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ORIGINAL ARTICLE

Effects of grazing and livestock exclusion on soil physical and chemical properties in desertified sandy grassland, Inner Mongolia, northern China

Yuqiang Li · Halin Zhao · Xueyong Zhao · Tonghui Zhang · Yulin Li · Jianyuan Cui

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Abstract Heavy grazing is recognized as one of the main causes of vegetation and soil degradation and desertification in the semiarid Horqin sandy grassland of northern China. Soil physical and chemical properties were examined under continuous grazing and exclusion of livestock for 8 years in a representative desertified sandy grassland. Exclosure increased the mean soil organic C, total N, fine sand and silt + clay contents, inorganic C ($CaCO_3$), electrical conductivity, and mineral contents (including Al_2O_3, K_2O, Na_2O, Fe_2O_3, CaO, MgO, TiO_2, MnO), microelements (Fe, Mn, Zn, B, Cu, Mo), and heavy metals (Pb, Cr, Ni, As, Hg, Cd, Se), and decreased the coarse sand content, bulk density, and SiO_2 in the top 100 cm of the soil. Livestock exclusion also improved available N, P, K, Fe, Mn, and Cu, exchangeable K^+, and the cation exchange capacity, but decreased pH, exchangeable Na^+, and available S, Zn, and Mo in the top 20 cm of the soil. The greatest change in soil properties was observed in the topsoil. The results confirm that the desertified grassland is recovering after removal of the livestock disturbance, but that recovery is a slow process.

Keywords Grazing management · Soil properties · Desertification · Grassland restoration

Introduction

The Horqin sandy grassland of northeastern China (42°41′N–45°15′N, 118°35′E–123°30′E) has undergone severe desertification since the mid 1970s, primarily due to improper management of its natural resources. Heavy grazing has led to degradation of the soils and vegetation cover, and is often thought to be the major factor that has led to desertification (Zhu and Chen 1994). Desertification and frequent sand storms in the spring strongly affect the growth of the grassland vegetation and crops and greatly reduce their yields as a result of wind erosion and sand dune movement (Zhang et al. 2004).

To control desertification and reduce its influence on grassland and farmland in this area, various measures (e.g., planting indigenous trees, shrubs, and grasses; returning degraded farmland to grassland; fencing desertified sandy grassland) have been implemented in parts of the Horqin region in recent decades. Livestock exclusion in desertified sandy grassland is a good alternative to restore vegetation and attenuate soil losses caused by wind erosion in these erodible grasslands (Su et al. 2003). In recent years, intensive studies of the effects of grazing management on vegetation dynamics have been carried out in the Horqin sandy grassland (Li et al. 2000; Zhao et al. 2004), but few have focused on its effects on soil properties (e.g., Su et al. 2005). Information on these aspects is required for a better understanding of the restoration mechanisms and the biological feedback between restoration and desertification, and for developing appropriate management and conservation techniques for desertified sandy grassland.

The objective of this study was to compare the effects of continuous grazing and livestock exclusion on soil physical and chemical properties in the desertified sandy grassland of a region that is vulnerable to wind erosion.

Y. Li (✉) · H. Zhao · X. Zhao · T. Zhang · Y. Li · J. Cui
Cold and Arid Regions Environmental and Engineering
Research Institute, Chinese Academy of Sciences,
320 Donggang west road, Lanzhou 730000, China
e-mail: gsyqli@yahoo.com.cn

Materials and methods

Site description

The experiment was conducted near the Naiman Station of Desertification Research, Chinese Academy of Sciences. The Station is located in Naiman County, Inner Mongolia, China (42°55′N, 120°42′E, 385 m a.s.l.), at the southern part of the Horqin sandy grassland. The study area is characterized by sand dunes alternating with gently undulating interdunal lowlands, with sandy deposits 20–120 m thick. The zonal soils are identified as degraded sandy Chestnut according to the Chinese soil classification system (Chinese Soil Taxonomy Cooperative Research Group, Institute of Soil Science, Academic Sinica 1995), which are mostly equivalent to the Orthi-sandic Entisols of sandy origin in terms of the FAO-UNESCO system (FAO 1988). These soils are characterized by their coarse texture and loose structure, and are very susceptible to wind erosion. The mean annual precipitation is 366 mm, of which more than 85% falls from May to September. The mean annual pan evaporation is around 1,935 mm, which is equivalent to more than five times the annual precipitation. The mean annual temperature is around 6.4°C, and the lowest and highest monthly mean temperatures are −13.1°C in January and 23.7°C in July, respectively. A prominent period of wind erosion often occurs from April to mid June, before the rainy season arrives.

The area's original vegetation was composed of *Stipa grandis*, *Leymus chinensis*, and *Agropyron cristatum* communities, with sparsely scattered woody vegetation (mainly *Ulmus pumila*). However, the original vegetation has been greatly altered over the past several decades, primarily due to long-term heavy grazing and over-cutting of woody species for fuel. Vegetation in the degraded sandy grassland is dominated by *Artemisia halodendron* communities. The main fuel wood species are *U. pumila* and *Prunus sibirica* (Li et al. 2003).

The study sites (Fig. 1), located about 2 km northeast of Naiman Station, had been subjected to continuous livestock grazing and had undergone its most severe desertification (i.e., the development of a landscape characterized by mobile sand dunes) in the early 1990s. A restoration project was initiated in the summer of 1997 by establishing a fenced 500 m × 500 m area that excluded grazing and allowed the vegetation to recover naturally.

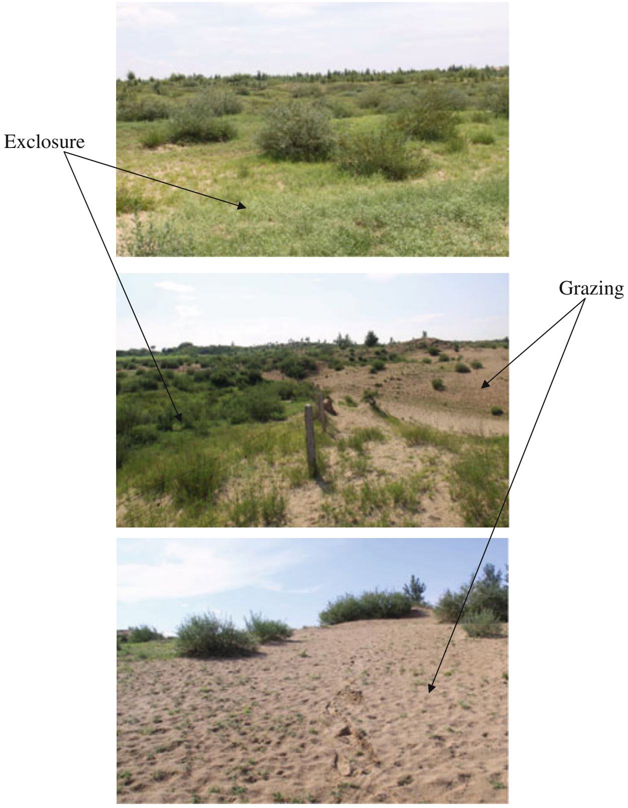

Fig. 1 The landscape of study sites

In the present study, we selected two sites for sampling: (1) in the grazing exclosure, livestock had been excluded for 8 years (from 1997 to 2005), and the vegetation cover is currently 30–50%. The dominant plant is *A. halodendron* (a native perennial shrub), with small numbers of *Caragana microphylla* (a leguminous shrub) and annual forbs such as *Euphorbia humifusa*, *Salsola collina*, and *Setaria viridis*. (2) At the continuous grazing site, an area outside the exclosure that had been subjected to continuous grazing, the vegetation cover was less than 10% and the dominant plant was the annual species *Agriophyllum squarrosum*, with very sparse distribution of *A. halodendron* and *C. microphylla.*

The aboveground biomass of herbage was 25.7 ± 19.4 and 24.8 ± 21.2 g m^{-2} in the exclosure and at the continuous grazing site, respectively, whereas the corresponding values for shrub biomass were 127.7 ± 36.2 and 6.1 ± 8.3 g m^{-2}, and those for surface litter were 7.8 ± 4.8 and 0.7 ± 0.5 g m^{-2}. The belowground biomass of live roots to a depth of 40 cm was 82.5 ± 14.7 and 27.7 ± 23.8 g m^{-2} in the exclosure and at the continuous grazing site, respectively, whereas litter incorporated into the soil totaled 165.2 ± 90.6 and 37.1 ± 22.1 g m^{-2}, respectively.

