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Spatio-temporal variations in soil hydrology of a typical semiarid sand-meadow-desert landscape

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Abstract

A good understanding of the interrelations between land cover alteration and changes in hydrologic conditions (e.g., soil moisture) as well as soil physicochemical properties (e.g., fine particles and nutrients) is crucial for maintaining the fragile hydrologic and environmental conditions of semiarid land, such as the Horqin Sandy Land in China, but is lacking in existing literature. The objectives of this study were to examine: (1) spatio-temporal variations of soil moisture and physicochemical properties in semiarid land; and (2) how those variations are influenced by land cover alteration. Using the data collected in a 9.71 km^2 well-instrumented area of the Horqin Sandy Land, this study examined by visual examination and statistical analyses the spatio-temporal variations of soil moisture and physicochemical properties. The results indicated that for the study area, the soil moisture and physicochemical properties were dependent on local topography, soil texture, vegetation density, and human activity. Long-term reclamation for agriculture was found to reduce soil moisture by over 23% and significantly (p-value < 0.05) lower the contents of soil organic matter, fine particles, and nutrients.

1 Introduction

Semiarid land, where precipitation is less than potential evapotranspiration (PET), such as the Horqin Sandy Land located between the Inner Mongolian Plateau and the Northeast China Plain (Fig. 1), usually has fragile hydrologic conditions that are very sensitive to land cover alteration from human activities (e.g., cultivation; Ma and Fu, 2005; Fu et al., 2006). The fragility is characterized by measurable spatial and/or temporal changes in soil hydrologic (e.g., soil moisture) and physicochemical (e.g., soil fine particles, organic matter, and nutrients) properties (Nicolson et al., 1998; Dai et al., 2004; Held et al., 2005; Fu and Ma, 2008). These changes usually result in land desertification and environmental degradation (Hennessy and Kies, 1986; Okin et al., 2001; Fu et al., 2006), which in turn is likely to reduce grassland agricultural productivity, reduce usable water resources, and intensify sandstorms in terms of both occurrence and magnitude (Kertész and Mika, 1999; Ma and Fu, 2007; Monger, 2010).

Given this fragility and its environmental consequences, extensive studies have been conducted in examining the causal effects of land cover alteration on losses of soil moisture, fine soil particles (i.e., silt and clay), and soil organic matter and nutrients (e.g., N, P, and K) (Giertz et al., 2005; She et al., 2010). Among those studies, Bhattacharyya et al. (2007) examined how to improve soil structure in the semiarid tropics of India by increasing soil organic carbon/matter, as measured by 23 selected soil physicochemical properties. They found that increasing the soil organic carbon increased the soil water holding capacity and improved overall soil environment health. On the other hand, Plaza et al. (2000) examined the temporal changes of soil moisture in a semiarid area in southeastern Spain at point and transect scales, and concluded that long-term average soil moisture had decreased for locations with noticeable land cover disturbance. Further, Pugnaire et al. (2004) found that increasing soil moisture and fertility can in turn facilitate build-up of soil organic matter. A continuous 5-year experiment in the semiarid Loess Plateau of China (Guo et al., 2010) indicated that the soil physicochemical properties were noticeably improved after cropland was converted back to grassland.

Zuo et al. (2008) conjunctively used statistical and geostatistical methods to identify spatial variations in soil properties across an area of the Horqin Sandy Land that has sand dunes grazed for 5 years and sand dunes recovered 20 years ago. Their results showed that the spatial variations in the soil physicochemical properties (e.g., total P) were more uniform in the areas of grazed dunes, but that the variations of soil moisture were more diverse in the areas of recovered sand dunes. Also, they found that the spatial distributions of the soil properties were strongly related to grazing intensity, topographic relief, and plant-induced heterogeneity of the sand dune ecosystems. In a different area of the Horqin Sandy Land that has a land cover of recovered dune, Hao et al. (2009) found that soil moisture, organic matter content, and cation exchange capacity decreased in the sequence order of rice field, upland field, forest, grassland, bush, and sandy land. In a larger area of the the Horqin Sandy Land that has the special physiography of marshland dunes, Shi et al. (2007) found that soil moisture in 10 cm or deeper soil layers was higher for the mobile dune than for the semi-fixed dune, which in turn was higher than for the fixed dune, but that the moisture within the top 10 cm was reversed. This is because the thicker dry sand layer of the mobile dune tended to limit soil water evaporation and because the vegetation on the semi-fixed and fixed dunes increased soil water loss to transpiration. These findings are consistent with those of Lei (1998).

The aforementioned studies revealed the research need to further examine interrelations between land cover alteration and changes in hydrologic conditions (in particular, soil moisture) as well as soil physicochemical properties (e.g., fine particles and nutrients) at long temporal and large spatial scales. A good understanding of such interrelations is crucial for maintaining the fragile hydrologic and environmental conditions of semiarid land, such as the Horqin Sandy Land in China and other similar areas all over the world. The objectives of this study were to examine: (1) spatio-temporal variations of soil moisture and physicochemical properties in semiarid land; and (2) how those variations are influenced by land cover alteration. The study was conducted in a selected area of the Horqin Sandy Land that is typical in terms of hydrologic condition, topography, soil, and land cover.

2 Materials and methods

2.1 Study area

A 9.71 km^2 area (122°36.15′ to 122°38.23′ E, 43°19.25′ to 43°21.10′ N) within the 51 700 km^2 Horqin Sandy Land (118°35′ to 123°30′ E, 42°41′ to 45°15′ N) (Fig. 1) was selected for this study because this area is a typical semiarid agro-pastoral transitional zone with diverse landscape features of sand dunes (54.5%), meadow (26.6%), agriculture (10.4%), lake (5.2%), and residential areas (3.3%). Based on Ma (2008), this area has a temperate and semiarid continental monsoonal climate, with an average annual precipitation of 389 mm, of which 69.3% falls during the growing season (i.e., from June to August), and an average annual PET of about 1412 mm. The average annual temperature is around 6.6 °C, with a minimum monthly mean temperature of −13.3 °C in January and a maximum temperature of 23.8 °C in July. The average annual wind speed is 3.8 $\mathrm{m\,s^{-1}}$, with a minimum monthly mean wind speed of 3.0 $\mathrm{m\,s^{-1}}$ in August and a maximum of 5.0 $\mathrm{m\,s^{-1}}$ in April. The prevalent wind direction in winter and spring is northwest, whereas in summer and autumn it is southwest.

