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Original Research

Effects of Livestock Exclusion on Soil Physical and Biochemical Properties of a Desert Rangeland

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Abstract

Livestock grazing is recognized as one of the main causes of vegetation and soil degradation and desertification in the arid and semiarid parts of northern China. The effects of grazing on soil enzyme activities, soil properties, and plant characteristics in a typical degraded area of desert steppe in the Alxa region were studied. We set sampling transects for vegetation property evaluation and soil sampling, and compared soil enzyme activities, soil properties, and plant characteristics under continuous year-long livestock grazing (FG), grazing excluded for six years (2002EX), and grazing excluded for 10 years (1998EX). Soil enzyme activities increased significantly with the duration of livestock exclusion. Compared with FG, activities in 1998EX of urease (URE), alkaline phosphatase (AKP), catalase (CAT), and saccharase (SAC) were 214%, 121%, 17%, and 76% higher, respectively. Exclusions also enhanced organic carbon (SOC), total nitrogen (TN) and phosphorus (TP), and inorganic nitrogen (IN) and phosphorus (IP) accumulation, but reduced soil pH and bulk density. Microbial biomass carbon (MBC) and nitrogen (MBN) were ranked 1998EX > 2002EX > FG. Soil enzyme activities were significantly positively correlated with SOC ($p<0.01$), MBC, and MBN ($p<0.01$), but negatively correlated with soil bulk density. While continuous overgrazing in the erosion-prone desert steppe is detrimental to soil and vegetation, this can be reversed and significant increases in soil fertility, cover, and biomass can be achieved by grazing exclusion. Our results also indicate that soil microbial biomass and enzyme activities are sensitive to exclusion, and thus may be important indicators of the soil changes associated with management history.

Keywords: desert rangeland, grazing, soil enzyme activity, soil properties, soil restoration

Introduction

Desertification is a major global environmental issue, and Asia currently has the greatest concentration of areas showing rapid land-cover change, particularly dry land degradation [1]. The total grassland area in China is 3.41×10^6 km^2, which covers approximately 36.08% of the total land area [2]. More than 100 million head of livestock are raised on these lands. Desertification in China has reached 27.3% of the national land area, and it is increasing by 2,460 km^2 per year. Four hundred million people are likely to be affected and the direct economic loss is esti-

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mated at 54 billion Yuan per year [3]. Among the human activities that degrade grasslands, overgrazing by livestock is one of the most significant [4] and is considered destructive to the plant community and soil because of the canopy cover reduction, destruction of topsoil structure, and compaction of soil as a result of heavy browsing and trampling of grazing animals [5]. These processes increase soil crusting, reduce soil water infiltration, and enhance soil erosion susceptibility [6]. The effects of overgrazing on soil quality have been detected in many rangeland ecosystems worldwide [7-10] and have resulted in severe soil erosion and land degradation [11, 12]. To ensure ecological security in environmental degradation in rangeland-based areas, since the 1990s China has pursued lots of ecological projects (including a grassland restoration program) to prevent grassland degradation [13]. But there is little information on soil physical and biochemical properties of desert rangeland affected by exclusion and grazing for a long period.

The Alxa is a severely degraded desert rangeland in northwest China due to heavy grazing that exceeded the local recommended grazing carrying capacity during the several decades [14]. Overgrazing in this region is detrimental to soil and vegetation cover and is often regarded as one of the main causes of desertification [15]. In recent years, studies on the effects of grazing management on vegetation dynamics and soil properties have been conducted in the arid Alxa desert steppe, and grazing suppression has been applied to restore vegetation in degraded desert steppes [16]. However, there is no information about the effect of livestock exclusion on soil microbial biomass and soil enzyme activities in the Alxa area.

Soil microbial communities play important roles in nutrient cycles and rely on materials produced by plants as energy sources for growth and reproduction [17]. They also produce exudates that contribute to the stability of soil micro-aggregates [18], thereby enhancing infiltration of water. Soil enzymes are important soil components that have very important roles [19]. Despite their small quantities, most of the biochemical transformations in soil are dependent on, or related to, the presence of enzymes [20]. Soil enzyme proteins catalyze reactions involved in energy transfer, nutrient cycling, environmental quality, and crop productivity [21]. Since soil enzyme activities may be sensitive to both natural and human-induced disturbances [22], they have been suggested as potential indicators of soil quality [23]. Several studies have indicated that heavy grazing can reduce soil microbial biomass and enzyme activities [18, 24]. Thus, we studied soil physical, chemical, and biological properties in Alxa for a more comprehensive understanding of restoration mechanisms during desertification, and appropriate management and conservation of desertified sandy grassland of this wind erosion-prone region.

