sheep units/(ha a). Cold-song and wheatgrass are the vegetation group, and the ground material is discontinuously distributed. The organic carbon contents of the four sites at 0–5 cm soil layers are 31.0, 25.5, 25.9, and 23.0 mg/g of organic matter. As shown in Fig. 1, grazing site (A) and forbidden grazing site (B) are located in the lower part of the hilly valley, the winter grazing site (C) on the higher parts of the valley, and the continuous grazing site (D) in a flat wide valley.

An area of 105 m × 135 m was selected from each sample site, and was divided into 15 m × 15 m grids, 80 sampling sites were established, and 20 other samples were set with a spacing of 5 m according to the terrain conditions between the two sampling sites of 80 locations. A total of 80 + 20 samples were taken in each site (the origin of the continuous grazing site was the southeast corner and the rest was the northwest corner). When present, litter was gently brushed off or removed by hand. A total of 100 samples were taken from the 0–5 cm soil

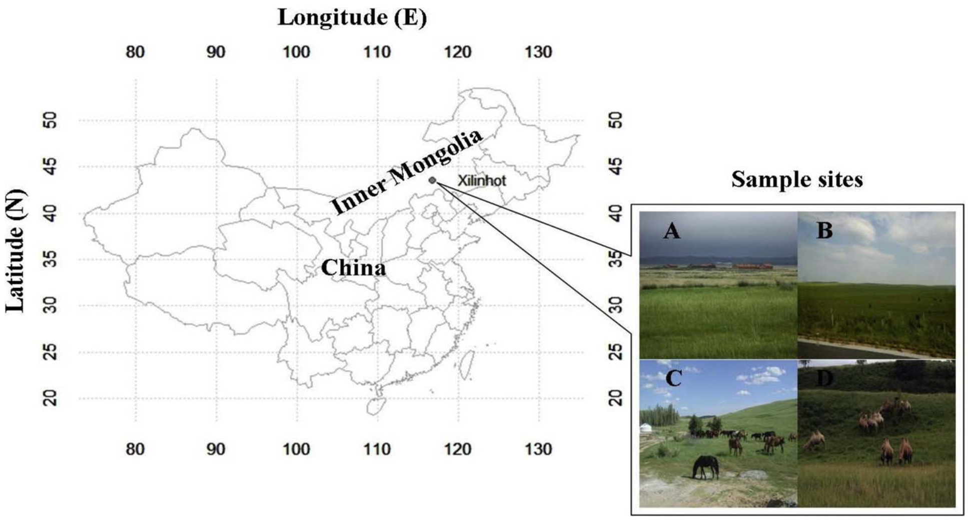

Fig. 1. Topography of Leymus chinensis Steppe plot.

layers in each site (size 1 × 1 m), and were transported to the laboratory in sealed plastic bags.

2.3. Determination of SWR

To understand the water-repellent properties of grassland soils, the WDPT was measured in triplicates for the 100 soil samples collected on each of the particular dates (July 20, August 20, and September 21, 2014). To further investigate the water repellency of the soil, evaluations were also performed on June 7, June 26, June 30, July 23, August 5, August 14, August 26, September 4, and September 15, 2015. The WDPT values of the 100 samples were obtained in situ and each measurement lasted 2–4 days due to limited natural conditions and human factors. The droplet penetration time of the SWR was determined by dropping 3 drops of distilled water (about 0.05 mL per drop) on the soil surface using a stainless steel syringe, which is durable and can be used again. When present, litter was gently brushed off or removed by hand. The time required to complete the penetration of the water droplets into the soil was measured using a stopwatch, and the arithmetic mean value was the result. The droplets were placed at a position no higher than 5 mm above the soil surface during the measurement, to avoid excessive kinetic energy, which affects the soil-droplet interaction (Wu et al., 2007). According to Dekker and Jungerius (1990), the water repellency was divided into five grades: 0 grade, no water repellency (dripping penetration time no more than 5 s); 1 grade, slight water repellency (5–60 s); 2 grade, strong water repellency (60–600 s); 3 grade, severe water repellency (600–3600 s); and 4 grade, extreme water repellency (> 3600 s).