The combination of the dry-windy climate and the vulnerable sandy soils favors wind erosion, likely resulting in the quick spread of desertification in this region (Wang, 2002) and large-scale dust storms (Wang et al., 2006; Bagan et al., 2010).The study area, which has a topographic elevation varying from 186 to 200 m above mean sea level and is mingled with rolling sandy dunes and desert as well as flat interdune (i.e., meadow) lowlands, agricultural land, and lakes, has an average dust storm outbreak frequency of 1.92 days per year. The sandy dunes are either bare or covered by sparse native plants, namely *Artimisia halodendron*, *Caragana microphylla*, *Salix gordejevii*, and/or *populus*, whereas the lowlands are mainly covered with *Leymus chinensis*, *Phragmites australis*, and/or *Ixeris chinensis*.

The Horqin Sandy Land, located between the Inner Mongolian Plateau and the Northeast China Plain (Fig. 1), is one of the four main sandy lands in northern China (Wu and Ci, 2001) and an important part of the Inner Mongolia's grassland resources (Liu et al., 1996). However, the Horqin Sandy Land has undergone severe desertification in recent decades (He et al., 2008; Wang et al., 2008); the desertified land has reached 57.8% of the Land's total area (Zhao et al., 2004), primarily because inappropriate reclamation for agriculture (e.g., chisel plough tillage in fall) and overgrazing (Zuo et al., 2008) adversely altered the natural hydrologic conditions. As a result, most of the sandy grasslands have evolved into mobile, semi-mobile and/or semi-fixed dunes with severe, moderate or light desertification (Zhu and Chen, 1994; Guan et al., 2000). The increased frequency and intensity of dust storms (i.e., sandstorms) resulting from the desertification have resulted in serious environmental concerns not only for the adjacent rural areas but also for the major metropolis in China, including the country's capital city of Beijing, as well as in neighboring countries such as Japan and Korea (Takemi et al., 2005). Similar concerns also exist in other regions in the world (Rooyen, 1998; Dey et al., 2004; Portnov and Safrielb, 2004). Thus, this study area can somewhat represent these systems.

2.2 Instrumentation and data collection

The study area was instrumented in 2003 to continuously collect data on meteorology, soil hydrology, and soil physicochemistry. The instrumentation, maintained through the Agula Ecohydrological Experiment Station of the Inner Mongolia Agricultural University, includes 18 co-located hydrologic and meteorological sites (HMSs) and 55 soil physicochemical sites (SPCSs). The SPCSs were located at intersections of the meridians 13 s apart and the parallels 12 s apart, and are named using combinations of letters (GB, GD, GF, GH, GJ, GL, GN, GP, and GR) and numbers (3, 6, 9, 12, 15, 18, and 21) (Fig. 1). Data collection at the SPCSs started on October 2003. Soils at 10, 20 and 30 cm vertical depths were extracted for tests of 14 soil parameters (Table 1). The HMSs were selected to monitor all combinations of the soils and land covers within the study area, and are named using combinations of the six letters from A to F with three numbers of 1, 2, and 3 (Fig. 1 and Table 2). The HMSs are fenced by wire netting to prevent any unexpected interference from livestock and are accessible through narrow observation brick roads to minimize disturbance to the natural conditions.

Manual data collection at the HMSs started in June 2006. Rainfall and snowfall were observed at the first two HMSs, listed and designated KTS in Table 2, using Siphon rain gauge (Vasvári, 2005) and weighing method (Liu et al., 2002), respectively, on a daily basis (Table 1). The first 12 HMS, designated KTS and GKT in Table 2, were instrumented to measure on a daily basis at sunrise, 08:00 a.m., 02:00 p.m., sunset, and 08:00 p.m., soil temperature and evaporation at belowground depths of 10, 20, and 30 cm. For a day when the sunset time was around 08:00 p.m., measurements were made at 08:00 p.m. and assumed to be identical to those at the sunset. Soil evaporation was measured using a set of PVC microlysimeters (MLs) with an inner diameter of 87 mm and a wall thickness of 5 mm. In order to minimize any disturbance to soil around the MLs, each ML was confined within a cylinder made of the same material as the ML but with a larger inner diameter of about 110 mm. The bottom of each ML was covered with gauze, through which the ML was hydraulically connected with the soil underneath it. Soil within the MLs was usually replaced every 3 to 5 days or as soon as possible after a heavy rain. By weighing the ML using a digital balance with an accuracy of 0.1 g, soil evaporation was determined based on a calibrated empirical relation that one gram reduction of the ML corresponds to 0.17 mm soil evaporation. Groundwater level was measured every 5 days at the KTS and GKTS sites.

In June 2007, the KTS sites (i.e., site A3 and C3 in Table 2) were further equipped with automated sensors (Table 3) for soil temperature and rainfall. The acquisition time interval for these sensors was set to 30 min. In addition, at the beginning of 2008, each of the KTS and GKTS sites was equipped with a neutron probe pipe, co-located with soil temperature sensors at 10, 20 and 30 cm depths. The neutron probe pipes were set to have a measurement frequency of once every 5 days.

All measured parameter values were prescreened on a daily basis by an experienced field technician for quality control. Data collected during periods when an instrument malfunctioned or was interfered by livestock were flagged as missing. The other data were checked in accordance with reasonable ranges of the parameters.

2.3 Analysis method

The number of years for which the parameters were measured varies from site to site (Table 1) and the measurement frequency at a given site is not consistent for all parameters. Thus, the raw data were first collapsed into a more manageable form. For a given day, the observed snowfall depth was multiplied by a prevalent conversion factor of 0.1 (Chang et al., 1982) to convert the snowfall into its equivalent water depth. The equivalent water depth was added to the observed rainfall on the same day to determine the daily precipitation. For each of the hydrometeorologic parameters with two or more measurements per soil depth per day (Table 1), including soil evaporation and soil temperature, its measurements at a given depth within a given day were used to compute a median. The median was assumed to be the daily value of the parameter at that soil depth on that day. For each of the parameters with just one measurement per soil depth per day, the measurement was assumed to be the daily value of the parameter at that depth. Subsequently, for each of the parameters (except for rainfall, snowfall, and groundwater level) presented in Table 1, its site value for a given day was computed as the geometric mean of the daily values on that day at different depths (Abramowitz and Stegun, 1972). The geometric mean was used because it indicates the central tendency or typical value of the parameter within the vertical soil profile, eliminating the dominance of a few large values (Coleman, 2008).

The site monthly mean values for the parameters were determined as follows: for a given month in an observation year, the daily precipitation was accumulated to determine the total precipitation for that month. Total precipitation for the same months was arithmetically averaged to compute the corresponding average monthly precipitation. For soil evaporation and soil temperature, the daily values within a given month were arithmetically averaged across the measurement years to compute the mean value of this parameter for that month. For soil moisture or groundwater level, daily values within a given month across the two measurement years (i.e., 2008 and 2009) were used to compute a median. This computed median was assumed as the soil moisture or groundwater level for that month. Further, the monthly values for each of these parameters were arithmetically averaged to compute the annual average for each measurement year. For the parameters that were measured one time only (Table 1), the measured values were assumed to be invariant because these parameters usually do not change measurably within short time periods (e.g., 3 years) unless dramatic management activities (e.g., conversion of land cover) had taken place (Awotoye et al., 2009).

