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Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia

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Abstract

We conducted a grazing experiment from 1992 to 1996 in Inner Mongolia to explore desertification processes of sandy rangeland. The results show that continuous heavy grazing results in a considerable decrease in vegetation cover, height, standing biomass and root biomass, and a significant increase in animal hoof impacts. As a result, small bare spots appeared on the ground and later merged into larger bare areas in the rangeland. Total bare area reached up to 52% and the average depth of wind erosion was 25 cm in the fifth year of the study. We conclude that sandy rangeland with wind-erodible soil is susceptible to desertification. Heavy grazing of such rangeland should be avoided.

Keywords: Sandy rangeland; Heavy grazing; Vegetation degradation; Soil erosion; Sandy desertification; Inner Mongolia

1. Introduction

Desertification processes have been defined as land degradation in arid and semi-arid areas resulting from various factors, including climatic variation and human

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activities (Gad and Abdel, 2000). Sandy desertification driven by wind erosion is one of the main types of desertification (Wang, 2000). In arid and semi-arid areas, wind erosion and heavy grazing, which are common problems in sandy rangeland (Hennessy et al., 1986), are the principal mechanisms of land degradation (Okin et al., 2001). Once soil is exposed due to heavy grazing, wind erosion occurs immediately in sandy rangeland (Whitford et al., 1995). Wind erosion and heavy grazing are the main causes of sandy desertification in desert areas (Okin et al., 2001).

Livestock grazing is a dominant land-use activity in semi-natural and managed rangelands (Soderstrom et al., 2001). Heavy grazing can disturb rangeland (Yates et al., 2000). A study of grazing effects on species diversity and richness of rangeland vegetation has reported that grazing impacts on species composition, vegetation cover, canopy height, biomass and soil environment were sensitive to grazing rate in the rangeland (Pour and Ejtehadi, 1996–1997). Heavy grazing often results in a dramatic decline of plant diversity, vegetation cover, primary production (Fensham, 1998), seed production and seed number in soil (Coffin and Lauenroth, 1989; Bertiller, 1996). With vegetation decrease due to consumption of plant matter exceeding re-growth over the long term, rangeland desertification can occur (Faraggitaki, 1985; Manzano and Navar, 2000). Heavy grazing can also cause soil erosion, loss of soil structure, and deterioration of soil environment (Faraggitaki, 1985; Scholl and Kinucan, 1996). The formation of desert occurs when soil is vulnerable to wind erosion once the soil cover has been removed (Okin et al., 2001). Controlled grazing can be beneficial to rangeland. It has been reported that zero grazing is beneficial to biomass accumulation and seed production, restricting rangeland desertification (Murphy et al., 1995), and medium grazing is conducive to sustaining stable rangeland vegetation (Wang et al., 1999).

In China, there are $3.9 \times 10^5\,km^2$ of sandy desertified land. Heavy grazing affects 28.3% of the total sandy desertified land (Zhang et al., 1998; Wang, 2000). Some researchers have investigated desertification types, the causes and distribution of sandy desertified lands, and the dynamics and risks related to desertification (Zhu and Chen, 1994; Xu and Liou, 1997). There is still a need for clarification of the desertification process caused by heavy grazing in China, and particularly of the particular desertification process caused jointly by heavy grazing and wind erosion in sandy rangeland (Zhang et al., 1998). The objectives of this paper are to describe the desertification process of sandy rangeland due to heavy grazing, to evaluate the quantitative effects of both wind erosion and heavy grazing on land degradation in sandy rangeland, and to discuss an appropriate grazing intensity at which desertification can be controlled.

2. Materials and methods

2.1. Study area

The study area is located in Naiman County (42°55′N, 120°42′E, 345 m a.s.l.) in the eastern part of Inner Mongolia, China (Fig. 1). Naiman is located at the