2.4. SWR assessment in different soil separates

After the 100 samples were equilibrated in a controlled atmosphere of 20% and 45%–55% relative humidity for 24 h (Doerr et al., 2000), each sample was carefully divided into four particle size fractions (0–0.05, 0.05–0.1, 0.1–0.2, and 0.2–2 mm) by dry sieving. Then, the water repellency was assessed using the WDPT method. This test involves placing five drops of distilled water (80 μL) onto the sample surface and recording the time for complete droplet penetration (Letey, 1969).

2.5. Data analysis

Assumptions of normality and homogeneity of variances for WDPT values were tested using the Shapiro–Wilk and Brown–Forsyth tests, respectively (Snedecor and Cochran, 1980). As both assumptions were rejected, the alternative non-parametric Kruskal–Wallis test was used. When the Kruskal–Wallis null hypothesis was rejected, post-hoc pairwise comparisons were performed to investigate the differences between the sample means (Bonferroni test). These procedures were performed using the Windows-based SPSS software, version 17.0. The figures were then plotted using Origin 9.0 in comparable formats.

3. Results

3.1. Statistical characteristics of the penetration time of the water droplets

The WDPT values measured at the surface under litter, or grass sod reflected the SWR intensity to a certain extent. As shown in Fig. 2, the WDPT values measured between 20 July 2014 15 September 2015 had a high standard deviation and variation coefficient for certain land use-types, which ranged from approximately 10%–40%. Moreover, the seasonal variation of SWR was also reflected in 2015. For example, WDPT was the largest by the end of August 2014, which reflected the strongest SWR. From July to September 2014, the trend was low-high-low. The trend from June 2015 to September 2015 was high-low-high-low-high. In these periods, the highest value was obtained in 2014, while the lowest value was obtained in 2015. The rainfall in July-September 2014 was less-more-less (Fig. 3a). The rainfall from June to September 2015 (Fig. 3b), and the trend of SWR reflected by the WDPT were also consistent. Between 20 May and 19 July 2014 a relatively long dry period occurred with a total of only 47 mm of rain. The WDPT was also measured on 17 September 2015, when a dry period occurred between 18 August and 17 September and rain amounted to a total to about of approximately 5 mm, and sites A and B manifested soil water repellency. The seasonal variation of SWR was possibly related to rainfall.

3.2. Seasonal variation of intensity of water-repellency in grassland under different land use types

Although WDPT can reflect the water repellency of soil to some extent, it has great variability. Thus, intensity of water repellency was divided into 4 grades according to the water repellency classification standard proposed by Dekker and Jungerius (1990). The proportion of the number of samples with different intensities of water- repellency was statistically analyzed (Figs. 4 and 5).

From July to September 2014, the intensity of SWR in the grassland under four land use types showed a weak-strong-weak trend. The most water-repellent samples were found in August. Several samples showed intense water repellency, but the intensities of SWR in four land use