For each parameter and measurement site, the preprocessing of the measured data resulted in two time-series datasets. The first dataset consisted of the annual monthly mean values, while the second dataset included the annual average values. These datasets were plotted to visually examine the spatial patterns as influenced by different land cover as well as the temporal trends for a given land cover. The daily patterns and trends were not examined because as discussed above, the parameters of soil moisture, soil evaporation and precipitation had distinctly different measurement frequencies, making it infeasible to make any comparison at a daily time step. A paired t-test (two-sample for means) was performed to identify whether the values of a parameter for one land cover were significantly different from the corresponding values of the same parameter for another land cover at a significance level of 0.05. The null hypothesis was that the differences between the means for the two land covers would be zero.

Further, the 55 SPCS sites, where the physicochemical parameters were measured, were classified into 5 groups based on land cover: semi-fixed dune (SFD, vegetation density 20 to 40%); fixed dune (FD, vegetation density $>40\%$); cultivated land (CL, primarily covered by maize); general meadow (GM, vegetation density $<50\%$); and control meadow (CM, vegetation density $>50\%$, with no detectable erosion and sand accumulation). The measured values were used to compute the Pearson correlation coefficients among the parameters. Multiple comparisons and analyses of variance (ANOVA) were implemented to test whether the within-group means of a given parameter were different at a significance level of $\alpha = 0.05$ (Zhao et al., 2006). In addition, for each group and for each of the physicochemical parameters presented in Table 1, the measured values were arithmetically averaged to compute the group mean of this parameter and were used to compute the within-group standard deviation of the same parameter. Subsequently, the group means along with the within-group standard deviations were plotted to examine the interrelations between the land covers and the soil physicochemical parameters.

3 Results and discussion

3.1 Soil moisture spatial patterns and temporal trends

The annual average soil moisture at a location within the study area was dependent on the local topography as well as soil texture (Fig. 2), which is consistent with Zuo et al. (2008). The moisture of the high-altitude (186.2 to 200.3 m) peripheral sandy areas was almost 10% lower than that of the medium-altitude (185.8 to 190.7 m) transitional zones, which in turn was about 18% lower than that of the low-altitude (188.6 to 189.5 m) interdune lowlands. This is because the high sand content (94.2 to 99.8%) and low silt-clay content (0.2 to 5.8%) in the sandy dunes lead to a greater hydraulic conductivity, facilitating the loss of soil water either to the atmosphere or aquifer underneath. In contrast, the decreased sand content (58.3 to 81.2%) and increased silt-clay content (18.8 to 41.7%) in the meadow lands (Fig. 2a) can retard such loss. In addition, depth to groundwater was also smallest in the lowlands and highest for the sandy areas (Fig. 4).

In addition, soil moisture was also influenced by vegetation density: locations with denser vegetation cover tended to have higher soil moisture. For example, although the soil texture at site C3 was similar to that at site D1 (Fig. 2a) and both sites had the same type of vegetation (i.e., *Leymus chinensis*), site C3 had a much denser vegetation coverage (Table 2) and thus a higher soil moisture (Fig. 2a). This is because vegetation roots can improve soil structure, increasing the soil water retention capacity of soils (Marshall and Holmes, 1988). Similarly, because of the denser vegetation coverage at site E3(U), soil moisture at this site was higher than that at E2(U). However, human activities could alter such relation between soil moisture and vegetation density (Campbell et al., 1994; Han et al., 2010). Site C2(M) used to have a vegetation cover identical to site C2(G), but site C2(M) incurred long-term reclamation for agriculture and the soil moisture at this site was at least 23% lower than that at site C2(G).

For the sandy dunes, soil moisture at 10 to 30 cm beneath the ground level of the mobile dunes was higher than that for the semi-fixed dunes, which in turn was higher than that for the fixed dunes (Table 1, Fig. 2). This is because the thickness of dry sand layer of the mobile dunes was greater than that of the semifixed dunes, which in turn was greater than that of the fixed dunes (Feng, 1994; Lv et al., 2006). Previous studies (e.g., Yamanaka et al., 1998; Yamanaka and Yonetanib, 1999; Mutziger et al., 2005; Romano and Giudici, 2009) indicated that the thickness and soil texture of the dry sand layer controls soil moisture dynamics because the dry sand layer can restrict evaporation and because it increases the distance of vapor diffusion. Liu et al. (2006) found that the presence of the 5 cm top dry layer in the Horqin Sandy Land reduced evaporation by about 70% relative to that under conditions without a dry sand layer, and that the reduction rate reached up to 92% for locations with a 30 cm or thicker dry layer. Although these findings were not verified in this study because the ET measurements were not designed for this purpose, these results are cited to explain the aforementioned soil moisture spatial patterns as influenced by land cover.

At a monthly time step, the soil moisture spatial pattern discussed above exhibited temporal variations for the study sites except for site A3, C2(G), C3, and E3(U). This is mainly caused by the seasonally varied precipitation and evapotranspiration (Fig. 3). From January to March, soil moisture at all sites except for site C2(G) and C3 exhibited a continuously increasing trend. This is because below the thawing front of the completely frozen soil layer (with a frozen depth of deeper than 1.0 m and a mean surface temperature of -4.7 to $-6.7\,^{\circ}$C), the thermal gradient tended to increase with the warmer temperature, driving up more liquid water and vapor from the unfrozen layer underneath (Shinoda et al., 2001). A field test conducted in October 2003 indicated that the volume of capillary water in sandy dunes and meadow lands accounted for up to 34 and 46% of the corresponding soil moisture, respectively. The marginal decrease of soil moisture at site C2(G) and C3 (Fig. 3) can be attributed to the development of roots of *Leymus chinensis* tending to break the capillary rise and/or that the depth to water table at site C3 was deep (>1.0 m; Fig. 4).

In April and May, soil moisture of the sandy dunes and at site B2 and E1 exhibited an increasing trend (Fig. 3). This is because the melting snow and sporadic rainfall started to fill the soil voids. Another explanation is that although the sandy lands had a higher

PET due to high wind speed, the aforementioned retarding effects of the dry sand layer made the actual ET much smaller. In contrast, soil moisture at the meadow sites (except for site D1) and at the transitional zones site E2(U), exhibited a decreasing trend (Fig. 3). This is mainly because soil water in the top layer was redistributed and drained downward into the lower soil horizons as a result of the disappearance of the thermal gradient. Another reason is that the increased ET resulting from warmer temperatures and vegetation emergence started to deplete soil moisture. The ET increase at site D1 was limited due to the sparse vegetation coverage (Table 1) and thus soil moisture at this site exhibited a synchronic trend with the rainfall.

