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Impact of Grazing Livestock and Distance from Water Source on Soil Fertility in Southern Mongolia

The impact of livestock grazing on soil nutrients and vegetation parameters was studied in dry montane steppes of southern Mongolia in order to assess the risk of habitat degradation. Data were collected along transects radiating away from permanent water sources. Dung unit density counts revealed gradients of livestock activity, but utilization belts around water sources overlapped, indicating that pastoral land use affects the entire landscape. Dung unit counts corresponded to gradients in soil nutrient parameters (C, N, P), which significantly decreased with distance from the wells. However, no significant correlation was observed for plant species richness and vegetation composition with distance from water source. This indicates that soil parameters and livestock grazing exert a relatively smaller influence on the vegetation than the high inter-annual variability in precipitation. Therefore, the ecosystem at the study site was found to react in a non-equilibrium way, which suggests that the risk of degradation is low, at least insofar as plant community composition is concerned.

Keywords: *Grazing; non-equilibrium dynamics; vegetation; soil; steppe; Mongolia.*

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Introduction

About 40% of the globe's terrestrial areas are grasslands in the wider sense (White et al 2000). They are typically located in semiarid regions, many at high altitudes. Some Asian countries are almost entirely covered by steppes of various moisture regimes, the most prominent examples being Kazakhstan and Mongolia. Mongolia is an upland country with 85% of its territory located above 1000 m, with most of the extensive grasslands found between 1000–2500 m (Hilbig 1995). Grasslands often support large herds of herbivores, and grazing is a cross-cutting issue in the ecology of semiarid environments. This is reflected by the traditional human land use of (semi-)nomadic pastoralism. Mongolia has a history of probably more than 4000 years of pastoral land use (Jettmar 1989), with domestic livestock numbers reaching a high 33 million at the end of the 20th century (National Statistical Office of Mongolia 2003).

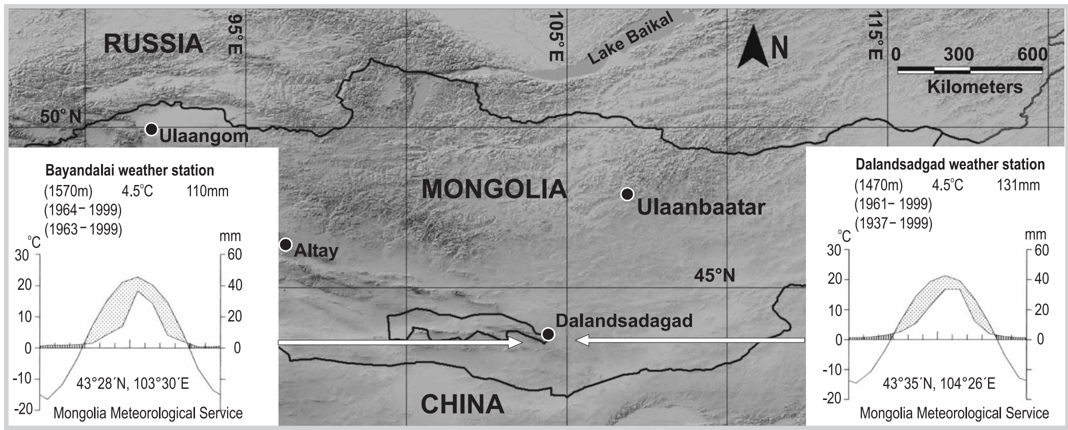
In comparison, numbers of wild ungulates have decreased in the last century, with the total population of the Mongolian gazelle (*Procapra gutturosa*) still at several million (Milner-Gulland and Lhagvasuren 1998), while other species such as Bactrian camels (*Camelus bactrianus ferus*) or wild ass (*Equus hemionus*) have become critically endangered (Reading et al 2001; Mix et al 2002).

