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Soil properties and their spatial pattern in a degraded sandy grassland under post-grazing restoration, Inner Mongolia, northern China

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Abstract. In this study, we use classical and geostatistical methods to identify characteristics of some selected soil properties including soil particle size distribution, soil organic carbon, total nitrogen, pH and electrical conductivity and their spatial variation in a 5-year recovery degraded sandy grassland after two different grazing intensity disturbance: post-heavy-grazing restoration grassland (HGR) and post-moderately grazing restoration grassland (MGR), respectively, in Horqin steppe, Inner Mongolia, northern China. The objective was to examine effect of grazing intensity on spatial heterogeneity of soil properties. One hundred soil samples were taken from the soil layer 0–15 cm in depth of a grid of 10 m × 10 m under each treatment. The results showed that soil fine fractions (very fine sand, 0.1–0.05 mm and silt + clay, <0.05 mm), soil organic carbon and total nitrogen concentrations were significant lower and their coefficients of variation significant higher under the HGR than under the MGR. Geostatistical analysis of soil heterogeneity revealed that soil particle size fractions, organic carbon and total nitrogen showed different degree of spatial dependence with exponential or spherical semivariograms on the scale measured under HGR and MGR. The spatial structured variance account for a large proportion of the sample variance in HGR plot ranging from 88% to 97% for soil particle fractions, organic C and total N, however, except for organic C (88.8%), the structured variance only account for 50% of the sample variance for soil particle fractions and total N in the MGR plot. The ranges of spatial autocorrelation for coarse-fine sand, very fine sand, silt + clay, organic C and total N were 13.7 m, 15.8 m, 15.2 m, 22.2 m and 21.9 m in HGR plot, respectively, and was smaller than in MGR plot with the corresponding distance of 350 m, 144.6 m, 45.7 m, 27.3 m and 30.3 m, respectively. This suggested that overgrazing resulted in an increase in soil heterogeneity. Soil organic C and total N were associated closely with soil particle fractions, and the kriging-interpolated maps showed that the spatial distribution of soil organic C and total N corresponded to the distribution patterns of soil particle fractions, indicating that high degree of spatial heterogeneity in soil properties was linked to the distribution of vegetative and bare sand patches. The results suggested that the degree of soil heterogeneity at field scale can be used as an index for indicating the extent of grassland desertification. Also, the changes in soil heterogeneity may in turn influence vegetative succession and restoration process of degraded sandy grassland ecosystem.

Introduction

Spatial heterogeneity of soil organic matter and nutrient pools at scales from the sizes of individual plants to field is a general characteristic in arid and semiarid grassland ecosystems (Hook et al. 1991; Schlesinger et al. 1996) that plant individuals and plant community composition affect the distribution of soil nutrients at a variety of spatial scales (Hook et al. 1991; Jackson and Caldwell 1993). Conversely, the scale and degree of spatial heterogeneity in soil properties contribute greatly to the spatially heterogeneous distribution of flora and fauna (Wang et al. 2002) and, in turn, can have important consequences for both plant community structure and ecosystem-level processes (Robertson et al. 1993). Many studies have shown that grazing practices of grasslands play an important role in creating high degree of spatially structured, local variability in soil resources and nutrient fluxes (Gibson 1988; Schlesinger et al. 1996; Augustine and Frank 2001). A variety of grazers promote fine-scale heterogeneity by diversifying plant species effects on soils and/or increasing the spatial variability in plant litter inputs (Augustine and Frank 2001). The interactions among selective grazing, urine deposition, and grazing pressure increase the structural and functional heterogeneity of grassland (Jaramillo and Detling 1992). Schlesinger et al. (1990) reported that long-term grazing of semiarid grasslands leads to an increase in the spatial and temporal heterogeneity of water, nitrogen, and other resources, and the development of soil heterogeneity is central to major changes in ecosystems undergoing desertification. In conformity with this, Franzluebbers et al. (2000) documented that grazing behavior can influence the spatial distribution of soil biochemical properties in long-term grazed pastures.

Desertification is one of the major problems among global environmental issues. It is defined by UNCED as land degradation in arid, semiarid, and subhumid areas resulting from various factors including climatic variations and human activities (UNCED 1992). Desertification has been characterized by many indicators, of which spatial heterogeneity has been shown to a useful and reliable one (Schlesinger et al. 1996; Seixas 2000). Schlesinger et al. (1990) suggested that the increase in spatial heterogeneity of soil resource induced by gazing is a main mechanism of biological feedback of desertification in arid and semiarid grassland ecosystem. Also, analysis of spatial heterogeneity in soil properties under different disturbances can enable us to have a deep understanding of the ecological relationships between soils and the environment (Rossi et al. 1992). With respect of this, studies concerning to changes in distribution of vegetation and soil properties might be particularly important in the desertification-prone sandy grassland. Unfortunately, although considerable research has addressed the impact of grazing on distribution patterns in soil nutrients in pastures and grasslands, little has been done in the semiarid Horqin sandy steppe of north China, where overgrazing is often regarded as one of the main causes of desertification (Li et al. 2000). The objective of this study was to characterize and compare spatial heterogeneity in some selected soil properties at field scale in recovering desertified grassland following the disturbance of two grazing intensities (heavy and moderately grazing). We hypothesized that soil properties would have larger spatial variations in post-heavy grazing recovering grassland than in post-moderate recovering grassland due to their different degrees of desertification, and the distribution of soil particle size distribution, soil organic carbon (SOC), total nitrogen (Total N), pH and electrical conductivity (EC) would exhibit various degrees of spatial autocorrelation due to their different responses to plant cover change and desertification.