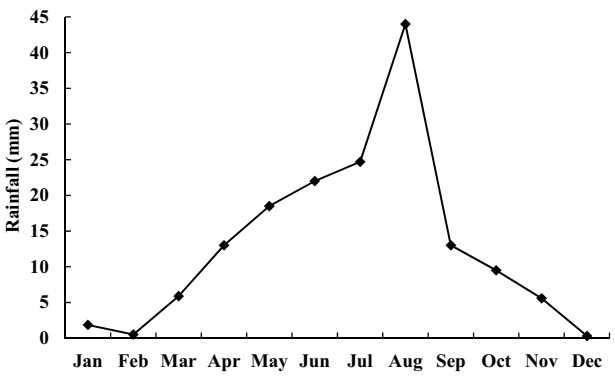

Fig. 1. The average monthly rainfall of the study area in the last 50 years.

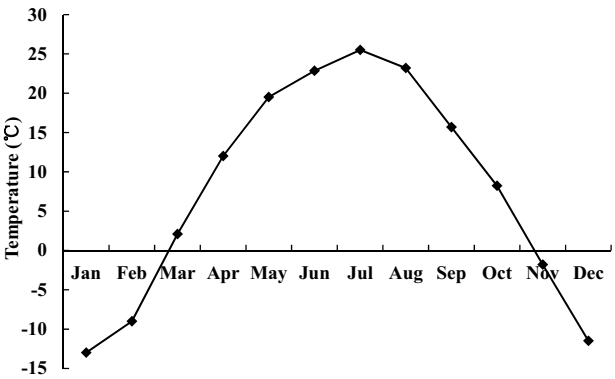

Fig. 2. The average monthly temperature of the study area in the last 50 years.

Materials and Methods

Study Areas

The study was conducted in a desert steppe of the Alxa region (105º35′E, 39º08′N; elevation 1,360 m), Inner Mongolia autonomous region, northwest China. The climate is arid with windy and dry winters and springs, but with warm and comparatively rain-rich summers followed by short and cool autumns. The 50-year mean annual precipitation is 145 mm, with 70% occurring between July and September (Fig. 1). The 50-year mean annual temperature is 7.4ºC with the coldest and warmest monthly means of -11.8ºC in January and 24.7ºC in July (Fig. 2). Mean annual wind velocity ranges from 3.44 to 4.74 $m \cdot s^{-1}$. The zonal soil is classified as a typical calciorthid by the Chinese Soil Classification System [25]. It is characterized by coarse texture and loose structure, which is highly susceptible to wind erosion. The desert vegetation consists of shrubs, grasses, and forbs. Shrub communities are generally dominated by *Zygophyllum xanthoxylum*, but include *Caragana brachypoda*, *Reaumuria soongorica*, and *Ceratoides lateens*. Non-shrub components include the grasses *Setaria viridis*, *Eragrostis poaeoides*, *Cleistogenes songorica*, and *Aristida adscesionis*, and the forbs *Artemisia scoparia*, *Plantago lessingii*, *Bassia dasyphylla*, *Euphorbia humifusa*, *Astragalus membranaceus*, *Chenopodium aristatum*, *Tribulus terrestris*, and *Corispermum elongatum*.

Study Plot

The study plot was a 200 ha open and flat natural desert rangeland with relatively homogeneous sandy soil and vegetation cover. It had been continuously grazed by sheep (one head per ha in average), and was severely degraded. In 1997 a grassland restoration program was initiated and exclosures were gradually established – one in 1998 and the other in 2002 – to prevent grazing by domestic herbivores and to allow the natural vegetation to recover. Initially, the dominant plant species were *Z. xanthoxylum*, *C. microphylla*, and *S. glareosa* and the average vegetation cover was 6.41% [16].