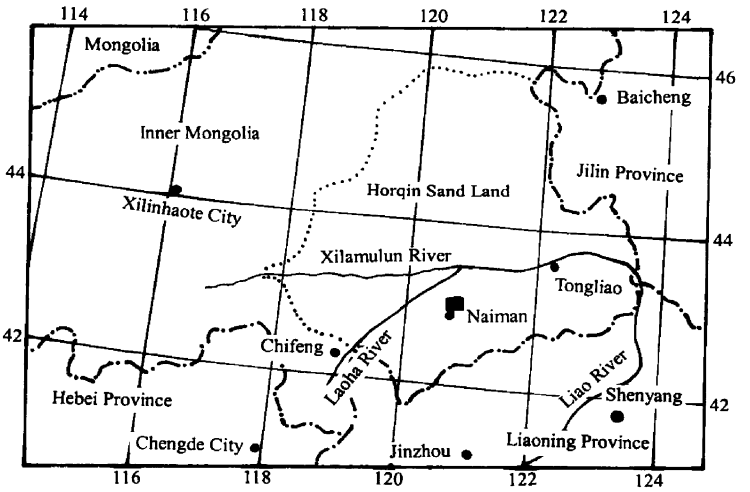

Fig. 1. Location of study area (Horqin Sand Land in Inner Mongolia). The black box indicates the experiment area.

south-western end of the Horqin Sand Land and belongs to the continental semi-arid monsoon climate regime in the temperate zone. The mean annual precipitation is 366 mm, of which the precipitation from November to April accounts for 8.3% (annual precipitation amounts during the experiment period were 401, 320, 533, 347 and 350 mm from 1992 to1996, respectively). The mean annual potential evaporation is 1935 mm. The mean annual temperature is 6.8 °C (mean annual temperatures during the experiment period were 7.2, 7.2, 7.9, 7.6 and 7.1 °C from 1992 to1996, respectively). The frost-free period is in the range of 130–150 days per year. The mean wind speed is 4.3 m s^{-1} in winter and spring. There are frequent gales (wind speeds $\geqslant$20 m s^{-1}). The sandy soil consists mainly of coarse sand and silt.

2.2. Experiment design

The grazing experiment was set up in an open and level natural rangeland in 1992. The dominant plant species in the rangeland included the perennial grasses and forbs *Pennisetum centrasiaticum, Phragmites communis, Leymus secalinus, Cleistogenes squarrosa, Melissitus ruthenicus, Kummerowia stipulacea,* and the annual grasses and forbs *Setaria viridis, Chloris virgata, Aristida adscensionis, Digitaria ischaemum, Artemisia scoparia,* and *Salsola collina*. The mean grazing intensity at the experiment site was 4.5 sheep ha^{-1} before the experiment (Zhao et al., 1999), and the rangeland was experiencing slight degradation due to heavy grazing by sheep which was determined based on the Zhu and Chen (1994) classification criteria for degree of desertification.

A total area of 16 ha was used in this experiment. This was first divided into three blocks of 5.3 ha each, as experimental replicates. Then each block was divided into four plots for experimental treatment: three plots of 1.5 ha each (75 m × 200 m) for grazing treatments and one plot of 0.8 ha (38 m × 200 m) for ungrazed control. Paddock division fences were constructed with concrete pilings and barbed wire. The four grazing treatments used on the plots were: heavy grazing (6 sheep ha^{-1}); moderate grazing (4 sheep ha^{-1}); light grazing (2 sheep ha^{-1}); and no grazing (0 sheep ha^{-1}). Grazing started on June 1 and ended on September 30 each year from 1992 to 1996.

2.3. Measurements and analysis

There were three (20 m × 20 m) sampling sites fixed in each plot. In addition, two quadrats (1 m × 1 m) were chosen in each sampling site at the end of each month to investigate changes in vegetation cover, canopy height, above-ground biomass and below-ground biomass. All green plant material 1 cm and higher above-ground inside the quadrats was cut. The biomass samples were put into paper bags in the field, oven-dried at 85 °C for 24 h and weighed in the lab. Vegetation cover was estimated visually. Canopy height was the mean height of the plants inside the quadrats. Soil cores were taken from the center of each quadrat at depths of 0–10, 10–20 and 20–30 cm. Soil cores were transported to the lab and washed through a 0.25 mm mesh screen in order to determine root biomass. The root samples were oven-dried at 85 °C for 24 h and then weighed.