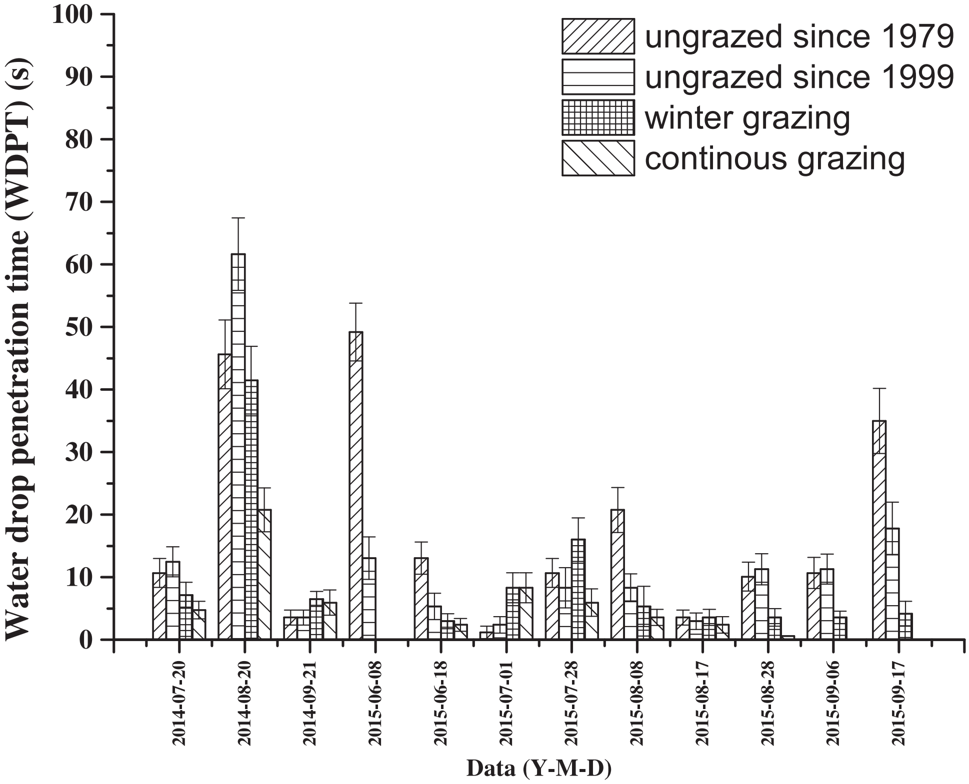

Fig. 2. The mean water droppenetration time (WDPT) (± SE) in different treatments between 20 July 2014 and 17 September 2015.

types were different in the same period (Fig. 4). More than 70% of the samples in the areas ungrazed since 1979 and the areas ungrazed since 1999 showed mild water repellency in July, and over 70% in winter and continuous grazing sites showed no water repellency. In August, more than 90% of the samples in the areas ungrazed since 1979 and the areas ungrazed since 1999 showed more than mild water repellency, and even more than 20% of them showed strong water repellency. More than 80% of the samples in the winter and continuous grazing sites showed no water repellency. In September, more than 90% of the samples in the areas ungrazed since 1979 and the areas ungrazed since 1999 showed no water repellency, whereas more than 50% of the samples in the winter and continuous grazing sites showed slight water repellency. Therefore, the number of water-repellent soil samples in July and August was greater in the areas ungrazed since 1999 than the areas ungrazed since 1979, which was greater than the grazing in winter that was greater than the continuous grazing. Fig. 4 shows that, in September, the number of water-repellent soil samples was in the following order: grazing in winter > continuous grazing > ungrazed since 1999 > ungrazed since 1979.

From June 2015 to September 2015, the trend of SWR in all four land use types varied (Fig. 5). The SWR intensity in the areas ungrazed since 1979 and the areas ungrazed since 1999 was strong (early June)-weak-strong (late July to early August)-weak-strong (mid-September). In July, the SWR intensity was weak-strong (mid-September), with three peak trends, and weak-strong (early July)-weak trend in the winter and continuous grazing treatments with a single peak. The