Soil sampling

Soil samples were collected from six random locations at each site to a depth of 100 cm. A soil profile (150 cm in width and 150 cm in depth) was also excavated at each location. Soil samples were collected from five depths: 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, and 60–100 cm. In each layer, a composite sample was prepared from soil collected at five sampling points using a knife made from bamboo to prevent contamination of the samples with metal from a metal sampler. Triplicate soil cores were also taken from each layer with a stainless-steel cylinder (100 cm^3 in volume) for the determination of soil bulk density.

Laboratory analyses

Prior to analysis, soil samples were air-dried and hand-sieved through a 2-mm nylon mesh to remove roots and other debris. Soil physical and chemical properties, including the soil particle size distribution, bulk density, organic C, inorganic C (carbonate), total N, electrical conductivity (EC), total mineral elements (SiO_2, Al_2O_3, K_2O, Na_2O, Fe_2O_3, CaO, MgO, TiO_2, P_2O_5, and MnO), microelements (total Fe, Mn, Zn, B, Cu, and Mo), and heavy metals (Pb, Cr, Ni, As, Hg, Cd, and Se) were measured to a depth of 100 cm, whereas soil pH, available nutrients (N, P, and K), and available microelements (Fe, Cu, Mn, Mo, Zn, and S) were only measured in the surface soil (0–10 and 10–20 cm).

The particle size distribution was determined using the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent (ISSCAS 1978). Soil pH was determined in a 1:2.5 (w/w) and EC in a 1:5 (w/w) soil:water suspension at 25°C (Multiline F/SET-3; WTW, Weilheim, Germany). Soil organic C was determined using the Walkley–Black dichromate oxidation procedure (Nelson and Sommers 1982), and the inorganic C (carbonate) content was determined using the volumetric method (ISO 1994). Total N was determined with the Kjeldahl procedure (McGill and Figueiredo 1993).

Available P was determined using the Olsen method (Olsen et al. 1954). Available N was determined by the alkaline diffusion method, and available K was extracted with 1 M ammonium acetate and measured by means of atomic absorption spectroscopy (ISSCAS 1978). Total concentrations of soil mineral elements were determined by means of inductively coupled plasma atomic-emission spectroscopy (ICP-AES), using lithium metaborate as a fused salt. Exchangeable cation concentrations (K^+, Na^+) and total cation exchange capacity (CEC) were determined by washing the soil with sodium acetate and then ammonium acetate, as outlined by Hesse (1972).

Microelement concentrations were determined as follows: B, by curcuma colorimetry following Na_2CO_3 fusion; Mo, by inductively coupled plasma mass spectrometry (ICP-MS) following $HF–HClO_4–HNO_3$ digestion; and Zn, Mn, Fe, and Cu by ICP-AES following $HF–HClO_4–HNO_3$ digestion. The heavy metal concentrations were determined as follows: Se and As, by means of aqua regia (1:1) digestion combined with hydride-generation atomic-fluorescence spectrometry (HG-AFS); Hg, by aqua regia (1:1) digestion combined with cold-atom fluorescence; Cd, by $HCl–HNO_3–HF–HClO_4–H_2SO_4$ digestion combined with graphite-furnace atomic-absorption spectrophotometry; Pb, by $HCl–HNO_3–HF–HClO_4–H_2SO_4$ digestion combined with ICP-AES; and Cr and Ni, by $HCl–HNO_3–HF–HClO_4–H_2SO_4$ digestion combined with ICP. The available microelement concentrations were determined as follows: available Fe, Cu, and Mn by means of diethylenetriamine pentaacetic acid (DTPA) extraction combined with ICP; available Mo by oxalic acid and ammonium oxalate extraction combined with polarography; and available Zn and S by DTPA extraction combined with atomic absorption.

Data analysis

All data were analyzed using version 13.5 of the SPSS software (SPSS, Chicago, IL, USA). We used independent-sample *t* tests to identify significant differences between the treatments. Correlations between parameters were calculated using Pearson's correlation coefficient.

Results

Soil particle size distribution and bulk density

The soil particle size distribution (Fig. 2) revealed that the exclosure had higher silt + clay (<0.05 mm) and fine sand (0.1–0.05 mm) contents and lower coarse sand contents at all depths than at the continuous grazing site. The differences were significant ($p < 0.05$) for the coarse sand (2–0.1 mm) and silt + clay contents to a depth of 10 cm, and for fine sand at depths of 0–10 and 10–20 cm. The mean coarse sand content to a depth of 100 cm was 8.7% lower in the exclosure, whereas the mean fine sand and silt + clay contents to this depth were 287 and 105% higher, respectively. The bulk density (Fig. 3) was lower at

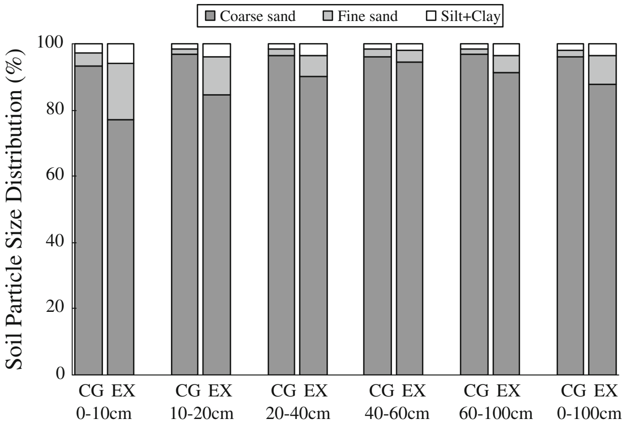

Fig. 2 Soil particle size distribution to a depth of 100 cm at the two sites. *EX* grazing exclosure, *CG* continuous grazing

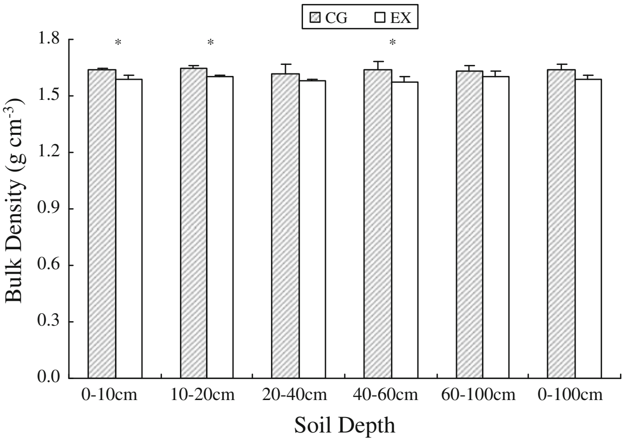

Fig. 3 Soil bulk density to a depth of 100 cm at the two sites. *EX* grazing exclosure, *CG* continuous grazing. *Asterisk* indicates significant difference between EX and CG at $p < 0.05$ level

all five depths in the exclosure, by 1.8–4.3%. The difference was significant at depths of 0–10, 10–20, and 40–60 cm. However, the mean value for all depths combined for the coarse sand and silt + clay contents and bulk density did not differ significantly between the exclosure and the continuous grazing site.

Soil organic C, inorganic C (carbonate), total N, and electrical conductivity

There were significant ($p < 0.05$) differences in soil organic carbon (SOC) content at depths of 0–10, 10–20, and 20–40 cm, whereas total N only differed significantly to a depth of 10 cm (Table 1). The greatest differences in SOC and total N content were observed to a depth of 10 cm, 157 and 92%, respectively, with both higher in the exclosure. Mean SOC and total N contents to a depth of 100 cm increased by 72.6 and 24.7%, respectively, compared with the continuous grazing site. The exclosure soil had a higher C:N ratio (ranging from 5.3 to 7.1) than at the continuous grazing site (ranging from 4.1 to 5.3) at all depths. The highest C:N ratio occurred to a depth of 10 cm at both sites. Mean soil inorganic C (SIC) was 28.6% higher in the exclosure, but only differed significantly between the two sites to a depth of 10 cm. Inorganic C accounted for a small proportion of total soil C: 11.0% at the continuous grazing site and 8.5% in the exclosure. Electrical conductivity exhibited differences similar to those of the SOC and SIC contents, with higher EC at each depth in the exclosure.