In June and July, the soil moisture of the sandy dunes and of the transitional zones site B2 and E1 exhibited a marginally increasing trend along with the rainfall. Again, although the potential ET in July was maximal, the retarding effects of the dry sand layer made the actual ET lower than the rainfall. The soil moisture of the meadow lands exhibited a marginally increasing trend as a result of the rainfall, whereas the soil moisture at site E2(U) and E3(U) exhibited an opposite trend because the hydrophilous vegetations (i.e., *Phragmites australis*) consumed much soil water (Alamusa and Jiang, 2009).

From August to October, soil moisture of the meadow lands and the transitional zones sites (except for site E1) exhibited a decreasing trend. This is mainly because of the sharply reduced rainfall and because the dense vegetation of the meadow lands was at the reproductive phase resulting in high transpiration rates. The soil moisture of the fixed dunes exhibited an increasing trend because of the water retention effects of the dense vegetation, whereas the soil moisture of the mobile dunes and semi-fixed dunes exhibited delayed responses to the rainfall. From November to late December, the soils started to freeze and vegetation growth stopped. As a result, the decreased ET and the increased thermal gradient discussed above tended to increase the soil moisture of the meadow lands. In contrast, the soil moisture of the sandy dunes either was stable or decreased slightly because of the limited capillary rise resulting from the large depths to the water table (Table 2 and Fig. 4).

3.2 Soil physicochemical properties variations

The silt-clay (particles < 0.05 mm) content for meadows (GM and CM sites) was up to 38% higher than that for dunes (SFD and FD sites) (Fig. 5). This is because fine particles were transported away from the areas currently covered by dunes (López, 1998). The loss of fine particles in turn resulted in a bulk density for dunes smaller than that for meadows. However, the compaction impacts from cultivation and grazing noticeably increased the bulk densities at the CL and GM sites. The values of other soil physicochemical properties, including organic matter, nutrients, and salinity, were greater for meadows than for dunes (Figs. 6–8). Compared with those at the CM sites, the soil organic matter at the SFD sites was 38 g kg^{-1} smaller (Fig. 6), the N and P contents were 85 to 95% lower (Figs. 7 and 8), and the K content was up to 12% lower (Figs. 7 and 8). An ANOVA test indicated insignificant differences for bulk density, K, pH, and electrical conductivity, but revealed significant differences for the other physicochemical properties, among dunes, cultivated lands, grazing meadows, and control meadows, at a family significance level of 0.05. These differences can be attributed to significantly different silt-clay and soil organic matter contents of these land covers. Soil water holding capacity will markedly decrease once silt-clay and organic matter are lost (López, 1998; Su and Zhao, 2003). Wezel et al. (2000) pointed out that in semiarid ecosystem soil organic matter is one of the most important factors that control soil nutrients.

For the study area, significant positive correlations ($R^2 > 0.7$) were found at a significance level of $\alpha = 0.05$ among soil silt-clay content, soil organic matter, total N, total P, available N, available P, and soil moisture characteristics (e.g., field capacity) (Table 4). This indicates that the decrease of silt-clay content will likely cause the decrease of soil organic matter, nutrients, and water holding capacity (López, 1998; Su and Zhao, 2003; Li et al., 2004), and that soil organic matter is key to maintaining soil nutrient and moisture levels (Larney et al., 1998; Zhao et al., 2006). Thus, the silt-clay content can be a surrogate of soil texture or particle size distribution. However, insignificant correlations were found between any of these soil properties and total K, available K, pH, bulk density, and EC, though the latter five physicochemical properties exhibited variations from site to site (Figs. 5–8).

The sand (particles > 0.05 mm) content in the study area was found to be very high: 60.3% by weight at the CM sites and significantly higher than this at other sites (Fig. 5). This was partially caused by persistent wind erosion as a result of inappropriate reclamation (e.g., fall tillage) and overgrazing (Su et al., 2002; Gomes et al., 2003). As expected, because of the positive correlations discussed above, a location with a reduced silt-clay content was found to have lower soil organic matter (Fig. 5 versus Fig. 6), nutrients (Fig. 5 versus Figs. 6 and 7), and moisture characteristics (Fig. 5 versus Fig. 9). The soil organic and moisture contents at the SFD, FD, CL, and GM sites were significantly lower than those at the CM sites at a significance level of $\alpha = 0.05$. Compared to those at the CM sites, the contents of N, P, and saturated and capillary moisture at the other sites were found to be significantly lower by over 40, 33, 10, and 10%, respectively. This implies that for the study area, overgrazing will cause degradation of meadows and that converting meadows to agricultural land is likely to facilitate this degradation process. The continuation of this process would result in the formation of sand dunes, which will ruin the hydrologic and environmental conditions for sustainable development of grassland agriculture.

4 Conclusions

Maintaining the fragile hydrologic conditions of semiarid land such as the Horqin Sandy Land is crucial for preventing desertification and environmental degradation. Using the data collected in a 9.71 km^2 well-instrumented area of the Horqin Sandy Land, this study examined by visualization plots and/or statistical analyses the spatio-temporal variations of soil moisture and physicochemical properties as well as the interrelations between those variations and the land cover alterations. The results indicated that annual average soil moisture at a location within the study area was dependent on the local topography, soil texture, vegetation density, and human activity. Soil moisture of the mobile dunes at 10 cm and deeper was higher than that of the semi-fixed dunes, which in turn was higher than that of the fixed dunes (Table 2 and Fig. 2). At monthly time scales, the soil moisture spatial pattern exhibited temporal variations mainly due to the seasonally varied precipitation and evapotranspiration as well as the freezing-thawing effects. In addition, significant positive correlations ($R^2 > 0.7$) were found at a significance level of $\alpha = 0.05$ among the soil silt-clay content, soil organic matter, nutrients, and soil moisture characteristics. The levels of these soil physicochemical properties were significantly lower for the semi-fixed dunes, fixed dunes, and cultivated lands than for the meadow lands where there was no detectable erosion and sand accumulation. Further, within the study area, a location that incurred long-term reclamation for agriculture and/or other land disturbances tended to have worse soil hydrology conditions and physicochemical properties.