Materials and methods

Description of the study area

The study was conducted at the Naiman Desertification Research Station (NDRS) of Chinese Academy of Sciences (42°58′120°43′ E, 360 m elevation), located in the south-west end of the Horqin steppe (Naiman county, Inner Mongolia). Horqin sandy steppe (42°41′ – 45°15^′ N, 118°35^′–123°30′ E, elevation 180–650 m) is a representative of severe degraded grassland ecosystems. Primary landscape is sand land sparse steppe on interdune lowlands alternated with dunes. Activation of stabilized dunes occurs to differing degrees due to long-term overgrazing, excessive farming, and vegetation disruption by fuelwood gathering, resulting in a fragmented landscape having shifting dunes and semi-shifting dunes with stabilized dunes in alternation. Furthermore, the distribution of vegetative patchiness and soil characteristics at relatively small scale within a degraded grassland community showed high degree of spatial heterogeneity due to the influence of micro-topographic conditions, grazing disturbance, and wind erosion. Especially, accelerated wind erosion induced by disorganized grazing result in occurrence of bare sand patches and development of desertification, and, in turn, increased degree of spatial heterogeneity of grassland landscape.

The study area belongs to the semiarid continental temperate monsoon climate, with windy and dry winters and springs, and warm and comparatively rain-rich summers followed by short and cool autumns. The 40-year mean annual temperature is 6.5 °C (range from 5.1 to 7.7 °C) with the coldest and warmest monthly mean temperatures of −13.1 °C (−16.6–9.7 °C) in January and 23.7 °C (21.6–25.8 °C) in July, respectively. Mean annual precipitation is 366 mm and mean annual pan evaporation is about 1935 mm. Rainfall is erratic and shows strong seasonal and annual variability. The mean annual wind speed ranges from 3.4 to 4.1 m s^{-1}, with frequent occurrence of gales (wind speed >20 m s^{-1}) in winter and spring. The zonal soils are identified as degraded sandy Chestnut soils, which are mostly equivalent to the Orthi-Sandic Entisols of sand origin in terms of the FAO-UNESCO system. These soils are characterized by their coarse texture and loose structure with high proportion of sand (85–95%) and low organic matter content (0.15–0.5% organic C) (Su et al. 2002). Due to these characteristics, the soils are highly susceptible to wind erosion. The degraded sandy grassland is covered by weed communities and generally dominated by psammophytes (Su and Zhao 2003; Su et al. 2003).

The field site is typical degraded sandy grassland which is about 2 km away from NDRS. It was fenced with posts and barbed wire as in the grazing experiment of 1992. Prior to establishing the experiment in 1992, this site had been slightly desertified due to poor management (disorganized and continuous grazing). Dominant plants were graminoids (*Cleistogenes squarrosa* (Trin.) Keng, *Setaria viridis* (L.) Beauv., *Phragmites australis* Trin.ex Steudel Nomencl., *Digitaria ciliaris* (Rotz.) Koeler, *Leymus chinensis* (Trin.) Tzvel., and *Pennisetum centrasiaticum* Tzvel.), accompanied by some legumes and forbs (*Mellissitus ruthenicus* (L.) C.W.Chang, *Salsola collina* Pall., *Corispermum elongatum* Bge. ex Maxim., *Agriophyllum squrrosum* (L.) Moq., *Artemisia scoparia* Waldst. et Kit.), shrubs and subshrubs were few. But the characteristics of vegetation cover and soil were relatively homogeneous (Zhao et al. 1997; Li et al. 2000). The grazing experiment field consisted of four plots, i.e., Plot A, ungrazed (no sheep), Plot B, lightly grazed (two sheep per ha), Plot C, moderately grazed (four sheep per ha), and Plot D, overgrazed (six sheep per ha). Plot A was 0.74 ha (200×37 m) and each of the other three plots had an area of 1.5 ha (200×75 m). Grazing started on 1 June and ended on 30 September each year for 5 years from 1992. A full descriptive of site locations and characteristics is given by Li et al. (2000). From 1998 to 2002, non-grazing for 5 years was done for vegetation recovery. In this study, the two adjacent plots, i.e., post-heavy-grazed recovering plot (plot D, HGR) and post-moderately-grazed recovering plot (plot C, MGR) were selected to compare the long-term effects of different grazing intensities on soil properties and their distribution patterns. This was done because Plot A (ungrazed treatment) had smaller area and had been suffered from severe destruction of sand invasion and deposition due to the cultivation of grassland adjacent to Plot A in 1999. In addition, heavy grazing and moderately grazing in the studied area were two dominant kind of grazing activity, and the comparison between them is of practical importance.