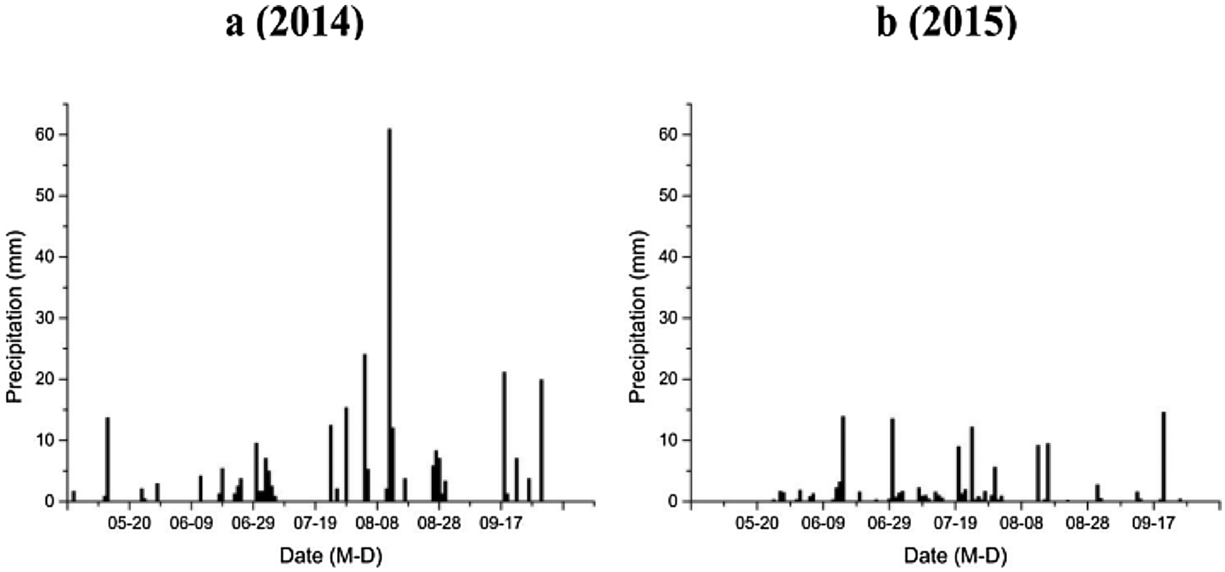

Fig. 3. Daily Precipitation distributions during experimental period in 2014 and in 2015.