There were three treatments in the experiments:

1) no grazing since 1998 (1998EX),
2) no grazing since 2002 (2002EX),
3) continuous grazing all year long at the average rate of one sheep per ha (FG).

The distance among the three treatments ranges from about 1.2 km to 1.8 km. Three replicated plots were used for each treatment. The plot size was 100 m×100 m to ensure good representation of sampling in desert rangeland [26]. The distances between each plot varied with the land because of flat dune topography of the research areas, but the shortest distance was 15 m.

Vegetation Measurements

In August 2008, two parallel 100 m transects 20 m apart were marked at random in each plot. According to the minimal area method for desert rangeland vegetation investigation [16, 26], a 4×4 m quadrat was used to ensure the accuracy of sampling and statistical requirements. Five quadrats (4×4 m) were set at 20 m intervals along each 100 m sampling transect for evaluating shrub vegetation, and smaller quadrats (1×1 m) were used for a detailed inventory of herbaceous vegetation. Grasses and forbs were identified and counted, and plant height determined in 10 random quadrats (1×1 m) per plot. Aboveground standing biomass was clipped by scissors in each quadrat, the plant material was dried at 60ºC for 48 h, and the dry weight determined. All shrubs were identified in 10 quadrats (4×4 m) per sampling plot. They were counted, heights and crown diameters were measured, the aboveground biomass clipped, and fresh and dry biomass weighed. Six random 50 m line transects were located in each sampling plot to monitor changes in vegetation cover [27].

Determination of Soil Bulk Density and Water Content

In August 2008, soil bulk density was determined by the core method. Ten random soil samples were taken with aluminum cylinders (5.0 cm diam. by 10.0 cm high, 196 cm^3 volume) at depths of 0-10 cm, 10-20 cm, and 20-40 cm in each plot and weighed. Soil water content was determined after oven-drying the sample at 105ºC for 48 h.

Soil Sampling

A further 15 soil samples at depths of 0-10 cm, 10-20 cm, and 20-40 cm were taken at random using a soil auger in each sampling plot. Five of the field moist samples were mixed to obtain three composite samples. All samples were sealed in a plastic bag immediately and kept at 4ºC in cold room.

Determination of Soil Microbial Biomass and Enzyme Activities

After removal of plant material and other debris, the soil samples were air-dried and sieved to pass through a 2 mm screen before analysis for pH (1:1 (w w^{-1}) soil: distilled water), soil microbial biomass, and enzyme activity. Soil microbial biomass was determined from a 15 g oven-dry equivalent and field-moist soil sample (sieved to <5 mm). Soil microbial biomass carbon (MBC) (mg $C \cdot kg^{-1}$ soil) was determined using the fumigation extraction method [28]. Soil microbial biomass nitrogen (MBN) (mg $N \cdot kg^{-1}$ soil) was determined by the sequential extraction method followed by chloroform fumigation [29].

Enzyme activities were assayed using field-moist soil with their appropriate substrate and incubated at their optimal temperature and pH. The result was expressed using the amount of the reacted substrate or released product per gram of soil after incubating for a certain duration. Soil catalase activity (CAT) was measured using the method of Johnson and Temple [30]. Urease activity (URE) was measured according to the methods described by Tabatabai and Bremner [31]. Alkaline phosphatase activity (AKP) was measured using the methods described by Tabatabai [32]. Saccharase activity (SAC) was estimated following the methods described in Zhang et al. [33].

Determination of Soil Chemical Properties

Subsamples were air-dried and finely ground to pass through a 0.5 mm sieve and were analyzed for soil chemical properties. Soil organic carbon (SOC) and total nitrogen (TN) were measured using the $K_2Cr_2O_7$-H_2SO_4 oxidation method of Walkley-Black [34], plus the Kjeldahl procedure [35]. Total soil phosphorus (TP) was determined by the ammonium molybdate ascorbic acid method after digestion with sulfuric acid-hydrogen peroxide [36]. Soil was extracted using 2 $mol \cdot L^{-1}$ KCl for NH_4^+-N and NO_3^--N, and extracts were analyzed colorimetrically by the indophenol blue method for NH_4^+-N [37] and by the vanadium oxidation method for NO_3^--N. Soil samples were extracted using 0.5 $mol \cdot L^{-1}$ $NaHCO_3$ for inorganic phosphorus (IP), and then the IP content was determined by the ammonium molybdate ascorbic acid method as described by Kalra and Maynard [38].