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Table 1. The manually measured parameters.[1]

Parameter	Definition	Measurement Method[2]	Measurement Year
R (mm)	Rainfall	Siphon gauge	2006 to 2009
SF (mm)	Snowfall	Weighing gauge	2006 to 2009
GWL (m)	Water table	Transducer	2008 to 2009
E_{soil} (mm)	Soil evaporation	Microlysimeter (±0.017)	2006 to 2009
T_{soil} (°C)	Soil temperature	LVDWZ-31sensor (±0.1)	2008 to 2009
		Thermometer (±0.1)	2007 to 2009
SMC (%)	Soil moisture	Neutron probe	2008 to 2009
SPS (%)	Soil particle size	Screening and hydrometer	2003
ρ_b (g cm^{-3})	Soil bulk density	Oven-dry	
SOM (g kg^{-1})	Soil organic matter	Potassium dichromate capacity titriation	
EC (µs cm^{-1})	Electrical conductivity	Conductivity meter	
pH	pH	pH meter	
TN (g kg^{-1})	Total nitrogen	Semi-micro Kjeldahl	
TP (g kg^{-1})	Total phosphor	Molybdenum blue	
TK (g kg^{-1})	Total potassium	Flame photometry	
AN (mg kg^{-1})	Available nitrogen	Alkaline diffusion	
AP (mg kg^{-1})	Available phosphor	Bray extraction	
AK (mg kg^{-1})	Available potassium	Flame photometry	
θ_s (%)	Saturated water content	Oven-dry	
θ_f (%)	Field capacity	Oven-dry	
θ_c (%)	Capillary water content	Oven-dry	

[1] R and SF were measured at 1 m above the ground surface on a daily basis, T_{soil} was measured at 10, 20, and 30 cm depths using LVDWZ-31sensor (Table 3), but measured at 5, 10, 15, and 20 cm depths using the thermometer method. The other soil parameters were measured at 10, 20, and 30 cm depths. E_{soil} and T_{soil} were measured 4 or 5 times per day, while SMC was measured once every 5 days. The remaining soil parameters were measured just once in October 2003.

[2] Designed based on Scherer et al. (2003); Amin and Flowers (2004); Tiyapongpattana et al. (2004); Jankauskas et al. (2006); and Zhao et al. (2006). The method accuracy noted in the parenthesis was determined based on manufacturers' specifications, field calibration, and/or literature values (e.g., Zhao et al., 2006; Wang et al., 2007).

Table 2. Characteristics of the manual hydrologic and meteorological sites.

Site	Group	Land Cover	Soil Texture	Elevation (m)	Dominant Vegetation Type	Vegetation Density (%)
A3	KTS	Mobile dune	Sand	199.8	*Artimisia halodendron*	< 20
C3		Meadow	Sandy loam	188.2	*Leymus chinensis*	> 50
A1	GKTS	Fixed dune	Sand	194.2	*Populus*	> 40
B2		Fixed dune	Sand	190.8	*Artimisia halodendron*	> 40
C2(G)		Meadow	Loamy sand	188.6	*Leymus chinensis*	20 to 50
C2(M)		Meadow	Loamy sand	189.0	*Zea Mays* L.	> 50
D1		Meadow	Sandy loam	188.5	*Leymus chinensis*	5 to 20
E1		Fixed dune	Sand	190.7	*Artimisia halodendron*	> 40
E2(U)		Meadow	Sandy loam	189.2	*Leymus Chinensis, Phragmites australis, Ixeris chinensis*	20 to 50
E3(U)		Meadow	Sandy loam	188.3	*Leymus Chinensis, Phragmites australis, Ixeris chinensis*	> 50
F1		Fixed dune	Sand	196.7	*Caragana microphylla*	> 40
F3		Semifixed dune	Sand	198.2	*Salix gordejevii*	20 to 40
B1	GTS	Fixed dune	Sand	190.1	*Artimisia halodendron*	> 40
B3		Fixed dune	Sand	191.9	*Artimisia halodendron*	> 40
D2		Meadow	Sandy loam	189.0	*Leymus chinensis*	> 50
E2(C)		Meadow	Sandy loam	189.1	*Leymus Chinensis, Phragmites australis, Ixeris chinensis*	20 to 50
E3(C)		Meadow	Sandy loam	188.2	*Leymus Chinensis, Phragmites australis, Ixeris chinensis*	> 50
F2		Semifixed dune	Sand	196.6	*Artimisia halodendron*	20 to 40

Table 3. Characteristics of the automated sensors.

Model	Manufacture	Parameter[1]	Accuracy[2]	Installation Site[3]
L3	Yangguang Co. Ltd. (http://jz322.shuoyi.com)	R (mm)	(±0.1)	KTS
DSJ-2	Huayan Co. Ltd. (http://www.chem17.com)	R (mm)	(±0.1)	KTS
TRM-ZF1	Yangguang Co. Ltd. (http://jz322.shuoyi.com)	SF (mm)	(±0.17)	KTS
PC-2X	Yangguang Co. Ltd. (http://jz322.shuoyi.com)	GWL (m)	(±0.01)	HMSs
LVDWZ-31	Xinlvyuan Co. Ltd. (http://www.caigou.com.cn)	T_{soil} (°C)	(±0.1)	KTS, GKTS
RM-003	Ruiming Com. (http://www.czruiming.com)	T_{soil} (°C)	(±0.1)	KTS, GKTS
CNC503-B	Qudao Co. Ltd. (http://www.chem17.com)	SMC (%)	(±0.4)	KTS, GKTS
TDScan40	EUTECH (http://www.eutechinst.com)	EC (µs cm^{-1})	(±0.01)	SPCSs
TS-2	Bangli Co. Ltd. (http://www.qilee.cn)	pH	(±0.05)	SPCSs

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[1] The symbols are defined in Table 1.

[2] The accuracy noted in the parenthesis was determined based on the manufacturer's specifications, field calibration, and/or literature values (e.g., Wang et al., 2007).

[3] See Table 2 and Fig. 1.