In each plot, 10 fixed quadrats (1 × 1 m) were set up to measure sheep hoof-print numbers, and belt transects were used to measure bare land ratio (Jiang, 1988). Thirty-two belt transects, each of 75 m length (38 m for ungrazed control), and separated from each other by 6 m, were set up across the width of each plot for sampling. Depth of soil erosion was measured at 20 surface locations. At each location, two graduated poles were set 1.5 m apart. Wind erosion depth was measured by erosion pins set at known heights between the two poles (Xu and Liou, 1997). All of the monthly data were used to calculate the monthly mean values. Multiple comparison and analysis of variance (ANOVA) were used to determine differences among the treatments (Sokal and Rohlf, 1995).

3. Results

3.1. Vegetation cover and canopy height

Different grazing intensities had different effects on vegetation. Vegetation cover and canopy height were decreased significantly ($P < 0.05$) with increased grazing intensity (Table 1). Vegetation cover in the heavy grazing plot was 58.6% lower than that in the no grazing plot in the first year, and 88.0% lower in the fifth year. Vegetation canopy height in the heavy grazing plot was 81.9% lower than that in the no grazing plot in the first year, and 97.0% lower in the fifth year. The vegetation cover and height increased slightly over the study period in the light grazing and moderate grazing plots.

Table 1
Plant height and cover in sandy rangeland of Inner Mongolia as affected by different grazing intensities, measured August 30 each year

Treatments	Years					Average
	1992	1993	1994	1995	1996	
Canopy height (cm)						
No grazing	32.6 ± 8.0	24.9 ± 6.2	33.7 ± 5.8	20.4 ± 4.1	33.1 ± 14.1	29.1 ± 6.1 [a]
Light grazing	11.0 ± 3.6	13.7 ± 3.1	26.3 ± 7.7	17.1 ± 7.6	18.7 ± 3.2	17.3 ± 7.3 [b]
Moderate grazing	6.1 ± 1.7	13 ± 4.1	10.8 ± 4.2	5.3 ± 10.2	16.6 ± 11.2	10.6 ± 4.5
Heavy grazing	5.9 ± 3.3	4.1 ± 0.7	3 ± 0.6	1.5 ± 1.0	1.0 ± 0.6	3.1 ± 1.3
Vegetation cover (%)						
No grazing	70.0 ± 5.0	80.3 ± 10.6	89.0 ± 14.9	78.7 ± 24.1	84.3 ± 6.0	80.5 ± 7.1 [a]
Light grazing	46.5 ± 2.9	62.3 ± 5.0	75.0 ± 8.9	59.3 ± 6.0	81.0 ± 3.6	60.9 ± 23.3 [b]
Moderate grazing	36.6 ± 30.6	64.3 ± 30.4	46.3 ± 25.1	48.0 ± 22.0	47.7 ± 15.1	48.6 ± 9.0 [b]
Heavy grazing	29.0 ± 12.8	34.7 ± 4.7	29.0 ± 44.5	24.0 ± 35.6	10.1 ± 17.3	25.3 ± 16.1 [b]

Values are means ± SD. Values with same letters are not significantly different at $P \leqslant 0.05$.

3.2. *Above- and below-ground biomass*

Standing crop biomass decreased significantly with increasing grazing intensity ($P<0.05$) (Table 2). The standing crop biomass decreased slightly, but not significantly, with grazing time at both the heavy grazing and moderate grazing treatments, while it increased significantly with grazing time in the light grazing treatment ($P<0.05$). The standing crop biomass in the no grazing treatment increased from 1992 to 1994 and showed a decreasing trend afterwards. This might be due mainly to litter accumulation, which restricted plant growth (Zhao et al., 1999).

Root biomass in the heavy grazing plot was significantly lower than that in other treatments ($P<0.05$) and the difference in root biomass was not significant among the moderate grazing, light grazing and no grazing treatments (Table 2). Root biomass in the surface soil (0–10 cm) of the heavy grazing plot was 9.6 $g\,m^{-2}$ in the fifth year, only about 7.1% relative to the no grazing treatment. One basic function of root systems is fixing soil. Decreases in root biomass mean a loss of resistance to wind erosion (Zhao et al., 1997).