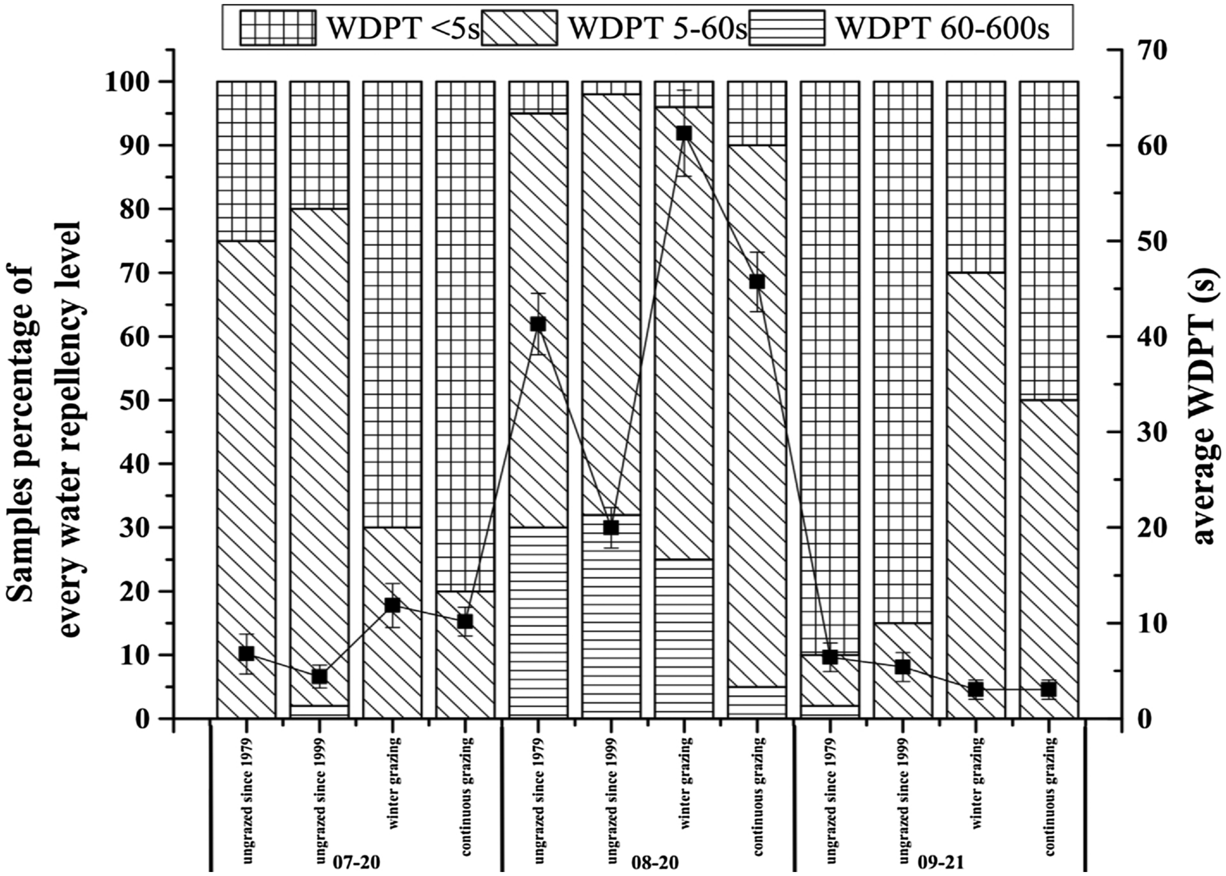

Fig. 4. Relative frequency distribution of water repellency of measured sites (n = 100) in different treatments in 2014, also the mean WDPT has been indicated. Squares represent mean values ± standard error (SE), and a line represents variation trend.

seasonal change of SWR in the areas ungrazed since 1979 and the areas ungrazed since 1999 occurred approximately half a month later than the grazing area. In addition, the soils in the ungrazed sites since 1979 and 1999 all showed strong water repellency in June, August, and September. However, in the winter and the continuous grazing sites, only several samples showed strong water repellency. In general, the water-repellency of soils between different treatments in 2015 was much difficult to compare within the same period because of the time lag. The lagging order of the general performance was as follows: the continuous grazing occurred first, followed by the area grazed in winter, the area ungrazed since 1999, and the area ungrazed since 1979.

In 2014 and 2015, the water repellency of grassland soils varied. In 2014, a single-vertex trend of weak-strong-weak was observed. In 2015, at least two trends were observed. In 2014, the number of soil samples with water repellency was higher than in 2015, and such difference may be related to the amount of rainfall in 2014. The rainfall from May to September in 2014 was 288.3 mm, and 125.1 mm in 2015. In addition, few measurements were taken outside the rainy season, and thus justification of whether the SWR intensity of the two years (Figs. 4 and 5) in the same period (Fig. 3a and b) can assess the rainfall distribution and the occurrence of SWR was often in the rainfall season is required. Overall, the actual water repellency was dependent on the wettability of the soil matrix but also on the presence of preferential flow via cracks, holes, and so on. However, the variability of the soil water content is not measured at all in the present study.

3.3. *Effect of particle size on soil water repellency*

The mean water repellency of soils with different sieve sizes is shown in Fig. 6. The water repellency of most of the dried 100 soil samples at 0–5 cm with different particle sizes decreased with the increase in particle size (Fig. 6). The SWR of the 0-0.05 mm sieve size fraction was significantly larger than that of the other sieve size fractions. The SWR of 0.05–0.1 mm was larger than that the 0.1–0.2 and 0.2–2 mm sieve size fractions. The water repellency of the 0.1–0.2 mm particle size was larger than that of the with the 0.2–2 mm particle size. The difference of SWR between soil sieve sizes in different land use types was not significant. The SWR of each sieve size under different land use patterns did not change significantly between 2004 and 2005.