Available nutrients, pH, exchangeable cations, and cation exchange capacity

The pH values were lower in the exclosure at both depths, but available N, P, and K were higher at both depths in the exclosure (Fig. 4); however, the difference was only significant for exchangeable K to a depth of 10 cm. In the exclosure, the mean value to a depth of 20 cm was 2.7% higher for available N, 22.5% higher for available P, and 17.3% higher for available K, but pH was 1.0% lower. The

Table 1 Soil organic C, inorganic C, total N, and EC to a depth of 100 cm at the two sites

	Depth (cm)					
	0–10	10–20	20–40	40–60	60–100	Mean
Organic C (g kg^{-1})						
CG	0.405 ± 0.084	0.367 ± 0.080	0.292 ± 0.046	0.337 ± 0.082	0.294 ± 0.085	0.339 ± 0.028
EX	1.040 ± 0.302	0.651 ± 0.117	0.492 ± 0.099	0.372 ± 0.042	0.371 ± 0.039	0.585 ± 0.064
t test	$p = 0.025$	$p = 0.025$	$p = 0.034$	$p = 0.543$	$p = 0.226$	$p = 0.004$
Total N (g kg^{-1})						
CG	0.076 ± 0.002	0.075 ± 0.012	0.071 ± 0.008	0.075 ± 0.002	0.070 ± 0.011	0.073 ± 0.006
EX	0.146 ± 0.040	0.091 ± 0.014	0.082 ± 0.001	0.070 ± 0.007	0.067 ± 0.004	0.091 ± 0.012
t test	$p = 0.038$	$p = 0.218$	$p = 0.119$	$p = 0.296$	$p = 0.753$	$p = 0.085$
Inorganic C ($CaCO_3$, g kg^{-1})						
CG	0.039 ± 0.009	0.043 ± 0.014	0.046 ± 0.009	0.042 ± 0.015	0.041 ± 0.006	0.042 ± 0.008
EX	0.071 ± 0.008	0.057 ± 0.008	0.055 ± 0.018	0.043 ± 0.021	0.044 ± 0.007	0.054 ± 0.010
t test	$p = 0.009$	$p = 0.204$	$p = 0.492$	$p = 0.943$	$p = 0.628$	$p = 0.194$
EC (μS cm^{-1})						
CG	13.33 ± 2.52	13.00 ± 3.46	13.33 ± 3.51	12.33 ± 2.52	12.00 ± 1.73	12.80 ± 2.03
EX	36.00 ± 3.61	25.67 ± 9.61	16.67 ± 3.21	17.67 ± 2.52	16.33 ± 2.52	22.47 ± 2.19
t test	$p = 0.001$	$p = 0.098$	$p = 0.292$	$p = 0.060$	$p = 0.070$	$p = 0.005$

Values represent means ± SD

EX grazing exclosure, *CG* continuous grazing

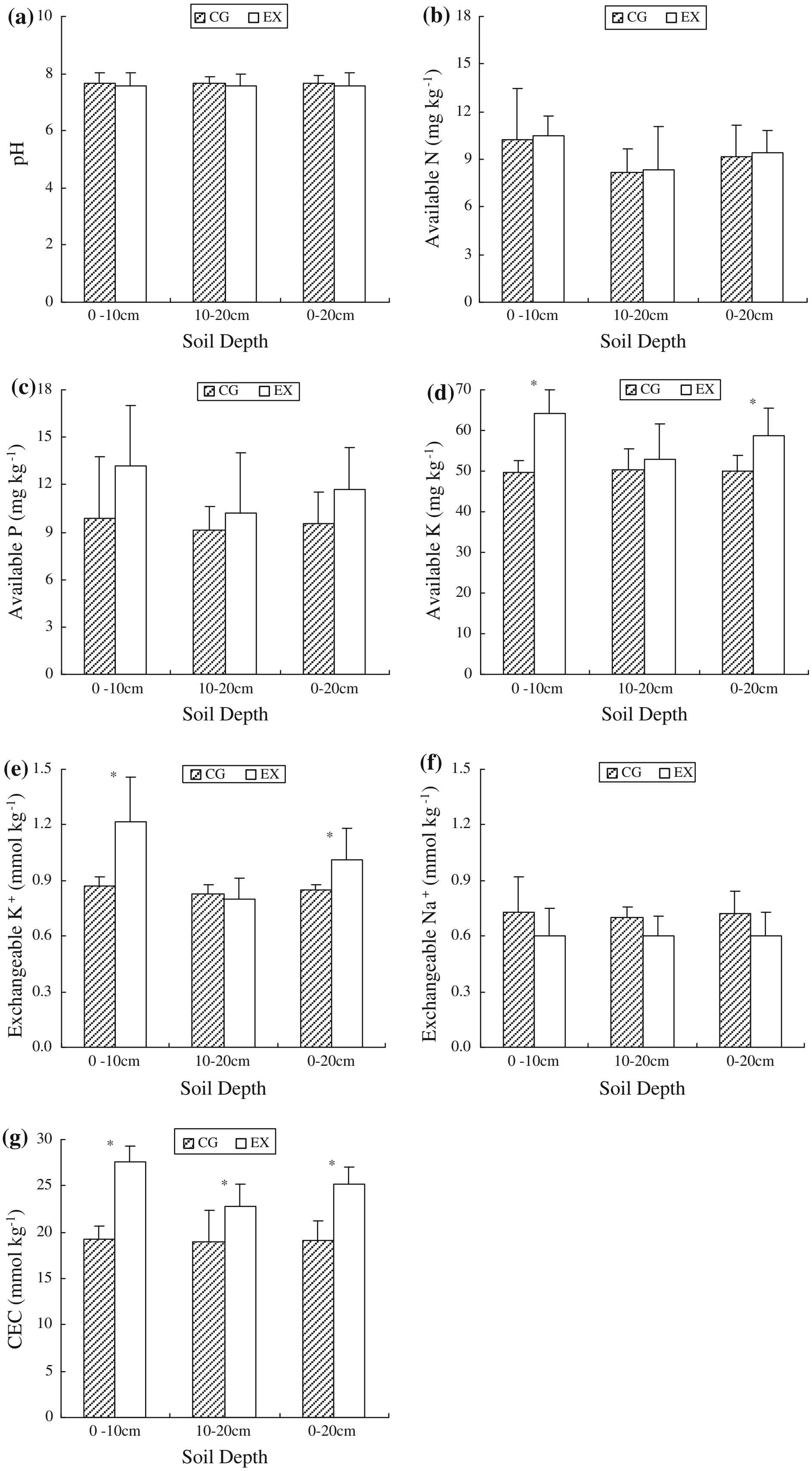

Fig. 4 Available nutrients, pH, exchangeable cations, and CEC to a depth of 20 cm at the two sites. **a** pH, **b** available N, **c** available P, **d** available K, **e** exchangeable K^+, **f** exchangeable Na^+, **g** CEC. *EX* grazing exclosure, *CG* continuous grazing. *Asterisk* indicates significant difference between EX and CG at $p < 0.05$ level

available nutrient ratio for N:P:K was about 1:1:5 in the top 20 cm at the continuous grazing site, versus about 1:1:6 in the exclosure. However, except for a significant ($p = 0.001$) difference in available K to a depth of 10 cm, there were no statistically significant differences between the sites. The mean K^+ content and CEC were significantly higher (by 18.8 and 31.5%), whereas mean Na^+ was lower (by 16.7%, but not significantly) in the exclosure.