Livestock numbers increased following political changes in the last decade of the 20th century, when the collapse of industry, administration, and state farms forced many people to return to rearing livestock. Thus Mongolia is currently one of the few countries where one can find 'new nomadism' (Müller 1999). The pastoral sector comprises some 36.5% of the country's Gross Domestic Product (National Statistical Office of Mongolia 2003), so sustainable use of the pastures is of tremendous importance. It is often stated that large areas of Mongolia are under threat of degradation or have already been degraded (eg Batjargal 1998; Batkhishig and Lehmkuhl 2003), but levels of grazing show strong geographical variation with high impact areas near towns or small settlements, and low impact regions particularly in the driest part of the country, where wells have often run dry because of poor maintenance.

Recent studies on several continents have demonstrated that the importance of degradation in drylands is often exaggerated and confounded with effects of climatic variability (Sullivan and Rohde 2002). The non-equilibrium theory of rangeland science states that (semi-)arid rangelands such as the southern part of Mongolia (ie <250 mm annual precipitation) with high inter-annual and spatial variation in precipitation are more likely to experience non-equilibrium than equilibrium dynamics. Under such conditions livestock numbers should have limited influence on vegetation dynamics because plant biomass recovers faster than livestock densities after a breakdown, so the dynamics of producers and consumers operate on different time scales (Ellis and Swift 1988). Under equilibrium conditions, vegetation composition is affected by grazing intensity and by differences in soil conditions, while in a non-equilibrium system vegetation dynamics are governed by precipitation and are relatively independent from grazing intensity and soil conditions. This implies that degradation should rarely occur in non-equilibrium systems as long as opportunistic (ie nomadic) management strategies are applied (Baker 2000).

In order to study the impact of livestock grazing on soil nutrient parameters and vegetation of dry steppes in southern Mongolia, a transect sampling design along gradients of livestock activity was chosen. This approach has been frequently applied in (sub-)tropical regions (eg Thrash 1998; Turner 1998), while data for central

FIGURE 1 Location of the Gobi Gurvan Sayhan National Protected Park in Mongolia. Climatic diagrams come from the 2 most closely situated governmental weather stations of the Meteorological Service of Mongolia. (Map by Henrik von Wehrden, GTOPO30 data from USGS)



Asia are sparse (Chuluun and Ojima 2002). Only one study concentrates on vegetation changes along grazing gradients in 3 major vegetation types in central Mongolia (Fernandez-Gimenez and Allen-Diaz 1999 and 2001).

Study area

Our study area is located in the Gobi in southern Mongolia (Figure 1), in the southern foreland of the Dund Sayhan (43°34–43°36′N, 103°43–103°48′E). The topography is governed by vast pediments surrounding the southeasternmost outcrops of the Gobi Altay, with summits reaching up to 2900 m. Grazing is intensive in the area despite its seemingly protected national park status. The climate is semiarid, with a mean annual precipitation of 110 mm at the lower pediments (around 1500 m), where the nearest permanent weather station is located (Meteorological Service Mongolia). Coefficients of inter-annual variation are 33–38%. Short-term measurements (Retzer 2004) suggest that mean annual precipitation at the upper pediments (2300 m) is 120–150 mm, while it might be 2 to 5 times higher on the upper mountain slopes. Interannual variability of precipitation is high in the mountains. At 2300 m the summer months of July and August received a total of 8 mm in 2001, 27 mm in 2002, and 94 mm in 2003. The present study was carried out under the dry conditions of 2001, when forage was scarce and herbivores had consumed almost all standing biomass (Retzer 2004).

The study area is located at an intermediate position in the altitudinal gradient (2100 to 2300 m) and supports an intermediate vegetation. The higher mountain slopes have relatively moist mountain steppes, while below 2000 m pediments are covered by dry desert steppes. The vegetation studied is characterized by the montane species *Stipa krylovii* together with *S. gobica* as a desert steppe species (Hilbig 1995). Further dominant species include *Agropyron cristatum*, *Artemisia frigida,* and *Arenaria meyeri*. Phytosociological classifications suggest that these steppes can be regarded as a separate community, namely *Stipa gobica* steppes. Thus, all our transects were placed in one fairly homogeneous vegetation unit. Soils on the pediments are also homogeneous; they can be classified as Burosems and often have a calcic A-horizon.