Statistical Analyses

Values from all sampling quadrats within each plot were averaged and expressed as mean±standard error (SE) of mean. One-way analysis of variance (ANOVA) was per-

formed to detect differences between means of the parameters examined at the three treatments (i.e. 1998EX, 2002EX, and FG). The least significant difference (LSD) was used to determine the significance of treatment means and significant differences were evaluated at the 0.05 level. Pearson correlation coefficients were also used to evaluate relationships between the corresponding variables. All statistical analyses were performed using SPSS 19.0 (SPSS Inc., Chicago, IL, USA).

Results and Analysis

Vegetation Measurements

Vegetation characteristics for each plot are summarized in Table 1. Ground cover, plant height, and dry weight were generally greater in the excluded than in the grazed plots.

Compared with the grazed plot (44.4 $g \cdot m^{-2}$), total biomasses in the 2002EX (65.4 $g \cdot m^{-2}$) and 1998EX plots (90.86 $g \cdot m^{-2}$) were 1.47 and 2.04 times greater, respectively, and ground cover by 1.23 and 1.42 times ($p<0.05$). Both herbaceous and shrub heights increased significantly with increased restoration time. Compared with the FG plot, shrub height was 1.63 to 2.32 times higher, and herb height increased by 1.41 to 1.77 times in the 2002EX and 1998EX plots ($p<0.05$), respectively.

Soil Physical Properties

In all three plots, the mean values of bulk density ranged from 1.47 to 1.60 $g \cdot cm^{-3}$, and lower bulk density values were found in the deeper soil layers, and the largest soil water content was in the 10-20 cm layer at all three plots (Table 2). Soil bulk density in 0-10 cm and 10-20 cm layers was highest in the FG plot and lowest in the 1998EX. There were no significant differences in soil bulk density between the two exclusion plots in the three layers, or among the three plots in the 10-20 cm layer ($p>0.05$). Soil water content in each layer was significantly ($p<0.05$) higher in the 1998EX plot than in FG.

Soil Chemical Properties

SOC, TN, IN, and IP decreased with soil depth while soil pH increased (Table 3). TP was highest at the soil surface and lowest in the 10-20 cm layer for all three plots.

SOC content in the topsoil (0-10 cm) ranged from 2.02 to 2.31 $g \cdot kg^{-1}$ – higher than that of other soil layers. SOC was highest in the 1998EX plot and lowest in the FG in each soil layer. It was significantly different between the 1998EX and the other two plots in each layer ($p<0.05$). TN values of the three plots varied between 0.21 $g \cdot kg^{-1}$ and 0.26 $g \cdot kg^{-1}$, and TN content was significantly higher in exclusion plots than in FG in all three layers ($p<0.05$), and there was no significant difference between the two exclusion plots. TP content was significantly higher in exclusion plots (ranged from 0.025 to 0.030 $g \cdot kg^{-1}$) than in FG (ranged from 0.019 to 0.020 $g \cdot kg^{-1}$) in the 10-20 cm and 20-40 cm layers ($p<0.05$), and no significant difference was observed between the two exclusion plots.

IP content increased while pH value decreased with longer exclusion times. IN was highest in the 2002EX and lowest in the FG plots in the 0-10 cm and 10-20 cm layers. There was no significant difference in IN content between the FG and 1998EX plots in other layers except in the surface layer.

Soil Biological Properties

MBC, MBN, AKP, URE, and SAC activity all declined with soil depth at all three plots, but the highest catalase activity was in the middle layer (Table 4).

Table 1. Ground-cover characteristics in three study plots (mean±SE).