Total concentrations of mineral elements

The two sites did not differ significantly in total mineral contents (Table 2), but the SiO_2 content was lower at each depth in the exclosure and the Fe_2O_3, MnO, TiO_2, Al_2O_3, CaO, MgO, and K_2O were higher at each depth in the exclosure. The Na_2O content was lower at 20–40 and 40–60 cm in the exclosure, whereas the P_2O_5 content was almost equal at all depths. The mean SiO_2 value was 2.5% lower in the exclosure, but was higher by 17.0% for Al_2O_3, 6.5% for K_2O, 6.8% for Na_2O, 36.3% for Fe_2O_3, 79.3% for CaO, 86.5% for MgO, 93.4% for TiO_2, and 25.0% for MnO. The mean contents of the elements at both sites declined in the following sequence: $SiO_2 > Al_2O_3 > K_2O > Na_2O > Fe_2O_3 > CaO > MgO > TiO_2 > MnO \geq P_2O_5$. The ratios of the elements along this sequence were 4,305:353:145:64:40:30:10:9:1:1 in the exclosure and 4,414:302:136:60:29:17:6:5:1:1 at the continuous grazing site.

Microelements and heavy metals

The differences in microelement contents between the two sites (Table 3) were similar to those in total mineral element contents. Apart from a lower Mn content at a depth of 60–100 cm and a lower Cu content at depths of 20–40, 40–60, and 60–100 cm, the microelement contents were higher in the exclosure. However, the mean contents of all microelements to a depth of 100 cm were higher in the exclosure. The difference was only significant for B and Zn. The order of the microelement contents at both sites was Fe > Mn > Zn > B > Cu > Mo. The mean Fe content was 23, 266, 468, 1,150 and 18,317 times the values for Mn, Zn, B, Cu, and Mo in the exclosure, respectively, versus 23, 265, 594, 959 and 18,611 times at the continuous grazing site.

Heavy metal contents (Table 4) were lower in the exclosure for Cr and Ni at a depth of 40–60 cm, but all other values were higher in the exclosure. Only the Pb, Hg, and Cd contents to a depth of 10 cm and the Cd content at a depth of 10–20 cm differed significantly between the two sites. The mean contents to a depth of 100 cm depth were 17.4, 20.0, 31.8, 22.7, 93.2, 61.7, and 62.3% higher for Pb, Cr, Ni, As, Hg, Cd, and Se in the exclosure than at the continuous grazing site, respectively. In the exclosure, the order of the element contents was Pb > Cr > Ni > As > Hg > Cd > Se. However, at the continuous grazing site, the order was Pb > Cr > Ni > As > Cd > Se > Hg.

Available microelements

Statistical analyses of the data on available microelements in the top 20 cm of the soil (Fig. 5) revealed that only the available Zn content at a depth of 10–20 cm differed significantly between the two sites. The available S content at both depths, Mo content to a depth of 10 cm, and Zn at a depth of 10–20 cm decreased in the exclosure, but others increased. The mean available S, Zn, and Mo were 15.7, 7.6, and 1.3% lower, respectively, in the exclosure, whereas the mean available Fe, Mn, and Cu were 2.7, 19.1, and 13.3% higher in the exclosure, respectively. In the exclosure, available Fe had the highest content, followed by available S, but the reverse occurred at the continuous grazing site. The sequence for the other elements was available Mn > available Cu > available Zn > available Mo at both sites.

Discussion

Effects of grazing exclusion on soil properties in desertified sandy land

Heavy grazing is a primary contributor to grassland desertification in arid and semiarid regions, and causes degradation of soil physical, chemical, and biological properties by reducing plant cover and exposing the soil to erosion by wind (Zhao et al. 2006; Pei et al. 2008). It is generally assumed that exclosures lead to the restoration of natural characteristics such as soil fertility, vegetation biomass, and vegetation species composition, as well as soil fauna numbers and diversity and water storage (Mekuria et al. 2007). Grazing exclusion is likely to increase CO_2 uptake by plants where heavy grazing has reduced plant cover or impaired soil fertility (Oesterheld et al. 1999). Soil organic carbon (SOC) increases, thereby improving soil quality by improving its water-holding capacity, fertility, and biodiversity, and this has a stabilizing effect on soil structure that can prevent erosion (Nosetto et al. 2006). The potential of grazing lands to sequester carbon has been investigated in various terrestrial environments, but the results are often inconclusive (Shrestha and Stahl 2008). Numerous studies have indicated that grazing exclosure in degraded land has a high potential to restore soil fertility, sequester soil organic carbon, improve biological activity, and reduce erosion (Hiernaux et al. 1999; Su et al. 2005; Mekuria et al. 2007; Pei et al. 2008; Steffens et al. 2008). But some contrasting

Table 2 Total concentrations (% of dry weight) of mineral elements to a depth of 100 cm at the two sites

	Depth (cm)					
	0–10	10–20	20–40	40–60	60–100	Mean
SiO_2 (%)						
CG	88.30 ± 0.35	88.03 ± 0.26	88.17 ± 0.18	88.34 ± 0.34	88.51 ± 0.61	88.27 ± 0.14
EX	84.70 ± 4.79	85.45 ± 5.22	86.71 ± 3.13	87.31 ± 2.61	86.33 ± 2.93	86.10 ± 3.71
t test	$p = 0.252$	$p = 0.492$	$p = 0.516$	$p = 0.579$	$p = 0.316$	$p = 0.418$
Al_2O_3 (%)						
CG	6.008 ± 0.383	6.063 ± 0.227	6.057 ± 0.189	6.063 ± 0.284	5.963 ± 0.330	6.031 ± 0.244
EX	7.460 ± 2.272	7.212 ± 2.798	6.869 ± 1.750	6.698 ± 1.558	7.049 ± 2.081	7.058 ± 2.080
t test	$p = 0.379$	$p = 0.573$	$p = 0.517$	$p = 0.569$	$p = 0.467$	$p = 0.491$
K_2O (%)						
CG	2.718 ± 0.079	2.707 ± 0.113	2.762 ± 0.123	2.763 ± 0.095	2.680 ± 0.078	2.726 ± 0.060
EX	2.907 ± 0.256	2.820 ± 0.250	3.027 ± 0.374	2.870 ± 0.225	2.887 ± 0.226	2.902 ± 0.256
t test	$p = 0.325$	$p = 0.536$	$p = 0.306$	$p = 0.497$	$p = 0.203$	$p = 0.352$
Na_2O (%)						
CG	1.199 ± 0.114	1.200 ± 0.032	1.195 ± 0.066	1.196 ± 0.108	1.196 ± 0.020	1.197 ± 0.064
EX	1.300 ± 0.200	1.742 ± 1.003	1.106 ± 0.181	1.036 ± 0.292	1.206 ± 0.075	1.278 ± 0.082
t test	$p = 0.495$	$p = 0.455$	$p = 0.460$	$p = 0.420$	$p = 0.848$	$p = 0.251$
Fe_2O_3 (%)						
CG	0.543 ± 0.117	0.534 ± 0.084	0.577 ± 0.140	0.537 ± 0.132	0.718 ± 0.494	0.582 ± 0.156
EX	0.903 ± 0.556	0.899 ± 0.677	0.684 ± 0.259	0.660 ± 0.234	0.821 ± 0.562	0.793 ± 0.457
t test	$p = 0.326$	$p = 0.459$	$p = 0.582$	$p = 0.476$	$p = 0.814$	$p = 0.512$
CaO (%)						
CG	0.339 ± 0.014	0.352 ± 0.029	0.339 ± 0.020	0.328 ± 0.035	0.332 ± 0.009	0.338 ± 0.020
EX	0.788 ± 0.740	0.624 ± 0.577	0.552 ± 0.406	0.598 ± 0.521	0.468 ± 0.296	0.606 ± 0.508
t test	$p = 0.395$	$p = 0.541$	$p = 0.474$	$p = 0.484$	$p = 0.539$	$p = 0.473$
MgO (%)						
CG	0.117 ± 0.017	0.114 ± 0.010	0.110 ± 0.024	0.110 ± 0.024	0.103 ± 0.028	0.111 ± 0.019
EX	0.271 ± 0.174	0.236 ± 0.194	0.180 ± 0.079	0.166 ± 0.081	0.183 ± 0.094	0.207 ± 0.124
t test	$p = 0.220$	$p = 0.374$	$p = 0.191$	$p = 0.300$	$p = 0.202$	$p = 0.271$
TiO_2 (%)						
CG	0.088 ± 0.008	0.098 ± 0.012	0.089 ± 0.012	0.087 ± 0.017	0.089 ± 0.005	0.091 ± 0.010
EX	0.204 ± 0.172	0.216 ± 0.246	0.126 ± 0.073	0.124 ± 0.074	0.212 ± 0.241	0.176 ± 0.161
t test	$p = 0.351$	$p = 0.549$	$p = 0.496$	$p = 0.466$	$p = 0.506$	$p = 0.428$
P_2O_5 (%)						
CG	0.020 ± 0.002	0.019 ± 0.001	0.019 ± 0.001	0.020 ± 0.001	0.021 ± 0.004	0.020 ± 0.002
EX	0.022 ± 0.004	0.019 ± 0.001	0.019 ± 0.002	0.019 ± 0.002	0.020 ± 0.002	0.020 ± 0.002
t test	$p = 0.433$	$p = 0.989$	$p = 0.970$	$p = 0.710$	$p = 0.659$	$p = 0.979$
MnO (%)						
CG	0.019 ± 0.002	0.021 ± 0.003	0.019 ± 0.001	0.019 ± 0.002	0.020 ± 0.001	0.020 ± 0.002
EX	0.024 ± 0.008	0.026 ± 0.014	0.023 ± 0.008	0.021 ± 0.004	0.029 ± 0.018	0.025 ± 0.010
t test	$p = 0.431$	$p = 0.671$	$p = 0.530$	$p = 0.561$	$p = 0.481$	$p = 0.533$