Soil sampling and analysis

During the grazing experiment period the vegetation cover, bare land fraction and wind erosion had been investigated each year by other researchers (Zhao et al. 2005). In this study, we focused on the effects of different grazing intensity disturbance and following non-grazing recovery on the distribution of soil properties. Before soil sampling, ground cover characteristics was measured. Ten 5-point transects with separate distance of 15 m each other in each plot were used to determine percent bare ground, live vegetation and dead vegetation.

Soil samples were taken in August 2002. Within each plot, five parallel transects 200 m in length equally spaced 10 m were located and 20, 1×1 m^2 quadrats with a distance of 10 m interval along each transect were marked out.

Within each quadrat, five soil samples on two diagonals at 0~15 cm depth were taken using a soil auger (diameter: 5 cm) and bulked to obtain a composite sample. This was done to eliminate effect of plant individuals on soil properties at a micro-scale. All plant litter was removed from the soil surface before soil samples were collected.

Soil samples were air-dried and hand-sieved through a 2-mm screen to remove roots and other debris. Soil particle size distribution was determined by wet sieve method (ISSCAS 1978). Soil pH and electrical conductivity (EC) were measured in a soil–water suspension (1:1 and 1:5 soil water ratio, respectively) (Multiline F/SET-3, Germany). Part of the air-dried samples were finely ground to pass 0.25 mm sieve and analyzed for SOC and total N by the $K_2Cr_2O_7$–H_2SO_4 oxidation method of Walkley–Black (Nelson and Sommers 1982) and by the Kjeldahl procedure (UDK140 Automatic Steam Distilling Uint, Automatic Titroline 96, Italy), respectively (ISSCAS 1978).

Statistical analyses

Mean, median, standard deviation (SD), minimum, maximum and coefficient of variation (CV) were determined for all data set. The distribution of the data was tested for normality by Kolmogorov–Smirnov test, kurtosis and skewness. Correlation analysis was performed for soil particle fractions, SOC, total N, pH and EC to determine the relationship between these variables. The significance level reported ($p < 0.05$) is based on the Pearson's coefficients. A Student's *t*-test was used to assess differences in concentration of different variables in soil between the two samplings. To test for effects of the grazing intensity disturbance and subsequent recovery on soil properties, independent-samples *t*-test was used to compare the mean values for MGR vs. HGR plots. All statistical analyses were carried out with the program SPSS 11.5 for Windows.

Geostatistical methods were applied to study spatial variability of the soil properties (Webster 1985). Experimental semivariogram for the given separate distance h was calculated according to:

$$r(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where $\gamma(h)$ is the semivariance at a given distance h; $Z(x_i)$ is the value of the variable Z at the x_i location, and $N(h)$ is the number of pairs of sample points separated by the lag distance h. Nugget variance, range and sill of each semivariogram were parameters provided for interpretation of spatial dependence. The nugget effect represented random variation caused mainly by measurement error or variation that could not be detected at the minimum sampling distance used. Usually, semivariance increases with sampling distances and then approaches a constant value called the sill (Trangmar et al. 1985). The separation distance at which the sill is achieved is called the range of spatial dependence. Samples separated by distances closer than the range are spatially related, while samples separated by greater distances are not spatially related. Kringing was used as an interpolating method based on spatial structure. Field maps are produced by ordinary block kriging.

GS^+ software (Version 5.1b, Gamma Design software) was used to create semivariogram for each variable at each plot and to choose the theoretical model type that best fitted the experimental semivariogram (modelized variogram). After the kringing process, we evaluated interpolation result quality by cross-validation.

Results

Ground cover characteristics

At the end of the grazing experiment in 1996, vegetation cover, canopy height, standing crop biomass had considerable decreased in the heavy grazing plot. As a result, small bare spots appeared on the ground and later merged into larger bare patches due to severe wind erosion. Total bare area reached up to 52% in the heavy grazing plot, greater 11 times than in the moderately grazing plot (Table 1). It can be seen that sandy grassland had became a highly fragmental landscape with a number of bare patches under continuous heavy grazing.

After 5 years of non-grazing recovery, ground cover (live vegetation and litter cover) increased due to vegetation recovery and litter accumulation, but bare patches still existed and significantly differed between the HGR and MGR treatments. Investigation showed that percent of bare ground was on average 47% higher in HGR than in MGR (Table 2).

Table 1. Vegetation cover and bare ground characteristics of degraded sandy grassland at the end of grazing experiment in 1996 (Zhao et al. 2005).

Treatment	Canopy height cm	Vegetation cover (%)	Standing crop biomass g m^{-2}	Bare ground characteristics		
				Bear patch number	Mean length m	Mean bare fraction (%)
HG[a]	1.0 ± 0.6	10.1 ± 17.3	3 ± 6	302	4.1	51.6
MG[b]	16.6 ± 11.2	47.7 ± 15.1	67 ± 40	87	1.3	4.7

[a] Heaving grazing plot.