Characteristics		Plot		
		1998EX	2002EX	FG
Ground Cover (%)	Herbaceous	42.4±2.9^{a}	40±1.3^{a}	32±0.7^{b}
	Shrub	11.7±0.4^{a}	6.7±0.3^{b}	6.1±0.5^{b}
	Total	54.1±2.5^{a}	46.7±1.1^{b}	38.1±1^{c}
Height (cm)	Herbaceous	7.8±0.5^{a}	6.2±0.2^{b}	4.4±0.3^{c}
	Shrub	35.5±2.4^{a}	24.9±1.1^{b}	15.3±1.2^{c}
Dry Weight ($g \cdot m^{-2}$)	Herbaceous	46.3±3.8^{a}	32.2±0.8^{b}	21.5±3.1^{c}
	Shrub	44.6±3^{a}	33.2±2.8^{b}	22.9±4.1^{b}
	Total	90.9±3.4^{a}	65.4±5.5^{b}	44.4±4.2^{c}

1998EX – study plot with no grazing since 1998,
2002EX – study plot with no grazing since 2002,
FG – study plot with continuous grazing all year long.
Means with different letters within a variable indicate significant differences at $P < 0.05$. Number of replicates: 3.

Table 2. Soil bulk density ($g \cdot cm^{-3}$) and water content ($g \cdot 100\ g^{-1}$) at three study plots (mean±SE).

Depth	Properties	Plot		
		1998EX	2002EX	FG
0-10 cm	Bulk density	1.57±0.02^{b}	1.57±0.04^{b}	1.60±0.05^{a}
	Water content	3.92±0.30^{a}	4.02±0.19^{a}	2.74±0.31^{b}
10-20 cm	Bulk density	1.56±0.02^{a}	1.54±0.04^{a}	1.53±0.04^{a}
	Water content	5.79±0.17^{a}	5.7±0.24^{ab}	5.36±0.19^{b}
20-40 cm	Bulk density	1.47±0.02^{b}	1.48±0.03^{b}	1.52±0.05^{a}
	Water content	3.04±0.14^{a}	3.25±0.29^{a}	2.59±0.29^{b}

1998EX – study plot with no grazing since 1998,
2002EX – study plot with no grazing since 2002,
FG – study plot with continuous grazing all year long.
Means with different letters within a variable indicate significant differences at $p < 0.05$. Number of replicates: 3.

Table 3. Soil chemical properties under different grazing regimes (mean±SE).

Depth	Properties	Plot		
		1998EX	2002EX	FG
0-10 cm	SOC ($g \cdot kg^{-1}$)	2.31±0.12^{a}	2.09±0.08^{b}	2.02±0.15^{c}
	TN ($g \cdot kg^{-1}$)	0.25±0.05^{a}	0.26±0.03^{a}	0.23±0.05^{b}
	IN ($g \cdot kg^{-1}$)	6.31±1.28^{a}	6.7±1.48^{a}	5.74±0.01^{b}
	TP ($g \cdot kg^{-1}$)	0.031±0.004^{a}	0.027±0.005^{a}	0.026±0.002^{a}
	IP ($mg \cdot kg^{-1}$)	7.32±0.41^{a}	6.04±0.37^{b}	5.63±0.5^{c}
	pH (H_2O)	8.25±0.2^{ab}	8.4±0.31^{b}	8.73±0.05^{a}
10-20 cm	SOC ($g \cdot kg^{-1}$)	2.16±0.32^{a}	1.62±0.23^{b}	1.59±0.22^{b}
	TN ($g \cdot kg^{-1}$)	0.24±0.01^{a}	0.26±0.03^{a}	0.21±0.01^{b}
	IN ($g \cdot kg^{-1}$)	5.74±0.01^{b}	6.22±1.17^{a}	5.74±0.02^{b}
	TP ($g \cdot kg^{-1}$)	0.029±0.001^{a}	0.025±0.006^{a}	0.019±0.005^{b}
	IP ($mg \cdot kg^{-1}$)	5.62±0.58^{a}	4.18±0.24^{a}	4±0.3^{b}
	pH (H_2O)	8.27±0.16^{ab}	8.65±0.21^{b}	8.93±0.09^{a}
20-40 cm	SOC ($g \cdot kg^{-1}$)	1.85±0.12^{a}	1.62±0.08^{b}	1.51±0.17^{b}
	TN ($g \cdot kg^{-1}$)	0.24±0.02^{a}	0.25±0.01^{a}	0.21±0.03^{b}
	IN ($g \cdot kg^{-1}$)	4.59±1.57^{a}	3.83±1.48^{a}	3.44±1.28^{a}
	TP ($g \cdot kg^{-1}$)	0.030±0.002^{a}	0.027±0.002^{a}	0.020±0.01^{b}
	IP ($mg \cdot kg^{-1}$)	5.23±1.04^{a}	4.14±0.73^{ab}	3.49±0.01^{b}
	pH (H_2O)	8.45±0.26^{ab}	8.74±0.09^{b}	8.94±0.14^{a}