EX grazing exclosure, *CG* continuous grazing

results contains that grazed soils have shown increases in carbon storage (Schuman et al. 1999; Weinhold et al. 2001; Reeder et al. 2004) or no change (Milchunas and Lauenroth 1993; McIntosh et al. 1997; Nosetto et al. 2006) compared with adjacent ungrazed soils.

In the present study, soil physical and chemical properties generally improved after 8 years of grazing exclosure. The improvements can be mainly ascribed to vegetation recovery and litter accumulation compared with a site subjected to continuous grazing (Su et al. 2005). In

Table 3 Microelement contents to a depth of 100 cm at the two sites

	Depth (cm)					
	0–10	10–20	20–40	40–60	60–100	Mean
Total Fe (mg kg^{-1})						
CG	3,831 ± 847	4,240 ± 1,347	4,281 ± 1,190	4,155 ± 1,064	5,267 ± 3,370	4,355 ± 1,204
EX	6,317 ± 3,890	6,287 ± 4,736	4,782 ± 1,810	4,615 ± 1,637	5,747 ± 3,930	5,550 ± 3,194
t test	$p = 0.034$	$p = 0.041$	$p = 0.709$	$p = 0.704$	$p = 0.880$	$p = 0.577$
Total Mn (mg kg^{-1})						
CG	184.9 ± 63.7	200.5 ± 108.1	180.7 ± 65.3	158.8 ± 30.2	224.6 ± 141.0	189.9 ± 81.2
EX	263.8 ± 203.7	288.4 ± 109.1	195.3 ± 45.6	228.6 ± 87.9	220.0 ± 158.3	239.2 ± 116.8
t test	$p = 0.037$	$p = 0.035$	$p = 0.767$	$p = 0.263$	$p = 0.972$	$p = 0.581$
Total Zn (mg kg^{-1})						
CG	20.94 ± 6.56	17.26 ± 1.69	14.21 ± 0.68	13.61 ± 1.18	16.02 ± 1.89	16.41 ± 1.22
EX	27.65 ± 4.08	21.04 ± 2.75	19.28 ± 3.93	17.30 ± 2.49	19.15 ± 1.90	20.88 ± 2.03
t test	$p = 0.206$	$p = 0.113$	$p = 0.092$	$p = 0.082$	$p = 0.113$	$p = 0.031$
Total B (mg kg^{-1})						
CG	7.57 ± 2.29	9.63 ± 1.58	6.00 ± 0.56	8.47 ± 1.14	4.97 ± 0.55	7.33 ± 0.78
EX	14.92 ± 3.62	12.40 ± 6.24	8.56 ± 6.85	14.46 ± 15.36	9.02 ± 6.87	11.87 ± 9.57
t test	$p = 0.041$	$p = 0.527$	$p = 0.584$	$p = 0.069$	$p = 0.415$	$p = 0.046$
Total Cu (mg kg^{-1})						
CG	5.182 ± 0.739	4.545 ± 1.033	4.321 ± 1.267	3.708 ± 0.948	4.958 ± 1.617	4.543 ± 0.859
EX	6.530 ± 0.210	6.649 ± 3.724	3.915 ± 0.706	3.489 ± 0.621	3.554 ± 0.344	4.827 ± 0.431
t test	$p = 0.038$	$p = 0.399$	$p = 0.653$	$p = 0.754$	$p = 0.215$	$p = 0.635$
Total Mo (mg kg^{-1})						
CG	0.199 ± 0.011	0.226 ± 0.057	0.262 ± 0.107	0.247 ± 0.107	0.238 ± 0.055	0.234 ± 0.057
EX	0.297 ± 0.205	0.272 ± 0.212	0.312 ± 0.220	0.295 ± 0.221	0.342 ± 0.255	0.303 ± 0.054
t test	$p = 0.457$	$p = 0.736$	$p = 0.744$	$p = 0.741$	$p = 0.523$	$p = 0.202$

EX grazing exclosure, *CG* continuous grazing

the grazing exclosure area, the increment of soil properties to a depth of 100 cm was 6.45% for fine sand, 1.92% for silt + clay, 0.246 g kg^{-1} for SOC, 0.018 g kg^{-1} for total nitrogen, 0.012 g kg^{-1} for inorganic C ($CaCO_3$), 9.67 μS cm^{-1} for EC, from 0 to 1.027% for total mineral elements (except SiO_2), 0.069–1,195 mg kg^{-1} for microelements, and 0.026–2.66 mg kg^{-1} for heavy metals; however, the coarse sand, bulk density, and SiO_2 indicated a decrease of 8.35%, 0.05 g cm^{-3}, and 2.17%, respectively. The mean value to a depth of 20 cm showed an increase of 0.25 mg kg^{-1} for available N, 2.14 mg kg^{-1} for available P, 8.63 mg kg^{-1} for available K, 0.16 mmol kg^{-1} for exchangeable K^+, 6.02 mmol kg^{-1} for CEC, 0.075 mg kg^{-1} for available Fe, 0.264 mg kg^{-1} for available Mn, and 0.032 mg kg^{-1} for available Cu, versus decreases of 0.08 for pH, 0.12 mmol kg^{-1} for exchangeable Na^+, 0.532 mg kg^{-1} for available S, 0.015 mg kg^{-1} for available Zn, and 0.001 mg kg^{-1} for available Mo.

Although heavy metal contents increased as a result of grazing exclusion, the changes were not statistically significant and the final levels were low enough that they do not represent a threat; instead, they appear to represent a more general trend of mobilization of chemical elements. Our results agree with previous research in which exclosure enhanced SOC and total N accumulation, and decreased pH and bulk density (Pei et al. 2008). The increased C:N ratio in the exclosure indicated that the exclusion of livestock grazing had stronger effects on organic C than on total N. Although grazing exclusion improved soil properties, the difference was only significant for the mean contents of fine sand, organic C, EC, total Zn, total B, available K, exchangeable K^+, and CEC, which represents a small proportion of the many parameters measured in this study. One possible reason is that the sandy grassland was severely degraded prior to construction of the exclosure. The degradation caused by grazing is easier to reverse during the initial stages of degradation, but much slower after severe degradation has occurred (Su et al. 2005).