[b] Moderately grazing plot.

Table 2. Ground cover characteristics of post-grazing restoration grassland.

Treatment	Canopy height cm	Percent ground cover (%)		
		Bear ground	Live vegetation	Litter
HGR[a]	13.2 ± 7.5 b	37.0 ± 20.6 a	34.5 ± 10.9 a	28.5 ± 19.5 b
MGR[b]	29.9 ± 8.4 a	25.2 ± 14.7 b	40.8 ± 13.5 a	34.0 ± 14.4 a

[a] Five year restoration grassland after heavy grazing for 5 years.
[b] Five year restoration grassland after moderately grazing for 5 years.

Soil physical and chemical properties

Descriptive characteristics for contents of soil particle size fractions, SOC and total N, and values of pH and EC in the HGR and the MGR plots are shown in Table 3. Soil texture differed significantly between the HGR and MGR treatments. The mean value of coarse-fine sand (2–0.1 mm) content was 22.6% higher in the HGR plot than in the MGR plot ($t = 4.02, p = 0.002$), but very fine sand (0.1–0.05 mm) and silt + clay (< 0.05 mm) contents were 18.2% and 22.6% lower in the HGR plot than in the MGR plot, respectively. Also, there were significant differences in soil organic C ($t = 3.45, p = 0.001$) and total N ($t = 1.79, p < 0.0001$) for the sample means between the HGR and the MGR plots, with higher averaged values for SOC and total N in the MGR plot than in the HGR plot. Soil pH was slightly lower in the MGR plot than in the HGR plot, but no significant difference was found ($t = 1.225, p = 0.113$). The mean EC value in the MGR soils was similar to that in the HGR soils. The differences between maximum and minimum values in SOC, total N and sand content were higher in the HGR plot than in MGR plot, indicating that the HGR soils had higher degree of variability.

The differences in SOC and total N content between the two treatments were related to the desertified extents of grasslands under different grazing intensity. We observed high degrees of positive correlations between SOC, total N and fine particle fractions (very fine sand and silt + clay) and high degree of negative correlations between SOC, total N and coarse-fine sand content. The value of

Table 3. Pearson's correlation coefficients of soil properties in post-grazing restoration grassland.

	SOC	Total N	Coarse-fine sand	Very fine sand	Silt + clay	pH	EC
SOC	1.00						
Total N	0.93**	1.00					
Coarse-fine sand	−0.65**	−0.59**	1.00				
Very fine sand	0.53**	0.48**	−0.96**	1.00			
Silt + clay	0.71**	0.67**	−0.69**	0.48**	1.00		
pH	0.36*	0.41**	−0.13	0.09	0.22*	1.00	
EC	−0.05	0.05	0.08	−0.04	0.14	0.20*	1.00

* and ** are significant at $p < 0.05$ and $p < 0.01$, respectively.

pH had significant correlations with SOC, total N and silt + clay content but no significant correlation with coarse-fine sand and very fine sand content. The value of EC had no correlation with soil variables except to pH (Table 4).

Soil properties measured in the experimental grassland presented a considerable spatial variability in the both plots, as can be deduced from the high values of the coefficient of variations (18.7–42.6%) (Table 3). Comparison of the two treatments revealed that soil particle size fractions, SOC and total N contents had higher variation in the HGR plot (CV: 37–42.6%) than in the MGR plot (CV: 26.8–33.7%). For pH and EC, however, CVs in HGR plot were similar to those in MGR plot.

Semivariance analysis of soil properties

To further describe the spatial variation of soil properties, a semivariogram for each data set was developed. Frequency distribution and Kolmogorv–Smirov tests for normality showed that the most variables were normally distributed, with exception of silt + clay content, pH and EC in the MGR plot. After a log-transformation, silt + clay content passed the normal distribution test, but pH and EC were still not normally distributed, indicating no correlation exists between sampling location and change in value within the scale sampled. Hence, pH and EC in both plots were not tested for semivariance.

Sample semivariogram models and best-fitted model parameters based on the smallest residual sum of square (RSS) are given in Figure 1 and Table 5.

Table 4. Statistical characteristics of soil properties in post-grazing restoration grassland ($n = 100$).

Soil properties	Treatment	Mean	SD	CV%	Maximum value	Minimum value	Skewness	Kurtosis
Soil texture								
Coarse-fine sand	HGR[a]	50.7	18.7	37.0	91.4	16.7	0.34	−0.85
(2–0.1 mm,%)	MGR[b]	41.2	13.9	33.7	78.6	16.3	0.85	0.22
Very fine sand	HGR	37.8	15.5	40.6	65.2	5.8	−0.41	−0.90
(0.1–0.05 mm,%)	MGR	44.8	12.0	26.8	68.5	12.6	−0.74	0.33
Silt + clay	HGR	11.5	4.8	42.6	24.8	2.6	0.07	−0.78
(< 0.05 mm,%)	MGR	14.1	4.5	31.9	31.1	5.7	0.81	1.47
Organic C	HGR	2.32	0.97	41.8	4.65	0.43	0.27	−0.48
g kg^{-1}	MGR	2.72	0.74	27.0	5.57	0.85	0.43	1.7
Total N	HGR	0.257	0.104	40.5	0.53	0.06	0.17	−0.28
g kg^{-1}	MGR	0.279	0.072	27.2	0.58	0.14	1.04	2.73
pH (H_2O)	HGR	7.88	0.173	22.0	8.3	7.33	−0.14	1.13
	MGR	7.74	0.145	18.7	8.05	7.09	−1.6	4.88
EC	HGR	49	12.8	26.1	83	22	0.16	−0.03
μs cm^{-1}	MGR	50	14.4	28.8	114	27	1.36	3.29