SOC – soil organic carbon, TN – soil total nitrogen, IN – soil inorganic nitrogen, TP – soil total phosphorus, IP – soil inorganic phosphorus
1998EX – study plot with no grazing since 1998, 2002EX – study plot with no grazing since 2002, and FG – study plot with continuous grazing all year long.
Means with different letters within a variable indicate significant differences at $P < 0.05$. Number of replicates: 3.

Table 4. Soil enzyme activities under different grazing regimes (mean±SE).

Depth	Properties	Plot		
		1998EX	2002EX	FG
0-10 cm	URE	19.18±3.37^{a}	14.75±1.84^{a}	6.25±1.31^{b}
	AKP	50.65±4.43^{a}	38.81±4.67^{a}	27.04±3.13^{b}
	CAT	1.58±0.03^{a}	1.44±0.04^{b}	1.34±0.08^{b}
	SAC	3.9±0.42^{a}	2.61±0.05^{b}	2.29±0.11^{b}
	MBC	70±6.38^{a}	53.86±7.84^{b}	48.58±1.29^{b}
	MBN	27.7±1.92^{a}	19.57±0.68^{b}	13.78±1.72^{c}
10-20 cm	URE	10.29±1.24^{a}	7.61±1.58^{a}	4.01±0.49^{b}
	AKP	21.1±2.01^{a}	11.18±1.27^{b}	9.04±1.23^{b}
	CAT	1.74±0.02^{a}	1.58±0.06^{b}	1.57±0.03^{b}
	SAC	3.31±0.16^{a}	2.34±0.13^{b}	2.06±0.03^{b}
	MBC	39.6±5.6^{b}	34.46±6.32^{a}	33.05±1.33^{a}
	MBN	11.64±0.96^{a}	9.45±2.73^{a}	7.23±1.23^{b}
20-40 cm	URE	7.09±1.81^{a}	4.44±1.64^{a}	1.39±0.23^{b}
	AKP	16.53±1.07^{a}	4.87±0.92^{b}	3.78±0.87^{b}
	CAT	1.58±0.02^{a}	1.38±0.05^{b}	1.29±0.05^{b}
	SAC	1.88±0.11^{a}	1.08±0.16^{b}	0.81±0.04^{b}
	MBC	9.1±2.02^{a}	8.29±1.91^{ab}	7.48±1.89^{b}
	MBN	0.018±0.005^{a}	0.016±0.005^{ab}	0.015±0.006^{b}

URE – urease activity, NH_3-N $\mu g \cdot g^{-1} \cdot 24\ h^{-1}$, AKP – alkaline phosphatase activity, p-nitrophenol $mg \cdot kg^{-1} \cdot h^{-1}$, CAT – catalase activity, 0.1N $KMnO_4$ $ml \cdot g^{-1} \cdot 20\ min^{-1}$, SAC – saccharase activity, glucose mg g^{-1} 24 h^{-1}, MBC – microbial biomass carbon, mg $C \cdot kg^{-1}$ soil, MBN – microbial biomass nitrogen, mg $N \cdot kg^{-1}$ soil.
1998EX – study plot with no grazing since 1998, 2002EX – study plot with no grazing since 2002, and FG – study plot with continuous grazing all year long).
Means with different letters within a variable indicate significant differences at $P < 0.05$. Number of replicates: 3.

All the soil biological properties had similar trends in the three treatments with the highest values in the 1998EX and lowest in the FG. There were significant differences in URE and AKP activities and MBN in the surface soil layer (between 2002EX and FG, $p<0.05$), but no significant differences in other biological properties between the two plots.