Table 4. Pearson correlations among the soil physicochemical properties.[1]

	TN	AN	TP	AP	TK	AK	pH	SOM	EC	ρ_b	θ_c	θ_s	θ_f	SD
AN	0.99*													
TP	0.87*	0.87*												
AP	0.86*	0.86*	0.99*											
TK	0.24*	0.24*	0.27*	0.26*										
AK	0.24*	0.24*	0.26*	0.25*	0.98*									
pH	0.61*	0.61*	0.67*	0.65*	0.25*	0.25*								
SOM	0.89*	0.89*	0.82*	0.81*	0.21	0.19	0.59*							
EC	0.55*	0.55*	0.60*	0.57*	0.17	0.16	0.76*	0.47*						
ρ_b	0.18	0.19	0.20	0.20	0.17	0.16	0.39*	0.20*	0.24*					
θ_c	0.81*	0.81*	0.69*	0.66*	0.30*	0.29*	0.54*	0.85*	0.39*	0.21*				
θ_s	0.81*	0.81*	0.69*	0.66*	0.28*	0.27*	0.53*	0.85*	0.38*	0.18	0.99*			
θ_f	0.80*	0.80*	0.71*	0.68*	0.35*	0.34*	0.56*	0.82*	0.39*	0.20*	0.95*	0.96*		
SD	−0.87*	−0.86*	−0.83*	−0.81*	−0.29*	−0.26*	−0.70*	−0.88*	−0.52*	−0.36*	−0.85*	−0.84*	−0.86*	
SC	0.87*	0.86*	0.83*	0.81*	0.29*	0.26*	0.70*	0.88*	0.52*	0.36*	0.85*	0.84*	0.86*	−1.00*

[1] TN: total N; AN: available N; TP: total P; AP: available P; TK: total K; AK: available K; SOM: soil organic matter; EC: electrical conductivity; ρ_b : bulk density; θ_c : capillary rise water; θ_s: saturated water content; θ_f : field capacity; SD: sand content; SC: silt-clay content.

* Significant at a significance level of $\alpha = 0.05$.

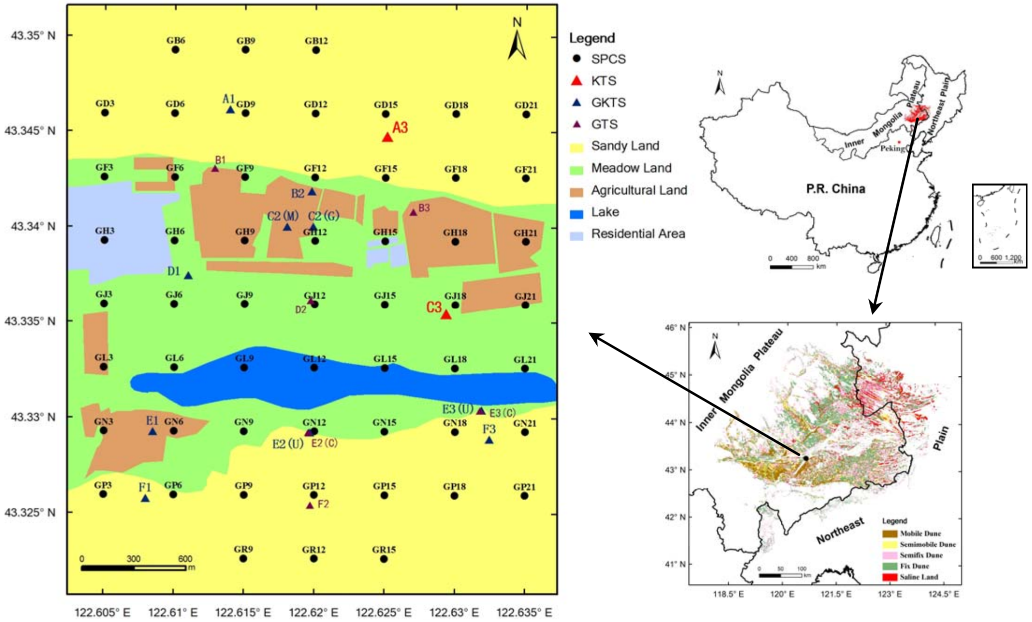

Fig. 1. Map showing the location and landscape features of the study area, soil physicochemical sites (SPCS) and hydrologic and meteorological stations (KTS, GKTS, and GTS).

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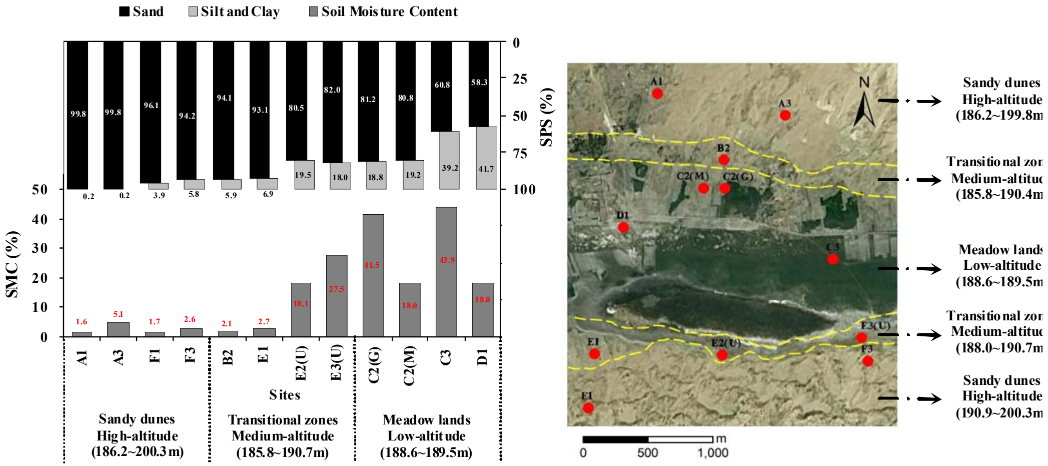

(a) (b)

Fig. 2. **(a)** The mean annual soil moisture (SMC) and soil particle size (SPS) at experiment sites (Table 2), and **(b)** a topography, of the study area.

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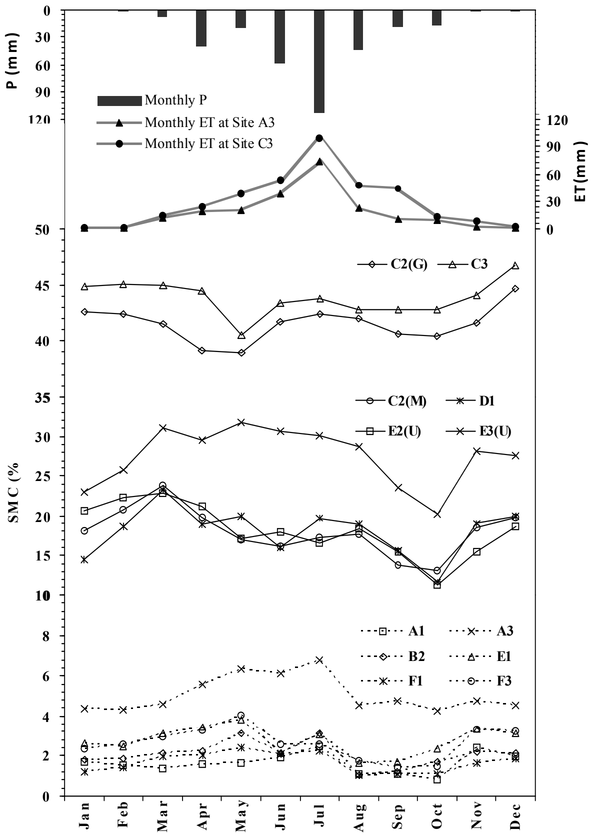

Fig. 3. Monthly soil moisture (SMC) at the experiment sites (Table 2) and monthly areal precipitation (P) and evapotranspiration (ET) at site C3 and A3. Site A1, A3, F1 and F3 are located in the sandy dunes (high altitude, 186.2 to 200.3 m); site B2, E1, E2(U) and E3(U) are located in the transitional zones (medium altitude, 185.8 to 190.7 m); and site C2(G), C2(M), C3 and D1 are located in the meadows lands (low altitude, 188.6 to 189.5 m).