4. Discussion

Our results showed that the seasonal variation of SWR was possibly related to rainfall, as well as to evaporation, and high temperature, which were also highest in the same period. Jaramillo et al. (2000) showed that when rainfall was high, the biomass was high, and the organic matter entering the soil and the corresponding water-repellent substance were high. In addition, the current research stated that SWR is induced by soil water repellent substances (Doerr et al., 2000). Primary species were divided into three plant functional groups (PFGs) on the basis of life forms: perennial rhizome grass (PR), perennial bunchgrasses (PB), and perennial forbs (PF) (Bai et al., 2004).Rainfall may increase the aboveground biomass of the grassland (Bai et al., 2004; Wu et al., 2008), resulting in more water-repellent substances, thereby enhancing the SWR during the rainy season indirectly.

Although the study of SWR in foreign countries can be traced back to more than 100 years ago, the mechanism researches in SWR only have a history of nearly 50 years. However, some water-repellent substances were difficult to be extracted, and the relationship between SWR and the soil chemical characteristics remained unknown (Ma'shum and Farmer, 1985; Doerr et al., 2000). Therefore, this preliminary study

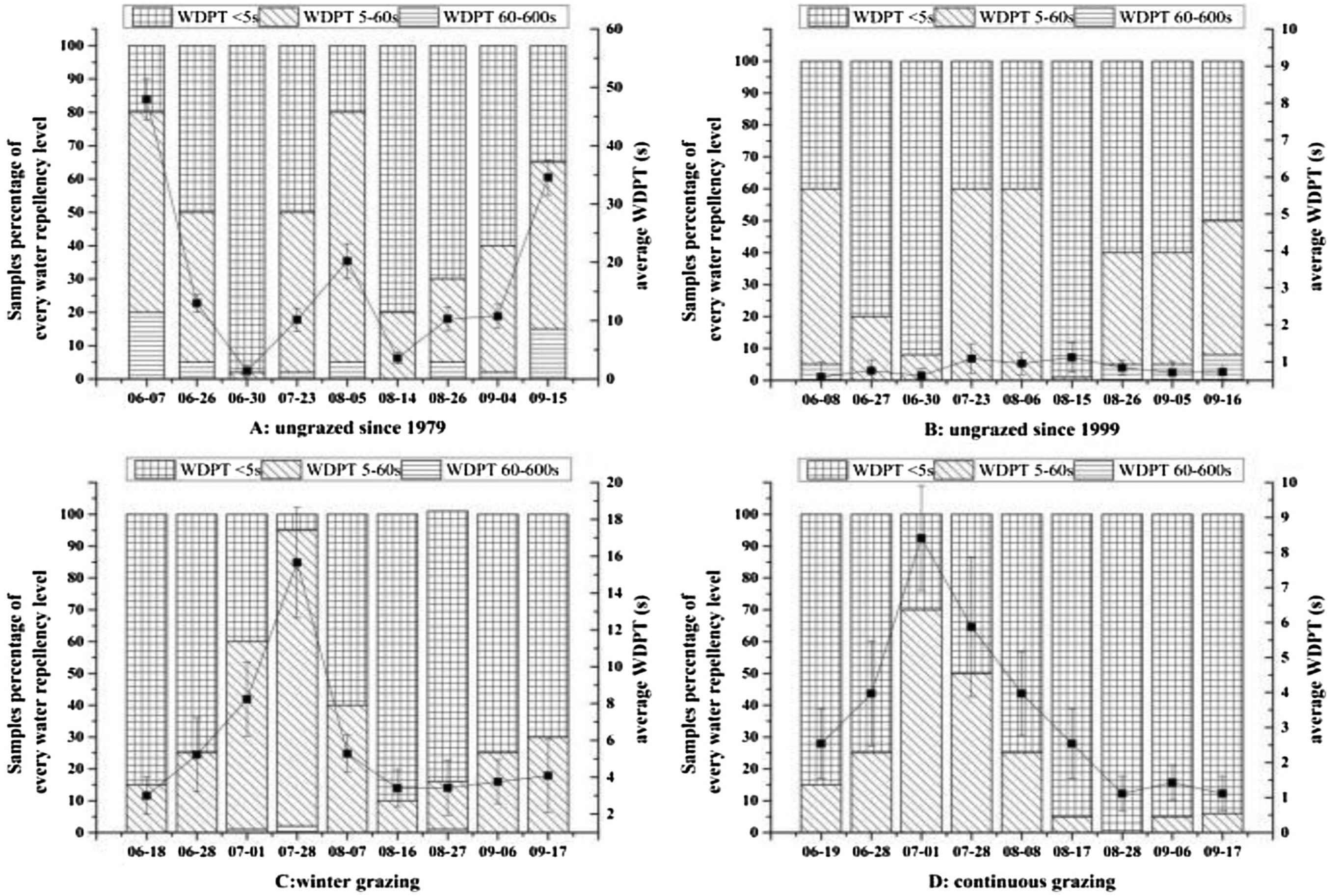

Fig. 5. Relative frequency of water repellency of measured sites (n = 100) in different treatments in 2015, also the mean WDPT (± SE) has been indicated, with different range per diagram from 0 to 10 to 0–60 s.

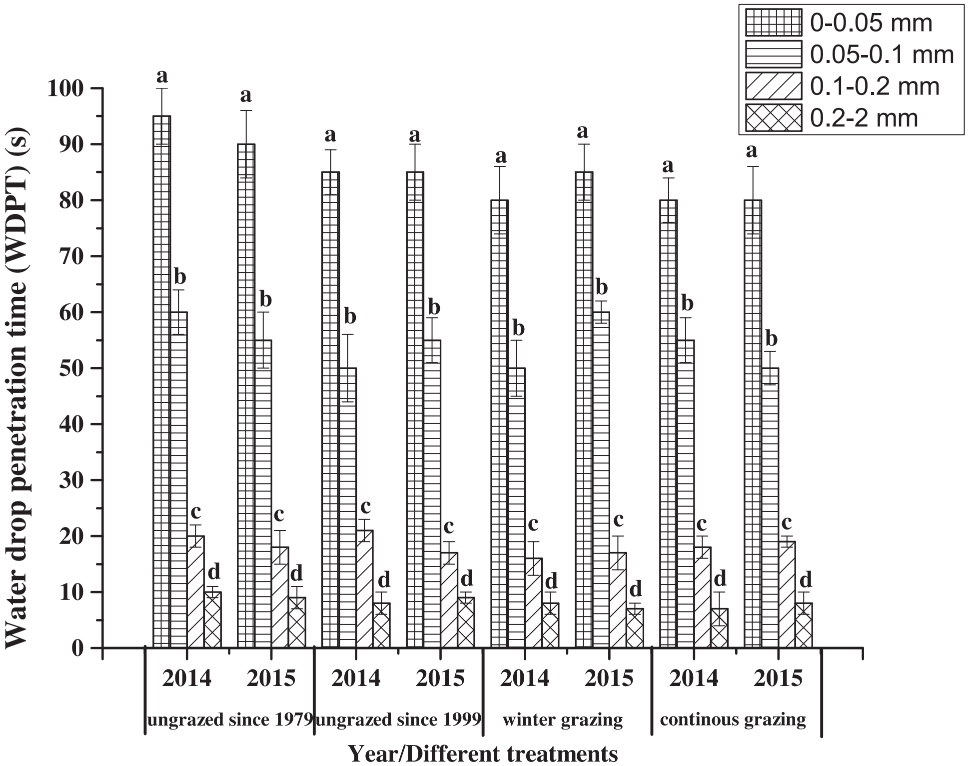

Fig. 6. The mean water droppenetration time (WDPT) (± SE) of different particle sizes with different land use types and durations (n = 100). Letters over each bar represent significant difference (Student *t* test, $p < 0.05$).