We selected 5 sites with permanent water sources that were used by herders as summer places (Table 1). We conducted non-formal interviews with all families, asking for herding practices, sources of fuel, and fodder value of selected plants. The most numerous livestock species were sheep and goats (87% of all observed animals), while in terms of traditional Mongolian Sheep Units, sheep/goats (34%) and horses (42%) were the dominant species. Providing pastures are sufficient, herders move to the upper pediments in May, often shift their camps again depending on forage availability at that altitude, and move back to their winter camps in September or October (commonly at around 1800 m; Retzer 2004). In drought years this pattern is disrupted as herders migrate to less affected regions (eg more than 200 km to the Middle Gobi Aimag, as in late summer 2001).

Camps are usually located in the direct vicinity of water sources (<100 m), so livestock that are kept near the *gers* (yurts) have easy access to water. Sheep and goats spend the night near the water sources, so the maximum distance these species wander during the day is limited. The distance between camps is usually below 3 km, making it probable that utilization belts overlap.

Wild ungulates (mainly gazelles and some argali) account for less than 2% of the livestock units on the upper pediments (Retzer 2004), but *pikas* (*Ochotona pallasi*) are abundant in the region (Retzer 2004). Their distribution is not influenced by distance to water sources and their grazing impact was assumed as spatially continuous in the present study.

TABLE 1 Numbers of families and livestock at the 5 wells at the time of the study. Figures were given by herders and refer to adult animals only. Equivalents of traditional Mongolian Sheep Units were calculated with standard conversion factors. (Source: National Statistical Office of Mongolia 1996)

Water source	1	2	3	4	5					
Human and livestock population	Atat	Bayan Tsav	Schand	Sarool	Ulaan Tolgoi	*Atat*	*Bayan Tsav*	*Schand*	*Sarool*	*Ulaan Tolgoi*
Number of families in 2000	2	2	1	2	1					
Number of families in 2001	2	1	1	2	1	Equivalents in Mongolian Sheep Units (MSU)				
Goats in 2001	320	135	240	470	100	288	122	216	423	90
Sheep in 2001	210	70	160	240	100	310	70	160	240	100
Horses in 2001	50	0	50	55	30	350	0	315	385	210
Cattle in 2001	9	0	7	27	4	54	0	42	162	24
Camels in 2001	8	0	0	20	6	40	0	0	100	30

Methods

Data collection

Four transects were sampled from each water source radiating west-, north-, east- and southwards. Plots were placed at distances of 50, 150, 300, 750 and 1500 m from the water source. Shorter distances would have introduced confounding effects due to higher moisture conditions and severe trampling near the wells. Larger distances would have been within the 1500 m belt around the next water source. Plots were 10 x 10 m in size—an area large enough to contain all typical plant species present in the vegetation. Species cover percentages were estimated directly; percentages were estimated by several people and were reasonably consistent after a few trials. Identifications were carried out based on Grubov (2001), and later checked in the Herbarium at the University of Halle.

The presence of grazing gradients was assessed by counting livestock dung units as a proxy for grazing activity (same transects, but plot size 150 m^2). Mixed topsoil samples were collected for three typical transects at depths of 5 and 20 cm, ie the layers where most of the roots were concentrated in our study region (Borisova and Popova 1985). C and N contents were measured by combustion in a CN Analyser (Vario EL, ELEMENTAR, Germany), P was extracted using Ca-Lactate at pH 3.6 and assessed with an EPPSTEIN photometer. The same instrument was used to measure NH_4 and NO_3 after extraction with a KCl solution. Conductivity and pH were measured in water (50 ml per 20 g soil). Cations were extracted with NH_4Cl, and analyzed with atomic absorption spectrometry (Ca, Mg), and flame spectrometry (Na, K; AAS VARIO, Analytik Jena, Germany).