Pearson Correlation Coefficient of Soil Properties

There were strong positive correlations ($p<0.01$) between soil microbial biomass (MBN and MBC) and all soil enzyme activities measured except CAT, TN, TP, soil bulk density (BD), and pH (Table 5). All four soil enzyme activities were also significantly positively correlated ($p<0.01$) with SOC, IN, IP, and soil water content. Soil water content was significantly positively correlated ($p<0.01$) with all biochemical properties, except SOC, TN, and TP. BD was negatively correlated with AKP ($p<0.01$), CAT ($p<0.05$), IP ($p<0.01$), and soil water content ($p<0.01$), but not with other biochemical properties. Soil pH was significantly positively correlated with IP ($p<0.01$) and soil bulk density ($p<0.05$), but negatively correlated with SOC content ($p<0.05$).

Discussion

Livestock grazing (especially overgrazing) in erosion-prone sandy grassland is detrimental to vegetation [16]. Our results indicate that continuous grazing significantly reduced vegetation cover, plant height, and biomass, which is consistent with the results of other studies in the rangeland of northern China [39-41]. In general, grazing leads to

Table 5. Correlation coefficient (r value) between soil enzyme activities, and soil physical and chemical properties.

Variable	URE	AKP	CAT	SAC	SOC	TN	IN	MBC	MBN	TP	IP	SW	BD	pH
URE	1.00													
AKP	0.82**	1.00												
CAT	0.66**	0.82**	1.00											
SAC	0.85**	0.85**	0.65**	1.00										
SOC	0.63**	0.50**	0.37**	0.57**	1.00									
TN	0.28	0.23	0.13	0.28	0.16	1.00								
IN	0.56**	0.56**	0.45**	0.65**	0.31*	0.03	1.00							
MBC	0.79**	0.68**	0.39*	0.74**	0.71**	0.22	0.51**	1.00						
MBN	0.77**	0.59**	0.30	0.69**	0.74**	0.17	0.46**	0.96**	1.00					
TP	0.31	0.30	0.20	0.23	0.19	-0.03	-0.06	0.23	0.22	1.00				
IP	0.54**	0.69**	0.47**	0.54**	0.11	-0.20	0.44**	0.49**	0.44**	0.10	1.00			
SM	0.58**	0.66**	0.50**	0.66**	0.25	0.16	0.57**	0.78**	0.70**	0.06	0.73**	1.00		
BD	-0.20	-0.42**	-0.37*	-0.26	-0.18	-0.01	-0.28	-0.26	-0.13	-0.02	-0.64**	-0.71**	1.00	
pH	-0.10	-0.28	-0.29	-0.01	-0.36*	-0.22	-0.14	-0.17	-0.16	0.01	0.42**	-0.10	0.38*	1.00

URE – soil urease activity, AKP – soil alkaline phosphatase activity, CAT – soil catalase activity, SAC – soil saccharase activity, SOC – soil organic carbon, TN – soil total nitrogen, IN – soil inorganic nitrogen, MBC – soil microbial biomass carbon, MBN – soil microbial biomass nitrogen, TP – soil total phosphorus, IP – soil inorganic phosphorus, SM – soil water content, BD – soil bulk density.
**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2–tailed)

a reduction in plant cover, biomass of standing vegetation, and input of organic matter from litter-fall due to litter consumption and trampling by livestock [42, 43]. In addition, animal grazing has a severe effect on soil properties [43]. Due to the destruction of soil aggregates by frequent trampling of sheep, higher soil bulk density found in FG than in the exclusion areas. Other researchers have reported that grazing exclusion reduced soil bulk density in both degraded sandy grassland [16] and alpine meadow [44]. Fenced desert rangeland (1998EX, 2002EX) also had higher soil water content than the grazed one (FG), consistent with the results of Jeddi and Chaieb [45], which showed that grazing exclusion increased soil water content in an arid steppe due to the reduced compacting effect on soil surface, resulting in higher infiltration rates and lower infiltration times compared with grazed areas [46].