[a] Five year restoration grassland after heavy grazing for 5 years.

[b] Five year restoration grassland after moderately grazing for 5 years.

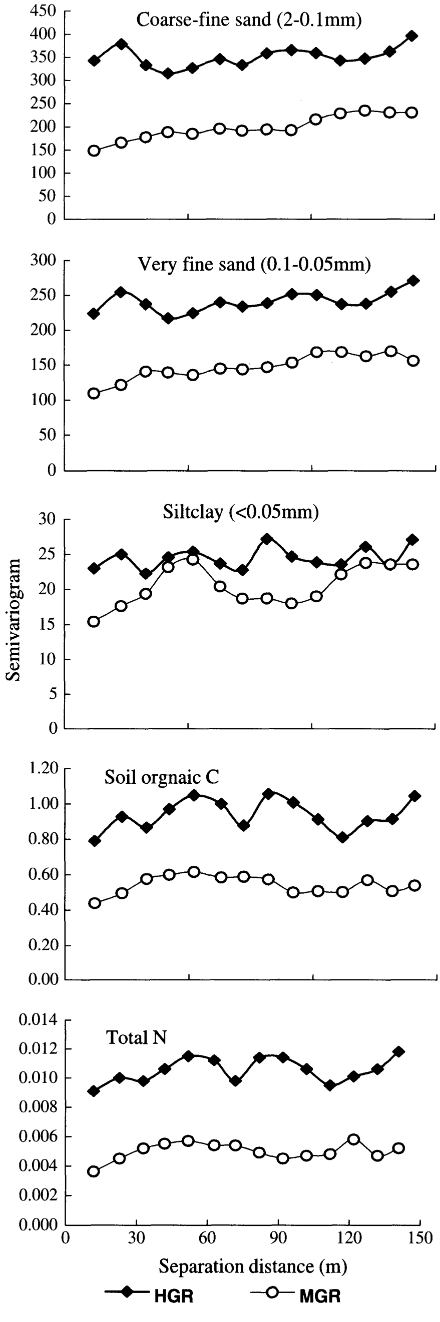


Figure 1. Sample semivariograms for soil particle size fractions, soil organic C and total N in the surface soils (0–15 cm) in MGR and HGR plots.

Table 5. Semivariogram models of soil properties and corresponding parameters.

Soil properties	Treatment	Model	Nugget C_0	Sill $(C_0 + C)$	$C/(C + C_0)$	Range A_0(m)	Cross-validation ME
Soil texture							
Coarse-fine sand	HGR	Spherical	15.00	351.2	95.7	13.7	0.300
(2–0.1 mm)	MGR	Spherical	150.4	300.9	50.0	350	0.223
Very fine sand	HGR	Spherical	10.9	242.2	95.5	15.8	0.219
(0.1–0.05 mm)	MGR	Exponential	84.7	169.5	50.0	117	0.193
Silt + clay	HGR	Spherical	0.75	24.59	96.9	15.2	0.253
(< 0.05 mm)	MGR	Spherical	10.66	21.35	50.1	45.7	0.159
Organic C	HGR	Exponential	0.106	0.955	88.9	22.2	0.218
	MGR	Exponential	0.052	0.554	90.6	27.3	0.217
Total N	HGR	Exponential	0.0012	0.0107	88.8	21.9	0.230
	MGR	Exponential	0.0005	0.0052	50.9	30.3	0.175