of the SWR in Inner Mongolia grassland only focused on the different soil water conditions and different grazing intensities. The frequent occurrence of SWR in the rainfall season requires in-depth study. Bond and Harris (1964) found that with the decrease of soil water content, the soil water repellency gradually increased, and finally reached the extreme value and when the soil water content reached a certain humidity, soil water loss ceased. King (1981) and Carrillo et al. (2000) described the relationship between soil water repellency and water content, and pointed out that the critical soil water content was 3.0–4.0 vol.% when the soil water repellency ceased. Dekker and Ritsema (1996) observed that the critical water content in the study of the Dutch sand, and the water repellency in some of the Dutch sand disappeared when the soil water content was less than 2 wt.%. This SWR finding related to the water content provides a basis for land use planning and agricultural farming. However, without the texture and organic matter content, the interpretation of this phenomenon requires in-depth studies.

SWR is induced by hydrophobic organic matter in the soil, mainly from plant and soil microbes. Studies have shown that some few organic matter with hydrophobic properties can lead to severe water repellency because only 0.35 g of water-repellent compounds can induce 1000 g of sand to produce a serious water repellency (Ma'shum et al., 1988). González-Peñaloza et al. (2012) found that agricultural practices (e.g., conventional tillage) reduced the organic matter content, and soils remained wetTable Subcritical water repellency (with water drop penetration times below 5 s) was observed in soils under no-agriculture practices (e.g. no-tillage treatments). However, Roper et al. (2013) indicated that water infiltration was best under no agriculture disturbance (no-tillage) and poorest under human influence (stubble cultivation) and further impacted crop productivity. SWR is different between different land-use types, although soil profiles and the height of the location in the field may differ. Possibly, the prohibition of grazing in grasslands is the effective approach, to some extent, to ameliorate SWR.

The SWR decreased with the increase of the particle size (Fig. 6), thereby supporting the results of Bachmann et al. (2000) and Ramírez-Flores et al. (2008). In addition, the soil particle sizes of 0–0.05 and 0.05–0.1 mm could significantly increase SWR. The increase in soil particle size in the two size sections of 0.1–0.2 and 0.2–2 mm did not increase SWR. The increase in SWR may be due to the combined effect of particle size-dependent wettability, capillary phenomenon, and organic matter content as soil particles were reduced (Li et al., 2009). Given that the coarse sandy loam has a smaller specific surface area, it is considered more prone to water repellency and has received extensive attention in the early stages (Emerson and Bond, 1963). However, further studies have shown that medium soil texture (20% –30% clay), or even clay, may also exhibit strong water repellency (Chan, 1992; Dekker and Ritsema, 1996). The high SWR was due to the presence of intermittent fine organic matter on the finest fraction, as found by other researchers (Bisdom et al., 1993)

5. Conclusion

Grassland soils under different land use types in Inner Mongolia showed low water repellency or no water repellency. The trend of water repellency of steppe soil in different seasons and years varied. Among the observed SWR in different months, this phenomenon was most evident in the rainy months with the highest evaporation. To some extent, different land use types, influenced the changes in SWR in various seasons with time lag. Generally, the continuous grazing soil was the first to show high water repellency in the rainy season, followed by winter grazing, ungrazed sites since 1999, and ungrazed sites since 1979. The high intensity of grazing reduced infiltration and hence increased the susceptibility to erosion at the grazing sites. Significant correlations existed between the SWR and the soil particle size class at 0–0.05 and 0.05–0.1 mm because the finest fraction may consist of fine organic matter. The water repellency of the soil samples with different particle sizes decreased as particle size increased. These results emphasized the need to consider SWR in soil utilization because grazing intensity affects the soil repellent properties in steppe soiland providing a basis for the development of grassland management.

Conflict of interest

The authors declare no competing financial interest.

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