Data analysis

An initial outlier analysis (Bray-Curtis Distance, threshold 2 SD) led to the exclusion of one transect, which was dominated by the salt-tolerant grass *Achnatherum splendens*. Thereafter, Detrended Correspondence Analysis (DCA) was used to visualize the general relationships between community composition and structure. Cover values were transformed ($y = \log [x+1]$), rare species were downweighted. DCA axes were interpreted by means of post-hoc correlation (Pearson's "r") with the available environmental parameters. The relationship between vegetation parameters and soil conditions was additionally tested with a Mantel test (999 runs).

The significances of simple univariate gradients were analyzed with Pearson's "r". For dung unit counts initial Levene Tests indicated heterogeneous variances, so trends were analyzed by a Kruskal-Wallis test. Analyses were performed with SPSS 10.0.5 (SPSS Inc. 1999) and PC-ORD 3.15 (McCune and Mefford 1997).

Results

Dung unit counts supported the idea that distance from the water source can be used as a proxy for animal activity (Figure 2). Dung unit densities were clearly higher in the first 300 m of the transects and remained relatively low between 300 and 1500 m. Spatial trends were significant for all groups of livestock at $p < 0.015$. At 1500 m, unit numbers tended to increase again, indicating that the utilization belt around the next water source was presumably reached.

DCA revealed short floristic gradients of some 2.7 standard deviations (Figure 3), translating to slightly more than half a species turnover between the most dissimilar samples, thus implying that the data set was indeed relatively homogeneous. There was a tendency for more distant samples from the wells to cluster together in the center of the diagram, while heavily grazed plots were placed in the outer parts of the ordination, indicating less homogeneous conditions. Corre-

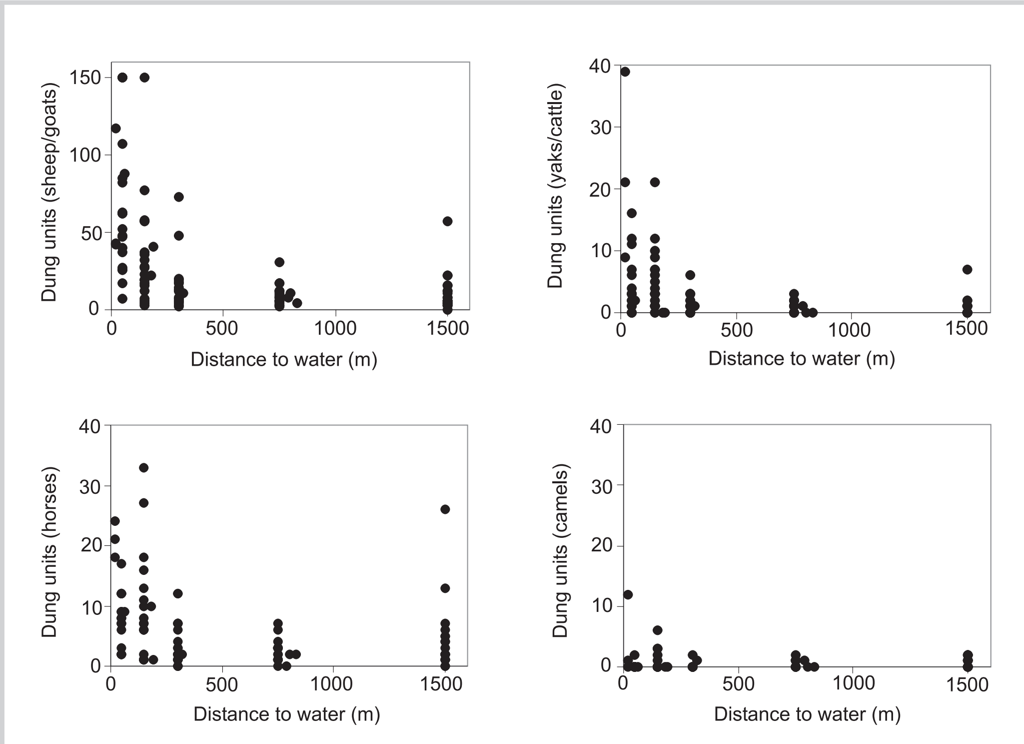


FIGURE 2 Gradients in dung unit density along transects radiating from water sources (n = 97).