3.3. *Trampling intensity*

In the case of limited forage grass, sheep activity was significantly increased in the heavy grazing plot ($P<0.05$). The mean hoofprint numbers per unit area in the heavy grazing plot were 3.87 and 9.6 times those in the moderate grazing and light grazing plots, respectively (Table 3), and the mean hoofprint numbers per unit area per sheep were 2.6 and 3.2 times. At the same time, trampling intensity was increased with heavy grazing time ($P<0.05$). The hoofprint number per unit area in

Table 2
Standing crop biomass and below-ground biomass in sandy rangeland of Inner Mongolia as affected by grazing intensity

Treatments	Years					Average
	1992	1993	1993	1995	1996	
Standing crop biomass ($g\,m^{-2}$)						
No grazing	266±62	347±271	335±108	220±58	242±44	282±57 [a]
Light grazing	70± ±40	117±33	158±19	192±47	218±52	151±59 [b]
Moderate grazing	98±75	113±97	86±87	57±20	67±40	84±23
Heavy grazing	38±16	27±10	24±37	24±37	3±6	23±13
Below-ground biomass ($g\,m^{-2}$)(0–30 cm)						
No grazing	359±93	389±100	355±83	180±86	232±87	303±91 [a]
Light grazing	200±87	387±125	258±91	171±50	163±32	236±92 [a]
Moderate grazing	324±73	369±68	128±61	208±61	82±22	222±123 [a]
Heavy grazing	117±55	125±56	60±61	41±10	21±8	73±46 [b]

Values are means±SD. Values with same letters are not significantly different at $P \leqslant 0.05$.

1996 was 5.39 times that in 1992. On the contrary, the hoofprint numbers in the light grazing plot were decreased by 26.2% in the same period. Heavy trampling often leads to fragmentation of topsoil and fragmented topsoil is susceptible to wind erosion (Faraggitaki, 1985).

3.4. Ground surface denudation processes

In the heavy grazing plot, there were 19 bare spots in the first year, 5 (26.3%) of these having diameter >2.5 m. Mean bare-ground fraction was 1.8% of plot area in the first year. Bare ground increased to 302 spots in the fifth year, with 137 (45.7%) of these having diameter >2.5 m; mean bare-ground fraction was 51.6% of plot area (Table 4). The number of bare spots in the no grazing and light grazing plots were commensurate with that in the heavy grazing plot in the first year. However, the bare spots in the no grazing and light grazing plots rapidly decreased and at last disappeared in the fifth year. Emergence of bare spots and enlargement of bare area increase the possibility of wind erosion.

In addition to grazing, wind plays a role in the formation of bare spots. Bare ground fraction in three active-grazing treatments was markedly increased in the winter and spring (December–May) even without grazing (Table 5). The increasing fraction of bare ground caused by wind erosion from October to May each year was in the range of 3.72–20.0% in the heavy grazing plot, 3.27–3.82% in the moderate grazing plot, 0.05–0.11% in the light grazing plot and 0% in the no grazing plot. The ground denudation due to heavy grazing was 47.4% and that due to wind erosion was 52.6% throughout the experiment period. Apparently, once heavy grazing created bare spots, wind would impose further severe erosive impacts on the soil,

Table 3
Hoof print numbers (*n*) in the sandy rangeland as affected by grazing intensity

Items	Hoof print (n/m^2)				Hoof print (n/m^2/sheep)			
	1992	1994	1996	Average	1992	1994	1996	Average
Heavy grazing	14.2±5.2	18.4±10.5	76.5±40.9	36.4±34.8 [a]	1.6±0.6	2.0±1.2	8.5±4.5	4.0±3.9 [a]
Moderate grazing	8.2±4.5	9.8 ±7.2	10.1±4.8	9.4±3.1 [b]	1.4±0.8	1.6±1.2	1.7±0.8	1.6±0.2 [b]
Light grazing	4.2±3.4	4.0±3.7	3.1±2.2	3.8±0.6 [b]	1.4±1.1	1.3±1.2	1.0 ±0.7	1.3±0.2 [b]

Values are means±SD. Values with same letters are not significantly different at $P \leqslant 0.05$.