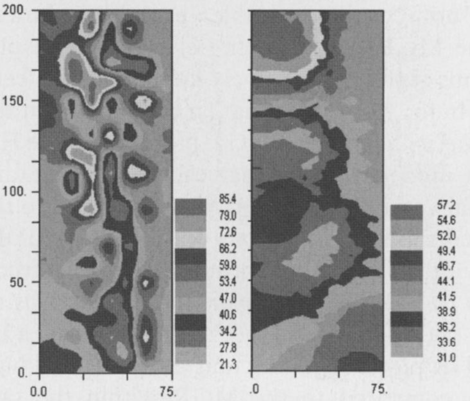
Semivariagrams of soil properties were fitted to a spherical or exponential model. It can be noticed that variables examined showed lower levels of semivariance in the MGR plot than those in the HGR plot (Figure 1). Soil particle size fractions showed a relatively large nugget effect and the values of nugget were larger in the MGR plot than in the HGR. But the nugget effect for SOC and total N was smaller in the MGR plot than in the HGR. Sill values for the semivariogram models showed that each variable examined had greater magnitude of spatial variability in HGR plot compared to those in MGR plot. All variables studied showed a moderate or strong spatial dependence in both MGR and HGR plots with the proportions of spatial structure $[C/(C + C_0)]$ ranging from 50% to 97%. In particular, the proportions of sample variance explained by small-scale patchiness $[C/(C + C_0)]$ showed a very high values for each variable in HGR plot, suggesting that the HGR had higher degree of fine-grained variability compared to the MGR within the sampling scale. The magnitude of spatial dependence in soil particle size fraction and total N was higher in HGR plot than in MGR plot, respectively. The range of autocorrelation (A_0) was 22.2 m for SOC and 21.9 m for total N in the HGR plot, which was less than that in the MGR plot (27.3 m and 30.3 m), respectively. The ranges of spatial autocorrelation for soil particle size fractions were much higher in the HGR (45.7–350.3 m) than in the HGR (13.7–15.8 m). These results indicated that the spatial variability in soil properties examined were greater in HGR plot than in MGR plot and their spatial distribution were related to the ground cover characteristics (Tables 1 and 2).

Kriging estimates of spatial distribution of soil properties

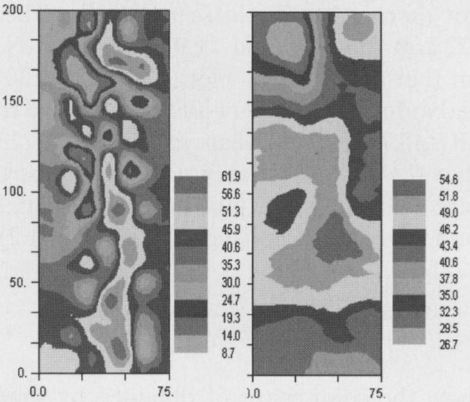
Figures 2 and 3 show the color maps of obtained by simple kriging for soil particle size fractions, SOC and total N. The maps show the high variability that was also observed in the results obtained by the classical statistics methods (Table 3). In general, the maps showed high heterogeneity and the degree of patch fragment were higher in the MGR than in HGR. Within the same plot, SOC and total N exhibited similar spatial pattern, and low level SOC and total N patches corresponded to areas of high coarse sand content and their high level patches corresponded to the areas of high fine fractions.

Validation

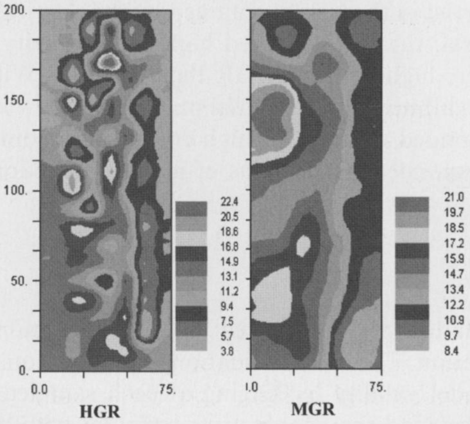
Two types of validation were conducted: internal validation (cross-validation) and external validation. The cross-validation technique consisted of testing the semivariagram model validity by kriging at each sampled location using all neighboring samples, and then comparing estimates with real values. The results showed that all soil properties determined had low mean error (ME) (Table 5), indicating a lack of systematic bias for prediction method and a



(a) Coarse-fine sand (2-0.1mm, %)



(b) Fine sand (0.1-0.05 mm, %)



(c) Silt+clay (<0.05 mm, %)

Figure 2. Spatial distribution of coarse-fine sand, very fine sand and silt + clay under two grazing patterns.

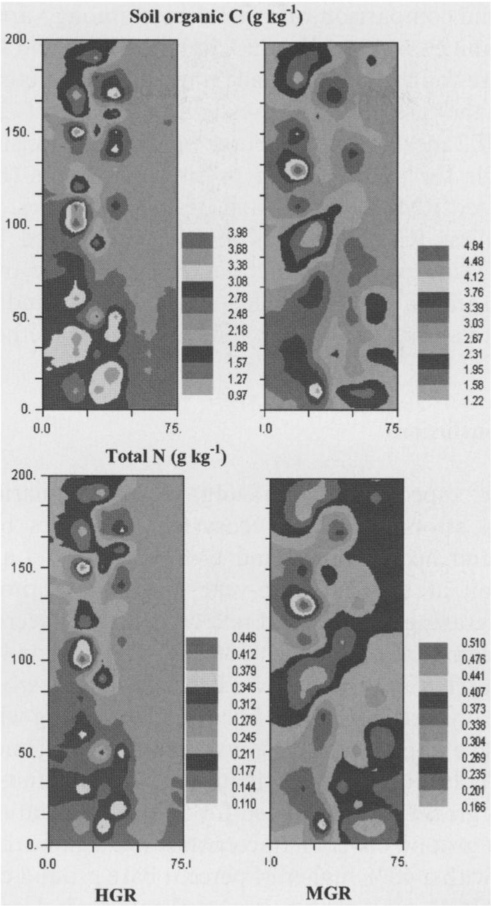


Figure 3. Spatial distribution of soil organic C and total N under two grazing patterns.

good fit of the semivariogram to the data set. However, this validation was only a comparison between the data from the fitted semivariogram and the original data, so validation did not confirm prediction method reliability for the external data. For external validation, data from the validation set were used to calculate a second mean error (ME2) and second mean square error (RMSE2) (Table 6).