Livestock exclusion improved not only vegetation properties and soil physical features, but also soil chemical and biological properties as compared with the continuously grazed area. SOC, TN, and TP were significantly lower in FG than in the other two plots, while soil texture was not significantly different among the three plots (FG, 1998EX, and 2002EX). Our result was in agreement with those reports in semi-arid grassland [47], in alpine desert rangeland [48], in typical steppe [49], and in Savanna [50]. The higher SOC and nutrient level in grazing exclusion plots could be a result of increased vegetation recovery and litter accumulation and reduced soil compaction [51]. On the other hand, continuous grazing and frequent trampling by sheep resulted in a more fragile soil surface, accelerating wind erosion, and consequently soil coarsening and loss of organic matter [52]. Livestock exclusion had a positive effect on soil biological properties. MBC and MBN were 40% and 50% higher, respectively, in topsoil of 1998EX than those of FG. In general, heavy grazing has a negative effect on soil microbial community composition and biomass [53]. Soil microbial communities rely on plant tissues and root excreta as energy sources for multiplication [54], and microbial activities are negatively related to soil bulk density and pH value [8] but strongly correlated with SOC and TN [55, 56]. Our results, however, showed that in the arid desert environment, the reduction of soil microbial biomass in FG is closely related to lower water content and organic matter content.

The greater enzyme activities in the exclusion areas could be an indication of improved soil microbial activities. Soil enzymes are mainly produced by soil microbes, although some of them may come from plant root excreta [57]. In our results, activities of URE, AKP, CAT, and SAC were strongly positively correlated with SOC, MBC, and MBN ($P<0.01$). High levels of organic matter can enhance microbial activity through supplying suitable substrates for microorganisms [21, 24], which in turn may stimulate soil enzyme synthesis. Also, experimental evidence obtained on the interactions between proteins and organic substances indicates that soil organic matter plays an important role in the enzyme immobilization in the soil by increasing the stability of soil enzymes and therefore the resistance to prote-

olysis [21, 58]. Measurements on soil enzyme activity also provide useful information on the functional activity of the microbial biomass. Due to the variety of enzymes involved in the mineralization pathway, however, it is difficult to define relationships between specific enzyme activities and particular ecological processes [18].

Notwithstanding this limitation, some broad relationships between certain enzyme activities and soil processes have been determined. For example, it is well established that phosphatase catalyzes the hydrolysis both phosphorus esters and anhydrides of phosphoric acid into inorganic phosphorus [59], peptidases and amidases, and of ammonification [60]. Our results indicate that soil IN and IP are strongly correlated with enzyme activities ($P<0.01$), hence the increased URE and AKP activities in the soil of exclusion plots suggests that N and P mineralization was enhanced. Since nitrogen is a limiting nutrient for grass growth in the semi-arid soil [15], the increase in urease activity in exclusion plots may eventually have positive effects on pasture productivity.

Soil enzymes are known to be involved in nutrient cycling, and are sensitive to variations induced by natural and anthropogenic factors [22]. As such, their activities can be used as biomarkers of degradation and (bio) remediation processes [55, 61, 62]. Grazing-induced reduction of enzyme activities has been reported in the literature [8]. In our study, URE, AKP, CAT and SAC activities increased with longer exclusion times. This indicates that the soil quality in the Alxa desert was significantly improved by livestock exclusion. It was also found that URE, CAT, and AKP activities improved following 10 years exclusion of livestock in Horqin sandy grassland in China [15]. Our results are consistent with previous studies that showed that enzyme activities can be a good indicator of soil changes associated with the management history [63].

Conclusions

The arid Alxa desert steppe is ecologically very fragile. Free grazing gives rise to a considerable reduction in ground cover and primary productivity, which in turn accelerates soil erosion by wind, resulting in coarseness of the surface soil and loss of nutrients. The results from our study indicate that continuous overgrazing causes degradation of the vegetation communities, followed by declines of essential soil nutrients, increases in wind erosion, and further desertification. Soil physical and chemical properties, especially enzyme activities, improved following six years of livestock exclusion, indicating that the rangeland can recover if managed properly. Soil microbial biomass and enzyme activities are sensitive to exclusion. They may be good biomarkers of soil degradation and remediation processes and changes of soil synthetical fertility in this erosion-prone area. Despite the fact that livestock exclusion may be an effective restoration strategy for degraded desert rangeland, future research is needed to explore the ways to make use of the desert rangeland in a sustainable way so as to provide livelihoods for the local herder communities.

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