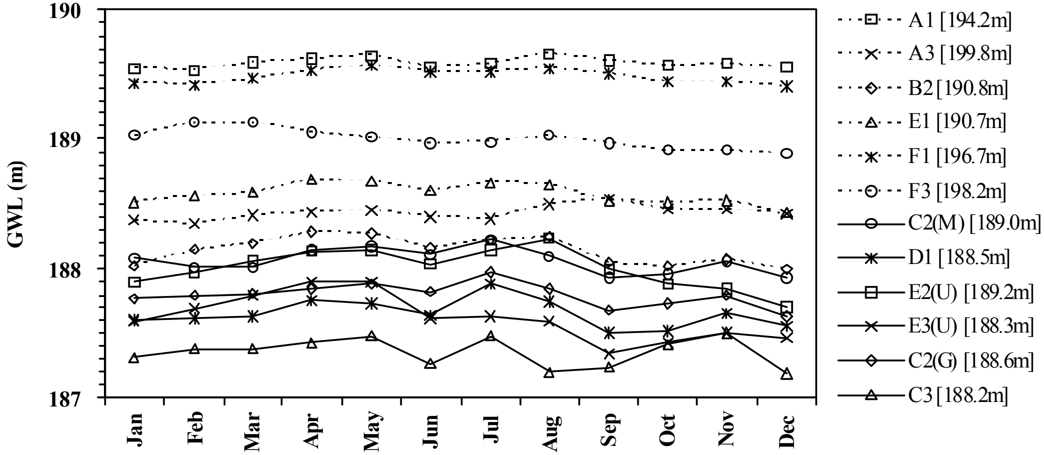

Fig. 4. Monthly water table (GWL) at the measurement sites (Table 2). Site A1, A3, F1 and F3 are located in the sandy dunes (high altitude, 186.2 to 200.3 m); site B2, E1, E2(U) and E3(U) are located in the transitional zones (medium altitude, 185.8 to 190.7 m); and site C2(G), C2(M), C3 and D1 are located in the meadows lands (low altitude, 188.6 to 189.5 m). The depth to water table at a site is computed as the ground surface level presented in the bracket next to the site name minus the GWL.

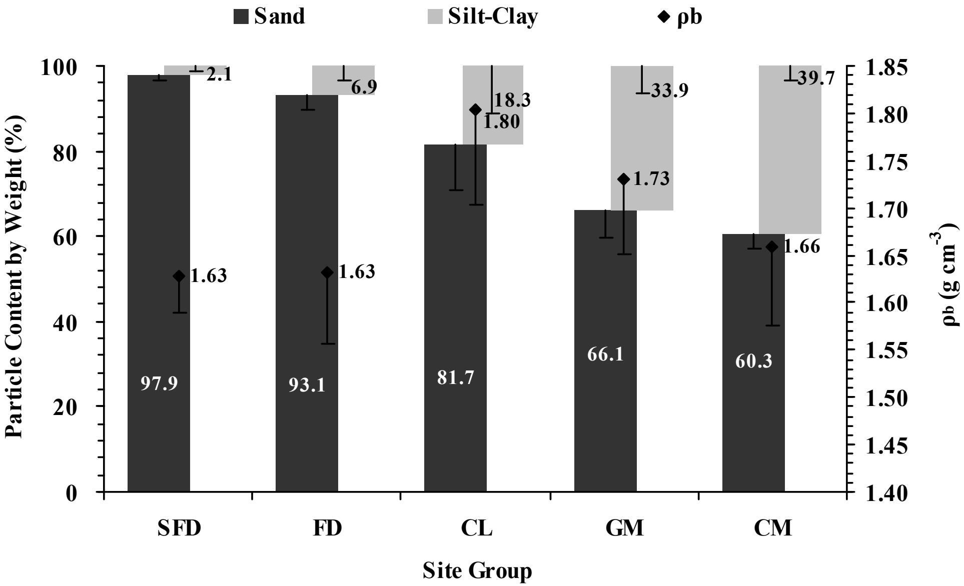

Fig. 5. The sand and silt-clay contents and bulk density (ρ_b) of the study area. Values are means ± standard deviations. SFD stands for semi-fixed dune sites, FD for fixed dune sites, CL for cultivated land sites, GM for general meadow sites, and CM for control meadow sites where there was no detectable erosion and sand accumulation.

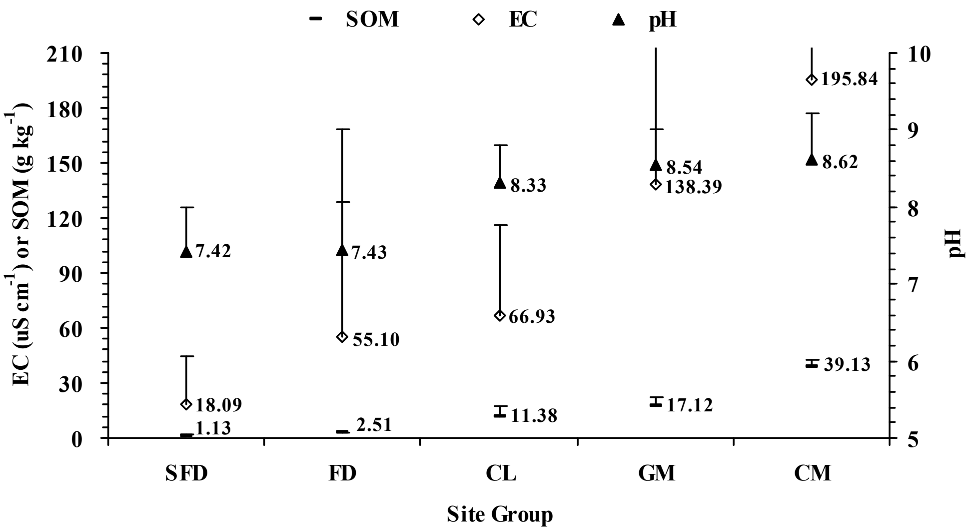

Fig. 6. The soil organic matter (SOM), electrical conductivity (EC), and pH of the study area. Values are means ± standard deviations. SFD stands for semi-fixed dune sites, FD for fixed dune sites, CL for cultivated land sites, GM for general meadow sites, and CM for control meadow sites where there was no detectable erosion and sand accumulation.