In general, soil particle size fractions, SOC and total N in the two treatments had very low ME2, indicating a lack of bias for the prediction method (Table 6) since ME2 measured the prediction bias and values close to zero, as confirmed by Bourennae et al. (1996). Coarse-fine sand and very fine sand contents in the MGR plot, and silt + clay content in the HGR plot had positive values, indicating that the prediction over-estimated observed values (Table 6). Mean error percent (ME2%) was calculated divided by the mean, and this allowed the comparison of mean errors among variables. In general, soil properties examined had small values in both HGR and MGR treatments. Highest values were found for SOC and coarse-fine sand content in the HGR plot, which had the greatest under-estimated value of 2.7% and 2.6%, respectively. RMSE2 measures the average prediction precision and should be as small as possible for unbiased and precise predictions (Bourennane et al. 1996). The calculated RMSE2 varied among soil properties. SOC and total N contents had smallest RMSE2 values in both HGR and MGR treatments (0.062–0.72), indicating precise predictions and negligible bias. On the other hand, coarse-fine sand in the HGR plot and very fine sand in the two treatments had greatest values (8.35–13.28), indicating some method bias (Table 6).

Discussions and conclusions

Livestock grazing, especially overgrazing, in the semiarid Horqin sandy grasslands exert a strong effect on ecosystem dynamics by decreasing the vegetative cover and accelerating wind erosion (Zhao et al. 1997; Li et al. 2000). Investigation at the end of 5-year grazing experiment showed that continuous heavy grazing had resulted in a considerable decrease in vegetation cover, canopy height and standing biomass, and a significant increase in number of bare patches and bare area (Table 1). In the erosion-prone sandy grassland, once heavy grazing created bare patches, strong wind would impose further severe erosive impacts on the soil and cause enlargement of continuous bare patches, finally leading to the formation of aeolian landscape (Zhao et al. 2005). After sheep grazing was excluded for 5 years, vegetation get recovery at certain degree, but ground cover characteristics still significantly differ between HGR and MGR, with a 48% higher of percent bare ground cover in the MGR plot than in the HGR plot (Table 2). Accelerated wind erosion due to the

Table 6. Mean error (ME2), percent of mean error (ME2%) and root mean square error (RMSE2) obtained from the external validation procedure.

Variable	Treatment	ME2 Property unit	ME2%	RMSE2 Property unit
Coarse-fine sand	HGR	−1.292	−2.6	13.28
(2–0.1 mm)	MGR	0.604	1.5	1.73
Very fine sand	HGR	−0.222	−0.6	11.37
(0.1–0.05 mm)	MGR	0.198	0.4	8.35
Silt + clay	HGR	0.088	0.8	3.68
(< 0.05 mm)	MGR	−0.200	−1.5	3.23
Organic C	HGR	−0.060	−2.7	0.72
	MGR	−0.006	−0.2	0.68
Total N	HGR	−0.002	−1.0	0.08
	MGR	−0.001	−0.2	0.06

decreased vegetation cover and litter accumulation under heavy grazing resulted in soil coarsening and loss of soil organic matter. Our results showed that very fine sand, which is most erodible fraction (Su et al. 2004), and silt + clay contents, as well as SOC and total N concentrations were significantly lower in the HGR soil than in the MGR soil. Correlation analysis showed that SOC and total N have significantly positive correlation with very fine sand ($r = 0.53$ and 0.48), silt + clay ($r = 0.71$ and 0.67) and negative correlation with coarse-fine sand (r: -65 and -0.59), indicating that the loss of fine fractions enriched in organic C and nutrients Lobe et al. (2001) contributed partly to depletion in SOC and total N. The mean value of pH under HGR was slightly higher than under MGR, but no difference for EC was found between the two treatments. This was in agreement with our previous studies that grassland desertification as a result of overgrazing can result in a slightly rise in pH but have no clear effect on EC (Su et al. 2005).