Interrelations among the soil properties in sandy land

Soil is a material with multiple physical, chemical, and biological properties, and there are many relationships and

Table 4 Heavy metal contents to a depth of 100 cm at the two sites

	Depth (cm)					
	0–10	10–20	20–40	40–60	60–100	Mean
Pb (mg kg^{-1})						
CG	12.17 ± 0.32	14.13 ± 1.88	13.36 ± 2.45	11.39 ± 1.06	12.10 ± 0.86	12.63 ± 0.83
EX	15.68 ± 1.21	16.08 ± 4.68	15.06 ± 3.40	15.59 ± 5.44	14.06 ± 2.28	15.29 ± 3.36
t test	$p = 0.008$	$p = 0.539$	$p = 0.520$	$p = 0.260$	$p = 0.235$	$p = 0.253$
Cr (mg kg^{-1})						
CG	9.21 ± 2.60	11.24 ± 3.78	8.11 ± 1.39	10.00 ± 3.55	7.59 ± 3.84	9.23 ± 2.74
EX	13.36 ± 4.54	14.93 ± 3.91	9.20 ± 8.26	9.79 ± 7.02	10.44 ± 4.55	11.54 ± 3.84
t test	$p = 0.242$	$p = 0.305$	$p = 0.842$	$p = 0.965$	$p = 0.454$	$p = 0.444$
Ni (mg kg^{-1})						
CG	2.887 ± 0.715	3.248 ± 1.050	3.004 ± 0.195	2.449 ± 1.431	2.918 ± 0.509	2.901 ± 0.673
EX	6.484 ± 2.669	5.728 ± 3.398	3.481 ± 1.335	1.979 ± 2.036	3.588 ± 1.536	4.252 ± 1.053
t test	$p = 0.087$	$p = 0.294$	$p = 0.573$	$p = 0.760$	$p = 0.513$	$p = 0.135$
As (mg kg^{-1})						
CG	1.924 ± 1.032	2.111 ± 0.908	2.067 ± 0.962	2.032 ± 0.964	2.018 ± 1.063	2.030 ± 0.985
EX	3.376 ± 0.026	2.341 ± 1.101	2.457 ± 0.328	2.759 ± 0.344	2.201 ± 0.606	2.627 ± 0.462
t test	$p = 0.072$	$p = 0.794$	$p = 0.543$	$p = 0.286$	$p = 0.807$	$p = 0.396$
Hg (mg kg^{-1})						
CG	0.009 ± 0.003	0.010 ± 0.004	0.010 ± 0.006	0.010 ± 0.003	0.010 ± 0.005	0.010 ± 0.004
EX	0.292 ± 0.306	0.176 ± 0.204	0.112 ± 0.110	0.080 ± 0.076	0.074 ± 0.069	0.147 ± 0.152
t test	$p = 0.039$	$p = 0.171$	$p = 0.160$	$p = 0.153$	$p = 0.162$	$p = 0.152$
Cd (mg kg^{-1})						
CG	0.039 ± 0.009	0.036 ± 0.005	0.031 ± 0.004	0.031 ± 0.004	0.035 ± 0.004	0.034 ± 0.003
EX	0.125 ± 0.021	0.078 ± 0.021	0.110 ± 0.104	0.069 ± 0.025	0.067 ± 0.033	0.090 ± 0.038
t test	$p = 0.003$	$p = 0.026$	$p = 0.260$	$p = 0.061$	$p = 0.236$	$p = 0.067$
Se (mg kg^{-1})						
CG	0.016 ± 0.011	0.015 ± 0.010	0.018 ± 0.014	0.014 ± 0.004	0.014 ± 0.006	0.015 ± 0.009
EX	0.046 ± 0.025	0.038 ± 0.021	0.039 ± 0.021	0.042 ± 0.024	0.039 ± 0.020	0.041 ± 0.022
t test	$p = 0.128$	$p = 0.165$	$p = 0.231$	$p = 0.179$	$p = 0.103$	$p = 0.140$

EX grazing exclosure, *CG* continuous grazing

interactions among these properties (Zhao et al. 2006). In the present research, we analyzed the correlations among the parameters that we measured to a depth of 100 cm. Of these parameters, the SiO_2 content was significantly negatively correlated with 25 parameters, and coarse sand was significantly negatively correlated with 23 parameters (Table 5), whereas the TiO_2, inorganic C ($CaCO_3$), Hg, fine sand, EC, CaO, SOC, MgO, and Al_2O_3 values were significantly positively correlated with 20–24 parameters, and total N, As, Silt + Clay, Fe_2O_3, total Se, Cd, Cr, and Ni were positively correlated with 15–19 parameters.

Soil organic matter content is a particularly important soil quality attribute, since it has far-reaching effects on soil physical, chemical, and biological properties (Laik et al. 2009). In the present study, grazing exclusion increased SOC, which was significantly positively correlated with a large proportion of the other physical and chemical parameters. These results agree with previous observations that there were significant positive correlations among the fine particle content, organic C, and total N in the Horqin sandy land (Su and Zhao 2003; Li et al. 2004; Zhao et al. 2006).

The relationships between soil properties and depth

Carbon accumulation patterns in soil have been found to differ among depths, and grazing exclusion tended to influence SOC in the surface soil more than in deeper soil layers (Shrestha and Stahl 2008). In the present study, SOC and 19 other parameters (which accounted for about 65% of all parameters measured to a depth of 100 cm) showed their strongest differences between sites to a depth of

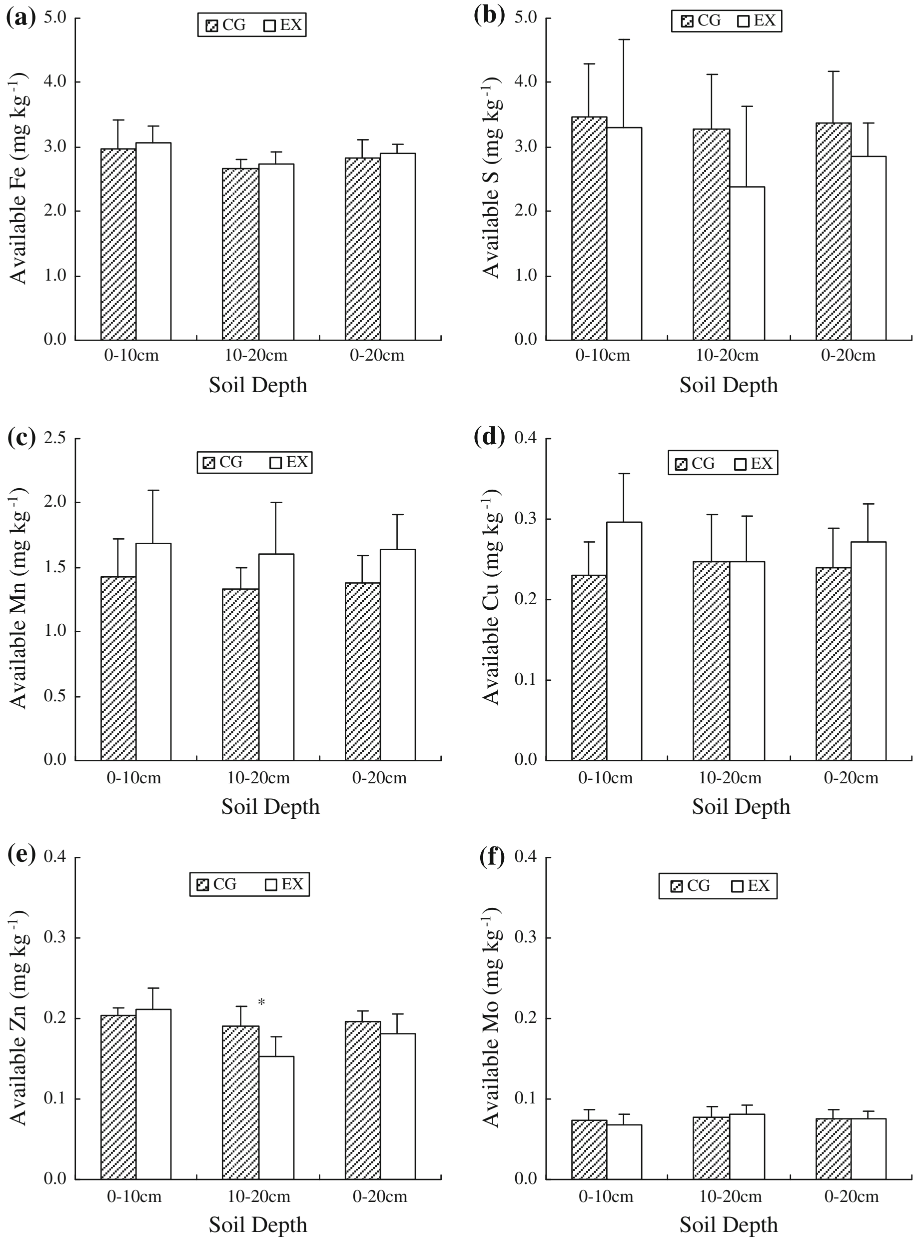

Fig. 5 Available microelement contents to a depth of 20 cm at the two sites. **a** Available Fe, **b** available S, **c** available Mn, **d** available Cu, **e** available Zn, **f** available Mo. *EX* grazing exclosure, *CG* continuous grazing. *Asterisk* indicates significant difference between EX and CG at $p < 0.05$ level