Table 4
Changes in the number of bare areas, their size class and bare land fraction as affected by grazing intensity

Items	Heavy grazing			Moderate grazing			Light grazing			No grazing		
	1992	1994	1996	1992	1994	1996	1992	1994	1996	1992	1994	1996
Bare areas (number)	19	358	302	37	33	87	20	2	1	19	0	0
Mean length (m)	2.3	2.4	4.1	1.6	1.6	1.3	2.3	1.4	0.5	0.8	0	0
Mean bare fraction (%)	1.8	35.8	51.6	2.5	2.2	4.7	1.9	0.12	0.00	0.06	0	0
0.5–1.5 m (number)	9	161	121	29	22	67	12	1	1	17	0	0
Bare fraction (%)	47.4	45.0	40.1	78.4	66.7	77.0	60	50	100	89.5	0	0
1.6–2.5 m (number)	5	85	43	3	7	13	2	1	0	2	0	0
Bare fraction (%)	26.3	23.7	14.2	8.1	21.2	14.9	10	50	0	10.5	0	0
2.6–3.5 m (number)	3	51	32	1	1	4	2	0	0	0	0	0
Bare fraction (%)	15.8	14.2	10.6	2.7	3.0	4.6	10	0	0	0	0	0
3.6–10.0 m (number)	2	61	77	4	3	2	4	0	0	0	0	0
Bare fraction (%)	10.5	17.1	25.5	10.8	9.1	2.3	20	0	0	0	0	0
>10 m(number)	0	0	29	0	0	1	0	0	0	0	0	0
Bare fraction (%)	0	0	9.6	0	0	1.2	0	0	0	0	0	0

Measured September 30 each year.

which caused small bare spots to merge together, resulting in enlargement of continuous bare patches. Wind impact was more severe than that of heavy grazing.

3.5. Wind erosion

Table 5 presents the measured results of soil erosion in the winter and spring of 1993–1994 and 1995–1996. Obviously, wind-eroded area and erosion intensity increased significantly with the increase in grazing intensity ($P<0.05$). In 1995–1996, 80% of sample points recorded wind erosion and the maximum erosion depth was 90 cm in the heavy grazing plot. Slight wind erosion appeared in the moderate grazing plot and no wind erosion in the light grazing and no grazing plots. Mean precipitation from October to April was only 25.6 mm throughout the experiment period; wind erosion was a direct cause of soil erosion and bare area spreading during windy winter and spring seasons.

Table 5
Comparison of bare land fraction (%) in autumn and spring among four grazing treatments from 1993 to 1997

Year	1993–1994		1994–1995		1995–1996		1996–1997		Average	
Date (month/day)	09/30	05/31	09/30	05/31	09/30	05/31	09/30	05/31	09/30	05/31
Heavy grazing	3.11	21.76	35.80	39.52	51.40	52.40	51.60	71.60	35.47	46.32
Moderate grazing	1.42	5.24	2.20	5.47	4.70	4.70	4.70	9.50	13.02	24.91
Light grazing	0.45	0.77	0.12	0.23	0.00	0.05	0.00	0.70	0.57	1.75
No grazing	0	0	0	0	0	0	0	0	0	0

4. Discussion and conclusions

This 5-year grazing experiment indicates that heavy grazing could impose severe impacts on sandy rangeland. Vegetation cover, canopy height, standing crop biomass and root biomass in the heavy grazing treatment were decreased by 88.0%, 92.6%, 98.8% and 90.8%, respectively, in the fifth year relative to the no grazing treatment. Bare ground surface was exposed as heavy grazing dramatically decreased vegetation cover and height. The development of bare ground surface was not uniform. It began first from the formation of small bare spots, which then increased in number, and gradually enlarged. Finally, the small bare spots merged into larger bare patches leading to marked increases in total bare ground fraction of the rangeland. Formation of bare spots was closely related to the non-uniform distribution pattern of the plant populations (Bisigato and Bertiller, 1997). Many plants presented a patchy distribution pattern in Horqin sandy rangeland, and some palatable plant species, including *P. centrasiaticum, P. communis, C. squarrosa, L. secalinus, S. viridis, and A. adscensionis* disappeared rapidly from the rangeland under heavy grazing activity. This resulted in an emergence of bare spots. Some unpalatable plants such as *Eragrostis pilosa, C. virgata* and *A. scoparia* became dominant species in the rangeland, but the density of their populations decreased after heavy grazing. This is consistent with the results of Kerley and Whitford (2000) in the Chihuahuan Desert. Increase and enlargement of bare spots resulted in an increase of bare area in the rangeland. Bare land fraction in the heavy grazing treatment increased from 1.8% in the first year to 51.6% in the fifth year (Table 6).