lations of explanatory parameters with ordination axes were generally low (Table 2). Axis 1 correlated weakly with distance from the water source, but also with exposure and dung cover of all livestock groups. The second DCA axis was related to the altitudinal gradient and the third to slope inclination. In summary, relationships between multivariate vegetation data and distance from the water source were rather unsubstantial but nonetheless present.

This was confirmed by univariate statistics. None of the analyzed parameters correlated significantly with proximity to the water source (Table 3), and correlations of vegetation parameters with dung cover yielded similarly low R^2 values (data not shown here). We analyzed some of the more important species for grazing-induced gradients, but none displayed significant trends except for *Eurotia ceratoides.* This shrub showed significantly higher cover values near the water sources ($H = 10.649$, $p = 0.031$).

Considering that the direct effects of grazing were limited, we tested whether animal activity had indirect effects on the vegetation through altered soil conditions. For soil samples taken at a depth of 20 cm, none of the analyzed parameters correlated significantly with proximity to the water source (Table 4). For samples at a depth of 5 cm, general soil parameters such as pH, carbonate content, and conductivity were also unaffected by distance to the wells, as were the cations. Soil carbon levels increased significantly with proximity to the water sources, and even more so phosphorus and total nitrogen, where levels were relatively low in general

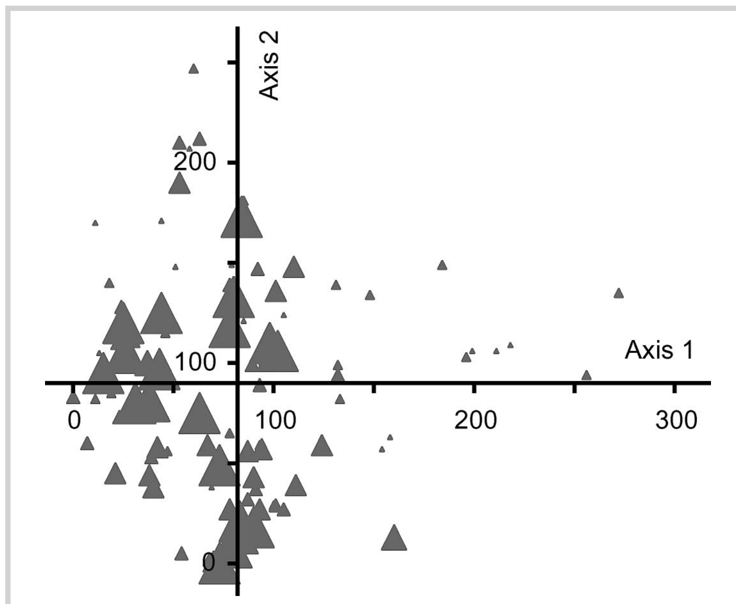


FIGURE 3 Detrended Correspondence Analysis of all samples except outliers. Axes are scaled in multivariate standard deviations (100 units = 1 sd; eigenvalue axis 1: 0.336; axis 2: 0.253, axis 3: 0.135). To facilitate interpretation, distance to the water source was overlayed on the ordination; the bigger the symbols, the larger the plot's distance to the water source.

(Figure 4), indicating that increased values could potentially influence the vegetation. In a final step we tested the influence of soil parameters on vegetation composition. A Mantel test for an association between vegetation composition and soil nutrient conditions (C,

TABLE 2 Post-hoc correlations of secondary data with the first 3 ordination axes of Detrended Correspondence Analysis (Pearson's "r").