10 cm. The mean SOC, total N, $CaCO_3$–C, and EC values across all five depths increased by 72.6, 24.7, 28.6, and 75.5%, respectively, in the exclosure, versus increases of 156.8, 92.1, 82.1, and 170.1% to a depth of 10 cm. Examination of the correlations between the soil parameters and depth revealed that fine sand, SOC, total N, $CaCO_3$–C, EC, CaO, Cu, and Hg were significantly negatively correlated with soil depth in the exclosure. However, at the continuous grazing site, a significant negative correlation with depth was only observed for MgO. Jobbágy and Jackson (2000) observed that SOC in the top 20 cm of soil of shrublands and grasslands averaged 33 and 42%, respectively, of the total in the first 100 cm. This was attributed to the differences in root distributions and in the above- and belowground biomass allocation patterns (Shrestha and Stahl 2008). In the present study, SOC and N storage to a depth of 100 cm totaled 524 and 118 g m^{-2}, respectively, at the continuous grazing site, versus 779 and 129 g m^{-2} in the exclosure. SOC storage in the top 20 cm of the soil accounted for 24% of the total amount at the continuous grazing site, versus 34% in the exclosure, whereas N storage in this layer accounted for 21 and 29%, respectively, at the continuous grazing site and in the exclosure.

Table 5 Correlations (Pearson's correlation coefficient, r; $n = 10$) between soil properties

	Coarse sand	Fine sand	Silt + Clay	Bulk density	SOC	Total nitrogen	Inorganic C ($CaCO_3$)	EC	SiO_2	Fe_2O_3	MnO	Al_2O_3	TiO_2	CaO	K_2O
Fine sand	−0.99**														
Silt + Clay	−0.97**	0.95**													
Bulk density	0.54	−0.53	−0.54												
SOC	−0.97**	0.98**	0.91**	−0.44											
Total nitrogen	−0.90**	0.91**	0.82**	−0.31	0.97**										
Inorganic C ($CaCO_3$)	−0.93**	0.94**	0.85**	−0.54	0.94**	0.91**									
EC	−0.97**	0.98**	0.89**	−0.55	0.97**	0.92**	0.93**								
SiO_2	0.94**	−0.94**	−0.91**	0.69*	−0.87**	−0.75*	−0.88**	−0.92**							
Fe_2O_3	−0.82**	0.82**	0.78**	−0.61	0.70*	0.58	0.73*	0.79**	−0.88**						
MnO	−0.57	0.55	0.65*	−0.53	0.41	0.24	0.45	0.48	−0.77**	0.77*					
Al_2O_3	−0.88**	0.87**	0.87**	−0.81**	0.78**	0.64*	0.81**	0.85**	−0.98**	0.88**	0.80**				
TiO_2	−0.81**	0.80**	0.81**	−0.61	0.67*	0.52	0.67*	0.77*	−0.93**	0.91**	0.91**	0.93**			
CaO	−0.89**	0.89**	0.82**	−0.82**	0.86**	0.76*	0.86**	0.92**	−0.92**	0.78**	0.54	0.93**	0.76*		
K_2O	−0.55	0.52	0.61	−0.87**	0.46	0.36	0.60	0.49	−0.67*	0.48	0.56	0.77**	0.54	0.71*	
MgO	−0.95**	0.95**	0.91**	−0.72*	0.89**	0.77**	0.89**	0.94**	−0.99**	0.88**	0.71*	0.98**	0.90**	0.96**	0.67*
P_2O_5	−0.59	0.59	0.57	0.03	0.67*	0.77**	0.55	0.59	−0.37	0.44	0.02	0.26	0.24	0.37	−0.02
Na_2O	−0.52	0.54	0.44	0.00	0.44	0.32	0.44	0.49	−0.52	0.58	0.43	0.41	0.58	0.32	−0.08
Total B	−0.68*	0.70*	0.58	−0.65*	0.70*	0.61	0.61	0.78**	−0.73*	0.51	0.37	0.74*	0.62	0.86**	0.48
Total Mo	−0.43	0.41	0.48	−0.83**	0.29	0.20	0.45	0.41	−0.65*	0.62	0.74*	0.77*	0.68*	0.61	0.84**
Total Mn	−0.73*	0.75*	0.62	−0.51	0.67*	0.54	0.64*	0.77**	−0.79**	0.89*	0.59	0.75*	0.79**	0.76*	0.25
Total Zn	−0.91**	0.90**	0.92**	−0.42	0.91**	0.84**	0.77*	0.86**	−0.81**	0.68*	0.50	0.74*	0.68*	0.78**	0.43
Total Cu	−0.71*	0.73*	0.60	0.04	0.74*	0.70*	0.64*	0.70*	−0.54	0.56	0.18	0.38	0.44	0.46	−0.12
Total Fe	−0.79**	0.79**	0.73*	−0.52	0.69*	0.59	0.72*	0.78**	−0.86**	0.99**	0.75*	0.83**	0.89**	0.74*	0.40
Total Se	−0.75*	0.74*	0.75*	−0.94**	0.65*	0.52	0.70*	0.75*	−0.88**	0.77*	0.71*	0.95**	0.82**	0.93**	0.84**
Cd	−0.85**	0.84**	0.85**	−0.80**	0.81**	0.73*	0.87**	0.81**	−0.88**	0.72*	0.57	0.89**	0.69*	0.92**	0.86**
Pb	−0.66*	0.67*	0.58	−0.79**	0.61	0.47	0.69*	0.71*	−0.81**	0.65*	0.60	0.83**	0.70*	0.86**	0.66*
Cr	−0.76*	0.78**	0.67*	−0.29	0.74*	0.63	0.67*	0.78**	−0.80**	0.64*	0.57	0.72*	0.77**	0.68*	0.25
Ni	−0.92**	0.93**	0.86**	−0.29	0.90**	0.84**	0.89**	0.89**	−0.87**	0.80**	0.58	0.75*	0.77**	0.72*	0.32
Hg	−0.97**	0.98**	0.91**	−0.66*	0.95**	0.88**	0.95**	0.98**	−0.95**	0.83**	0.55	0.91**	0.80**	0.96**	0.63
As	−0.79**	0.80**	0.71*	−0.71*	0.83**	0.82**	0.82**	0.87**	−0.78**	0.61	0.31	0.77**	0.57	0.93**	0.63