Sheep activity is greatly intensified with a decrease in standing crop biomass (Allred, 1996). Trampling intensity of sheep on the rangeland increased 7.25 times in the heavy grazing treatment relative to the light grazing treatment. Over-trampling by animal hooves loosens soil particles and creates a dispersed layer 10 cm deep (Faraggitaki, 1985). Continued decreases in vegetation cover, height and root biomass caused by heavy grazing mean a decrease in vegetation function to protect the ground and fix soil (Marticorena et al., 1997). Once grass is removed and loose, sandy soil is exposed, it is easily eroded by strong winds (Fredrickson et al., 1998; Manzano and Navar, 2000). The windy season occurs in the winter and spring in Inner Mongolia. Our results show that wind erosion occurred at about 90% of the surface measurement locations in the heavy grazing treatment, and the annual

Table 6
Wind erosion depth (cm) in the rangeland as affected by grazing intensity

Date	Sept.30, 1993–May 31, 1994			Sept.30, 1995–May 31, 1996		
Items	Max depth	Average	% of 20 samples	Max depth	Average	% of 20 samples
Heavy grazing	12.0	8.5 ± 0.43 [a]	70	90.0	25.0 ± 26.29 [a]	90
Moderate grazing	2.0	1.5 ± 0.79 [b]	20	2.0	2.0 ± 0.00 [b]	10
Light grazing	0.8	0.8 ± 0.00 [b]	10	0	0 [b]	0
No grazing	0	0 [b]	0	0	0 [b]	0

Values are means ± SD. Values with same letters are not significantly different at $P \leqslant 0.05$.

maximum erosion depth reached up to 90 cm in the 5th year, finally leading to the formation of an aeolian landscape. Vegetation is a protector of the soil against erosion as well as a casualty of soil erosion (Yates et al., 2000; Manzano and Navar, 2000). Vegetation harmed by windblown sand can naturally wither and be displaced in the process of soil erosion (Zhu and Chen, 1994), enlarging patches of bare ground (Ludwig and Tongway, 1995). Over the period of our experiment, the contribution of grazing and trampling to bare ground formation was 47.4% and that of wind erosion was 52.6%. The results also showed that there was almost no soil erosion in the no grazing and light grazing treatments (Table 4), only slight wind erosion at some bare spots in the moderate grazing treatment. Moderate grazing by itself would not lead to sandy grassland desertification under an average precipitation regime, but it might in dry years if the rangeland was not properly managed (Okin et al., 2001).

It is known that a soil with low organic matter content and no aggregate structure is vulnerable to wind erosion (Faraggitaki, 1985). The sandy rangeland soil of Inner Mongolia consists mainly of coarse sand and silts, and is very loose. The rangeland is at risk of desertification due to heavy grazing and wind erosion. Once the vegetation cover is removed by heavy grazing, the soil is exposed to wind erosion in the dry and windy seasons of winter and spring, which results in speedy development of sandy desertification (Zhu and Chen, 1994; Rubio and Bochet, 1998). The sandy rangeland was more sensitive to heavy grazing disturbance than the surrounding non-sandy grassland in Inner Mongolia (Wang et al., 1999). Heavy grazing has caused severe desertification in sandy grassland in Inner Mongolia (Zhu and Chen, 1994, Zhao et al., 1999), and heavy grazing should be stopped in sandy rangeland.

In theory, heavy grazing can be avoided by limiting the number of animals grazing the system (Faraggitaki, 1985; Peterjohn and Schlesinger, 1991). Although the vegetation cover, canopy height, above- and below-ground biomass in the light grazing treatment were lower than that in the no grazing treatment, vegetation condition improved significantly with time and land desertification was reversed (from the trend under heavier grazing prior to 1992). This indicated that lighter grazing is helpful in progressive vegetation restoration and community stability of deteriorated pastures (Bisigato and Bertiller, 1997). Although the vegetation cover, above- and below-ground biomass were not significantly different between light grazing and moderate grazing treatments, the bare ground fraction was higher in the moderate grazing plot. This implies that moderate grazing may have a risk of wind erosion and desertification in the dry and windy seasons (Laycock, 1991, Zhao et al., 1999). Our conclusion is that the proper grazing intensity is 2–3 sheep or sheep equivalents per hectare in sandy rangeland, Inner Mongolia.

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