Axis	1	2	3
Parameter	r	r	r
Vegetation cover	0.140	0.296	0.179
Bare soil	0.014	0.035	–0.165
Rock cover	–0.082	–0.170	0.081
Distance to well	–0.227	–0.232	–0.051
Altitude	–0.196	0.507	–0.100
Eastness (sin exp.)	0.250	0.038	–0.167
Northness (cos exp.)	–0.219	–0.085	0.223
Inclination	–0.033	0.074	0.573
Dung (sheep/goats)	0.212	0.148	–0.008
Dung (cattle)	0.385	0.307	–0.055
Dung (horses)	0.334	0.305	–0.034
Dung (camels)	0.109	0.126	–0.050

TABLE 3 Correlations of vegetation parameters with distance from the water source (Pearson's "r"; all correlations not significant, p >0.05).

Parameters	Distance to water (R^2)
Total cover	0.015
Species richness	0.016
Shrub cover	0.013
Shrub richness	0.050
Dwarf shrub richness	0.050
Hemicryptophyte richness	0.015
Geophyte richness	0.036
Annuals, richness	0.021

N, P) yielded a non-significant relationship (standardized r = 0.06, p = 0.325).

Discussion

Dung unit density is reasonably well related to animal activity in drylands (eg Turner 1998), and provides an integrated estimate on timescales of some months to one year. The significant gradients of dung unit density lend support to the design of our study, where distance from the wells was used as a proxy for the anticipated grazing gradients. Herders confirmed that the principal fuel source is dung that is collected around the *gers*, so gradients in dung unit density could be even steeper if dung were not so intensively collected around the camps.

Dung unit density counts suggest that there are merely two main levels of grazing intensity in the study region. There is a steep decline within the first 300 m around the water source, demarcating an inner belt of intensive use. Beyond this, animal activity appears to be low, but constantly present—a pattern often observed in similar studies (Tolsma et al 1987; Fernandez-Gimenez and Allen-Diaz 2001). In the study area, only sheep and goats are actively herded, but in summer horses also stay near the *gers*, where the foals are kept (in order to have the mares available for milking). The slight increase at 1500 m even suggests that grazing ranges of herds from neighboring wells overlap. In any case, all sites in the study region are grazed; virtually the entire Gurvan Sayhan region is under direct influence by pastoral land use.

Shrub cover is positively correlated with grazing pressure in many grasslands of the world, but not so in the Mongolian steppes (Fernandez-Gimenez and Allen-Diaz 1999). In contrast, shrub presence here is controlled by the substrate rather than by the grazing regime. The principal species are *Caragana leucophloea* and *Eurotia ceratoides*. Both species are preferentially grazed, and are also occasionally collected as fuel. We therefore expected shrub cover values to decrease under increasing grazing pressure. Our data contradict this, however; neither cover nor richness of large shrubs (eg *Caragana*) and dwarf shrubs (eg *Artemisia frigida*) appeared to be influenced by livestock activity. The only significant exception was *Eurotia ceratoides*. This is surprising since it is highly grazed. Unfortunately, our limited data set (<20 occurrences) does not make it possible to conclude whether or not this species is a positive grazing indicator.

It is widely considered that grazing alters plant community composition and structure in rangelands (Milchunas and Lauenroth 1993). However, since virtually no untouched vegetation is left in our study region, nor in comparable steppe regions of other countries, we can only state that differences between sites of high and low grazing intensity are small, and that no devastative processes were observed.

Both distance from the well and dung cover had only a limited effect on species composition, as shown in the ordination. Univariate parameters such as species richness showed no relation at all. Overall, dry mountain steppe vegetation in our study region displayed only weak grazing gradients in terms of plant community composition. This is in line with

TABLE 4 Pearson correlations of soil parameters with distance from the water source in 3 typical transects. Samples were taken at 2 different depths (n = 14; * = $p < 0.05$; where significant, negative trends are indicated by ↓).