Table 5 continued

	MgO	P_2O_5	Na_2O	Total B	Total Mo	Total Mn	Total Zn	Total Cu	Total Fe	Total Se	Cd	Pb	Cr	Ni	Hg
P_2O_5	0.38														
Na_2O	0.50	0.09													
Total B	0.78**	0.15	0.24												
Total Mo	0.62	−0.05	−0.04	0.41											
Total Mn	0.80**	0.34	0.68*	0.64*	0.35										
Total Zn	0.83**	0.65*	0.35	0.62	0.26	0.66*									
Total Cu	0.56	0.60	0.76*	0.32	−0.23	0.70*	0.69*								
Total Fe	0.84**	0.46	0.61	0.48	0.58	0.88**	0.63	0.58							
Total Se	0.90**	0.14	0.19	0.77**	0.82**	0.67*	0.66*	0.19	0.69*						
Cd	0.89**	0.39	0.17	0.66*	0.67*	0.59	0.79**	0.35	0.66*	0.89**					
Pb	0.82**	−0.03	0.34	0.78**	0.60	0.75*	0.58	0.33	0.61	0.86**	0.76*				
Cr	0.79**	0.18	0.77**	0.74*	0.21	0.73*	0.64*	0.67*	0.66*	0.55	0.52	0.65*			
Ni	0.85**	0.57	0.71*	0.50	0.28	0.76*	0.81**	0.84**	0.82**	0.55	0.68*	0.59	0.81**		
Hg	0.97**	0.54	0.45	0.76*	0.53	0.76*	0.85**	0.62	0.81**	0.83**	0.90**	0.76*	0.74*	0.88**	
As	0.82**	0.50	0.04	0.83**	0.53	0.59	0.72*	0.35	0.58	0.81**	0.84**	0.73*	0.51	0.60	0.88**

*,** Significant at $p < 0.05$ and $p < 0.01$, respectively

Conclusions

The semiarid Horqin sandy grassland is ecologically fragile, but shows considerable potential to recover when grazing is excluded. Excluding livestock grazing for 8 years increased the mean values of soil organic C, total N, fine sand, silt + clay, $CaCO_3$–C, EC, total mineral contents (Al_2O_3, K_2O, Na_2O, Fe_2O_3, CaO, MgO, TiO_2, and MnO), microelement contents (Fe, Mn, Zn, B, Cu, and Mo), and heavy metal contents (Pb, Cr, Ni, As, Hg, Cd, and Se), and decreased the mean values of coarse sand, bulk density, and SiO_2 to a depth of 100 cm. In the top 20 cm of the soil, excluding livestock grazing improved the available N, P, and K, the exchangeable K^+, CEC, and the available Fe, Mn, and Cu, but decreased pH, exchangeable Na^+, and available S, Zn, and Mo. These results indicate that desertified grassland is recovering after removal of the ongoing livestock disturbance. The results also suggest that this soil restoration is a slow process, and that improvements in the soil properties occur mainly near the surface. From the perspectives of ecological restoration, C sequestration, and nutrient recycling, grazing exclusion can therefore be regarded as a viable option for restoring desertified grassland in the semiarid Horqin sandy grassland. However, more studies will be required to ascertain the time scale of exclusion required to permit full restoration of this fragile ecosystem.

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References

Chinese Soil Taxonomy Cooperative Research Group, Institute of Soil Science, Academic Sinica (1995) Chinese soil taxonomy (revised proposal). Chinese Agricultural Science and Technology Press, Beijing

FAO (1988) FAO/UNESCO soil map of the world. Revised Legend (FAO/UNESCO/ISRIC). World soil resources reports # 60. FAO, Rome

Hesse PR (1972) A textbook of soil chemical analysis. Chemical Publishing Co Inc, New York

Hiernaux P, Bielders CL, Valentin C, Bationo A, Fernández-Rivera S (1999) Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. J Arid Environ 41:231–245

ISO (1994) Soil quality—determination of carbonate content—volumetric method. International Organization for Standardization, Geneva. Standard 10693. p7. Available at http://www.iso.org

ISSCAS-Institute of Soil Sciences, Chinese Academy of Sciences (1978) Physical and chemical analysis methods of soils. Shanghai Science Technology Press, Shanghai, pp 7–59 (in Chinese)

Jobbágy E, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10(2):423–436

Laik R, Kumar K, Das DK, Chaturvedi OP (2009) Labile soil organic matter pools in a calciorthent after 18 years of afforestation by different plantations. Appl Soil Ecol 42:71–78

Li SG, Harazono Y, Oikawa T, Zhao HL, Chang XL (2000) Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. Agric For Meteorol 102:125–137

Li FR, Zhang H, Zhang TH, Shirato Y (2003) Variations of sand transportation rates in sandy grasslands along a desertification gradient in northern China. Catena 53:255–272

Li FR, Zhao LY, Zhang TH (2004) Wind erosion and airborne dust deposition in farmland during spring in the Horqin sandy land of eastern Inner Mongolia, China. Soil Tillage Res 75:121–130

McGill WB, Figueiredo CT (1993) Total nitrogen. In: Carter MR (ed) Soil sampling and methods of analysis. Canadian Society of Soil Science/Lewis Publishers, Boca Raton, pp 201–211

McIntosh PD, Allen RB, Scott N (1997) Effects of exclosure and management on biomass and soil nutrient pools in seasonally dry high country, New Zealand. J Environ Manage 51:169–186

Mekuria W, Veldkamp E, Haile M, Nyssen J, Muys B, Gebrehiwot K (2007) Effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray, Ethiopia. J Arid Environ 69:270–284

Milchunas DG, Lauenroth WK (1993) Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecol Monogr 63(4):327–366

Nelson DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis, Part 2, 2nd edn. Agronomy, Madison, pp 539–577

Nosetto MD, Jobbágy EG, Paruelo JM (2006) Carbon sequestration in semi-arid rangelands: comparison of *Pinus ponderosa* plantations and grazing exclusion in NW Patagonia. J Arid Environ 67:142–156

Oesterheld M, Loreti J, Semmartin M, Paruelo JM (1999) Grazing, fire, and climate effects on primary productivity of grasslands and savannas. In: Walker LR (ed) Ecosystems of disturbed ground. Elsevier, Amsterdam, pp 287–306

Olsen SR, Cole CW, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Dept Agric Circ 939

Pei SF, Fu H, Wan CG (2008) Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner Mongolia, China. Agric Ecosyst Environ 124:33–39

Reeder JD, Schuman GE, Morgan JA, Lecain DR (2004) Response of organic and inorganic carbon and nitrogen to long-term grazing of the shortgrass steppe. Environ Manage 33(4):485–495

Schuman GE, Reeder JD, Manley JT, Hart RH, Manley WA (1999) Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. Ecol Appl 9(1):65–71

Shrestha G, Stahl PD (2008) Carbon accumulation and storage in semi-arid sagebrush steppe: effects of long-term grazing exclusion. Agric Ecosyst Environ 125:173–181

Steffens M, Kölbl A, Totsche KU, Kögel-Knabner I (2008) Grazing effects on soil chemical and physical properties in a semiarid steppe of Inner Mongolia (PR China). Geoderma 143:63–72

Su YZ, Zhao HL (2003) Losses of soil organic carbon and nitrogen and their mechanisms in the desertification process of farmlands in Horqin sandy land. Agric Sci China 2(8):890–897

Su YZ, Zhao HL, Zhang TH (2003) Influences of grazing and exclosure on carbon sequestration in degraded sandy grassland, Inner Mongolia, north China. NZ J Agric Res 46:321–328

Su YZ, Li YL, Cui JY, Zhao WZ (2005) Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. Catena 59:267–278

Weinhold BJ, Hendrickson JR, Karn JF (2001) Pasture management influences on soil properties in the Northern Great Plains. J Soil Water Conserv 56(1):27–31

Zhang TH, Zhao HL, Li SG, Li FR, Shirato Y, Ohkuro T, Taniyama I (2004) A comparison of different measures for stabilizing moving sand dunes in the Horqin Sandy Land of Inner Mongolia, China. J Arid Environ 58:203–214

Zhao HL, Li SG, Zhang TH, Ohkuro T, Zhou RL (2004) Sheep gain and species diversity: in sandy grassland, Inner Mongolia. J Range Manage 57:187–190

Zhao HL, Yi XY, Zhou RL, Zhao XY, Zhang TH, Drake S (2006) Wind erosion and sand accumulation effects on soil properties in Horqin sandy farmland, Inner Mongolia. Catena 65:71–79

Zhu ZD, Chen GT (1994) Sandy desertification in China, status and trends. Science Press, Beijing, p 250 (in Chinese)