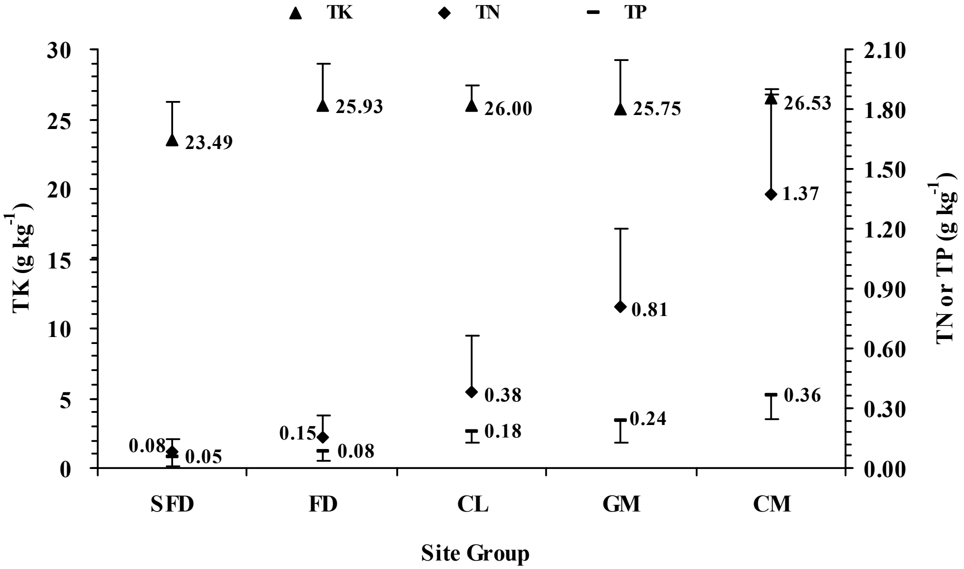

Fig. 7. The soil total N (TN), total P (TP), and total K (TK) of the study area. Values are means ± standard deviations. SFD stands for semi-fixed dune sites, FD for fixed dune sites, CL for cultivated land sites, GM for general meadow sites, and CM for control meadow sites where there was no detectable erosion and sand accumulation.

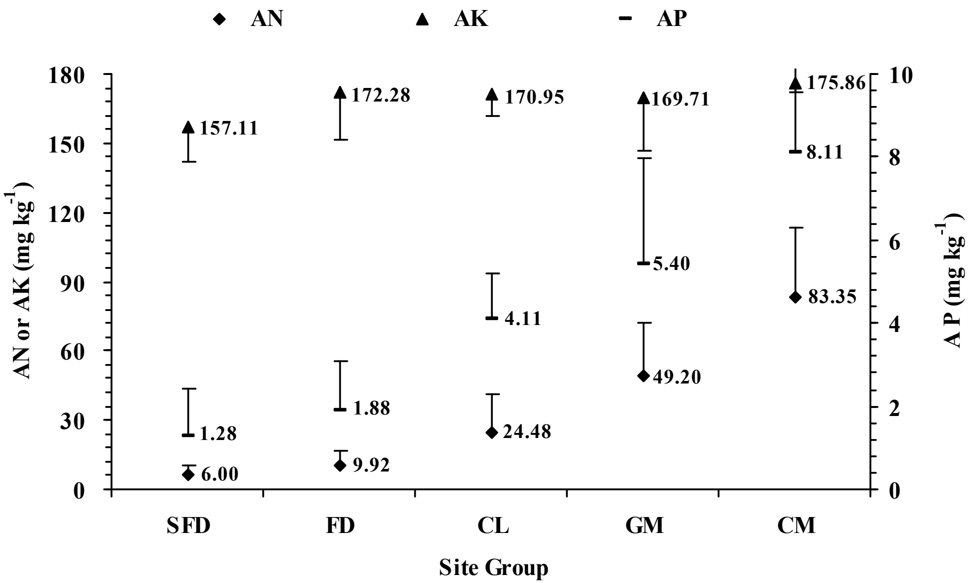

Fig. 8. The soil available N (AN), available P (AP), and available K (AK) of the study area. Values are means ± standard deviations. SFD stands for semi-fixed dune sites, FD for fixed dune sites, CL for cultivated land sites, GM for general meadow sites, and CM for control meadow sites where there was no detectable erosion and sand accumulation.

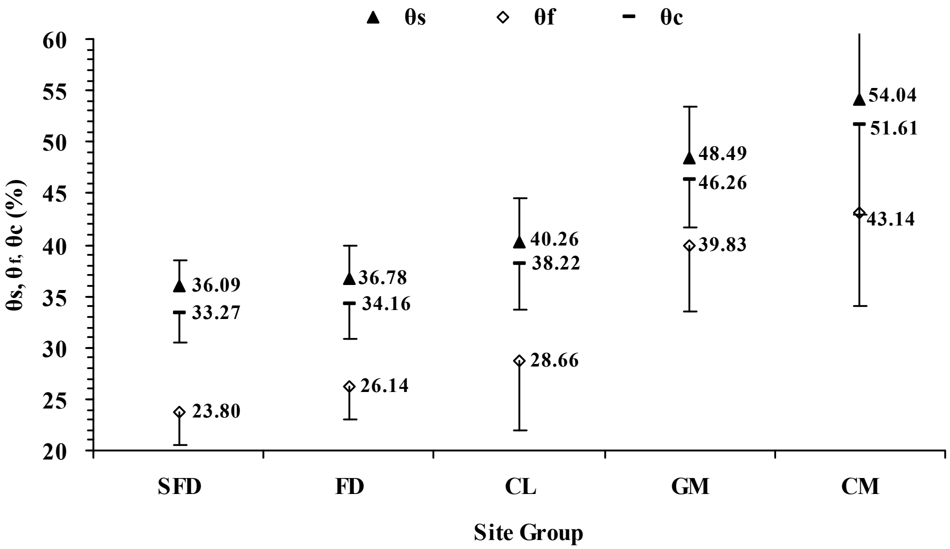

Fig. 9. The saturated soil moisture (θ_s), field capacity (θ_f), and capillary rise moisture content (θ_c) of the study area. Values are means ± standard deviations. SFD stands for semi-fixed dune sites, FD for fixed dune sites, CL for cultivated land sites, GM for general meadow sites, and CM for control meadow sites where there was no detectable erosion and sand accumulation.