Parameter / Depth	–5 cm R^2	–20 cm R^2
pH	0.040	0.002
Conductivity	0.149	0.008
Carbonate	0.003	0.012
K	0.158	0.074
Na	0.141	0.109
Ca	0.001	0.001
Mg	0.111	0.001
Total carbon	0.335*↓	0.014
Total nitrogen	0.348*↓	0.012
NH_4	0.009	0.138
NO_3	0.174	0.076
Phosphorus	0.341*↓	0.008

studies in desert steppes in central Mongolia, where distance from the well had an equally minor impact on community composition (Fernandez-Gimenez and Allen-Diaz 1999 and 2001). However, the same study found trends in moister steppes of the same region, where distance had a clear impact on plant communities and sites close to the water source had a reduced species richness. This difference can be explained in terms of the plant communities involved, which constituted relatively moist mountain steppes, while the dry steppes on the pediments in the Gobi Gurvan Sayhan are dominated by *Stipa gobica*, and are hence best referred to as desert steppes (Hilbig 1995). Thus, the vegetation in our study area is intermediate between the two community groups studied in central Mongolia.

Nutrient levels are generally low in the Gobi Gurvan Sayhan region, as they are in dry grass and desert steppes of central Mongolia (Fernandez-Gimenez and Allen-Diaz 2001). This supports the idea that land use might be responsible for large-scale nutrient depletion. Livestock consume a high proportion of the biomass, and there should be a centripetal transport of nutrients towards water sources or herders' camps. Moreover, herders rely almost exclusively on dung unit collection for fuel. Wells are spatially fixed, so herders visit the same summer places every year. As ash is discarded in the direct vicinity of the camps, nutrients are presumably not dispersed back to the steppes where they came from (except by wind).

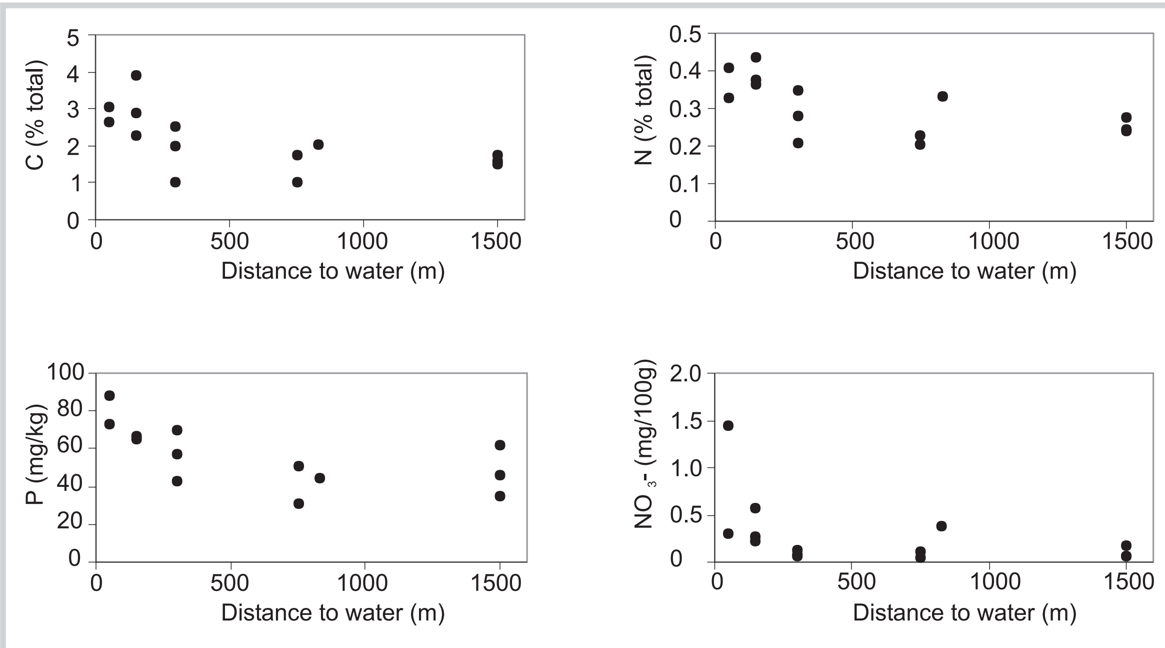
We did not address the latter pathway in this study but found strong evidence for centripetal nutrient translocation by livestock. Nitrogen, carbon, and phosphorus appear to be the crucial soil nutrients; bases such as calcium should be of minor importance with respect to the accumulation of cations near the surface in these dry environments. Similar centripetal trends of soil nutrients were also found in central Mongolia, but also in other rangelands under varying precipitation regimes (eg Tolsma et al 1987; Turner 1998; Augustine 2003). Phosphorus is generally important in this respect, as is total carbon. As in our study, results for inorganic nitrogen (NO_3, NH_4) are often less clear, reflecting their general mobility in the soil. Inorganic nitrogen is mainly deposited by urination and easily lost (Clark and Woodmansee 1992), while phosphorus and organic carbon are concentrated in the more stable droppings.