The results also showed that the HGR plot exhibited higher spatial variability in soil properties than the MGR plot. It can be seen from the coefficient of variation that soil properties examined have higher degree of overall variation in the HGR plot than in the MGR plot. The results of geostatistical analysis provided further evidence of difference of spatial heterogeneity in soil properties under the two grazing intensity. The result showed that sill values for the semivariogram models for each variable were greater in HGR than in MGR, and $[C/(C + C_0)]$ showed a very high values for each variable in HGR plot (Table 5, Figure 1), suggesting that soil particle size fractions, SOC and total N had greater spatial structured variance and fine-grained variability compared to those in MGR plot (Augustine et al. 2001). This spatial dependence was attributed to the distribution of vegetative and bare ground patches after the disturbance of two grazing intensity which still remained following 5 years of ungrazed recovery (Table 2). It was found that the ranges of spatial autocorrelation in soil particle size fractions, SOC and total N are shorter in the HGR plot than in the MGR plot, indicating that the MGR plot have a relatively uniform distribution of soil cover at the examined scale as compared to the HGR plot. It is noticed that the ranges of spatial autocorrelation in soil particle size fractions are much higher in the MGR plot (45–350 m) than in the HGR plot (13.7–15.2 m). In particular, the range of spatial autocorrelation in coarse-fine sand was greater than 150 m (350 m) in the MGR plot, indicating that change in coarse-fine sand composition was relatively small and high heterogeneous patches did not occur within the 10–200 m scale. The results from another study confirmed that the grassland kept a relatively higher vegetation cover and more uniform distribution and the ground surface stabilized under moderately grazing (Zhao et al. 2005), changes in soil particle size distribution were relatively small, and coarse-fine sand fraction was not easily eroded by wind under vegetation cover (Su et al. 2005). However, the vegetation cover decreased dramatically under continuous heavy grazing. Once grass is removed and loose, sandy soil is exposed, it is easily eroded by wind erosion. Accelerated wind erosion results in the enlargement of bare patches, at the same time it sorts the soil materials, removing fine size fractions, and leaving a more coarse-textured soil behind (Su et al. 2004). Studies have reported that the different size of bare patches in the heavy grazing plot exhibited a non-uniform distribution pattern with a large number (Zhao et al. 1997, 2005). This resulted in a high degree of spatial heterogeneity in soil particle composition under HGR. Furthermore, the kriging-interpolated maps of soil particle sized fractions, SOC and total N showed evident differences between HGR and MGR (Figures 2 and 3). It can be seen clearly that the HGR showed a finer grain of patchiness, indicating soil properties examined have more heterogeneous distribution in the HGR plot within the studied field scale as compared to the MGR plot.

Many studies in semiarid and arid grazed grasslands have documented a high spatial heterogeneity in soil nutrients at every scale from individual plants to plant communities to topographically variable landscapes (Hook et al. 1991; Jackson and Caldwell 1993; Gross et al. 1995; Schlesinger et al. 1996; Augusting and Frank 2001). In some areas with fragile environment, high degree of spatial heterogeneity in soil resources induced by grazing disturbance implied to the evolution of land degradation/desertification. It is suggested (Schlesinger et al. 1990) that long-term grazing of semiarid grasslands leads to increase in the spatial and temporal heterogeneity of water, nitrogen and other soil resources. Heterogeneity of soil resources promotes the invasion of these grasslands by desert shrubs, which leads to a further localization of soil resources under shrub canopies. This increase of soil heterogeneity associated with shrub encroachment has been implicated as a potential feedback to grassland desertification (Schlesinger et al. 1990, 1996). In the present study, we determine degrees of soil heterogeneity under two grazing patterns at a field scale (50 m × 200 m at 10-m spacing) and hypothesis that soil heterogeneity is associated with the distribution of vegetation and bare sand patches, disregarding influence of individual plant on small-scale spatial. The results showed that coarse-fine sand content was significant lower and its spatial distribution was more heterogeneous in the HGR than in the MGR, indicating that the HGR was in serious desertification stage. Kringing analysis for SOC and total N showed that their spatial distribution corresponded to that of soil particle size fractions within the same treatment plot, indicating that higher degree of soil heterogeneity in HGR is linked to the increase of bare sand patches and their non-uniform distribution under continuous heavy grazing. On the basis of the present study and the previous studies of desertification process (Zhao et al. 2005; Su et al. 2005), we suggested that the degree of soil heterogeneity at field scale can be used as an index for indicating the extent of grassland desertification.

Also, the levels of SOC and total N and their spatial variability may have profound effects on vegetative restoration and desertification reversion in the erosion-prone sandy steppe. Because the distribution patterns of SOC and N have significant feedbacks to plant establishment, growth and survival (Hook et al. 1991) and conversely, spatial patterns of plant distribution can influence rates of physical and biogeochemical processes that control ecosystem C and N balance (Schlesinger et al. 1990). Our investigation indicated that significant differentiation occurred in the plant species composition, functional group, and litter accumulation between the grasslands under the two grazing intensity after non-grazing restoration for 5 years (Su et al. 2002). The dominant plant species in the HGR plot were some forbs including *A. scopari*, *S. viridis* and *S. collia* and some desert shrubs and semishrubs were invaded. In the MGR plot, major species were annual and perennial grasses including *S. viridis*, *Cleistgenes mutica* and *P. australis*. Increase of soil heterogeneity can exert an important effect to the composition of plant community, vegetative succession and restoration process of degraded grassland ecosystem. The semiarid Horqin sandy grassland is ecologically very fragile, and heaving grazing of such grassland should be avoided.

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