We have no measure on changes in plant productivity, with respect to grazing and nutrient gradients, and the general picture might differ from that obtained for species richness, for example (Milchunas and Lauenroth 1993). However, the Mantel test indicated an apparent decoupling of soil conditions and vegetation composition. This is in line with several of the examples cited, where researchers found inter-annual climatic variability to be more important in terms of vegetation cover than grazing or nutrient gradients.

Conclusion

Ecosystems never behave exclusively in an equilibrium or non-equilibrium way but can be arranged along a gradient between these two extremes (Briske et al 2003). For Mongolia, relatively moist rangelands such as moist mountain steppes are expected to behave more in an equilibrium manner, while at precipitation levels below 250 mm non-equilibrium dynamics should occur (Fernandez-Gimenez and Allen-Diaz 1999). Our results indicate a prevailing non-equilibrium situation at our study site and, considering the even drier conditions in the lowlands, probably in the entire Gurvan Sayhan region. No significant correlations between distance from water source and vegetation parameters were found, thus neither levels of grazing nor nutrient gradients seem to exert any major influence on the vegetation composition. Precipitation appears to be the overwhelmingly dominant factor instead. This is supported by observations of our group in the study region, where standing crop in July fluctuated between some 230 kg/ha in 2001 and 440 kg in the moist year of 2003 (unpublished data). Moreover, livestock counts suggest that livestock densities do indeed behave in a non-equilibrium way, since herders left the region for better pastures in the drought of 2001 (Retzer 2004). Thus, local carrying capacity is definitely not a stable entity. Yet on a larger scale, livestock numbers for Mongolia as a whole

FIGURE 4 Gradients in concentrations of selected soil parameters for the three transects analyzed.



have been remarkably stable over the years (Retzer 2004), with figures reaching a high of 33 million in 2000 and dropping back to pre-1990 levels of 26 million animals in the following 2 years (National Statistical Office of Mongolia 1996 and 2003). Thus the stability of the system is heavily scale-dependent, as it is in other grassland regions (Oba et al 2003). In consequence, application of the non-equilibrium concept of rangeland science may need some refinement for the dry rangelands of inner Asia (Ho 2001).

The present vegetation in the Gobi Gurvan Sayhan region appears to be relatively stable with respect to grazing, which contradicts the theory of widespread and increasing rangeland degradation in southern Mongolia. Admittedly, we cannot tell whether grazing had previously changed the landscape profoundly, since virtually no remainders of untouched vegetation types are left. In any case, a hypothetical replacement of non-grazing resistant vegetation must have taken place long ago, given that pastoral land use is so old. The present vegetation is probably a grazing-induced pseudoclimax that is stable and grazing-resistant. Thus, unlike parts of Inner Mongolia, land degradation still has been comparatively minor in Mongolia (Neupert 1999), largely because herders maintained a migratory (semi-)nomadic life style, whereas in China many herders were settled (Ho 2001). The relatively healthy state of Mongolian pastures allows time to prepare for future problems the country is bound to face with an increasing human population (Sneath 1998).

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