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ORIGINAL ARTICLE

Spatial analysis of the driving factors of grassland degradation under conditions of climate change and intensive use in Inner Mongolia, China

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Abstract In recent years, steppe degradation in North China has become a serious environmental problem. Most research on steppe degradation is conducted at the level of communities or at the scale of small regions. To better understand the spatio-temporal variation and driving factors of grassland degradation, monitoring and analysis at broad regional scales are needed. This paper systematically describes the state and characteristics of steppe degradation at the Xilinhot plateau, makes an in-depth empirical analysis of the natural and man-made causes leading to degradation, and analyzes what driving factors have influenced degradation in this typical steppe region over the last 20 years. Ten biophysical and socio-economic variables, including altitude, slope, precipitation, temperature, soil conditions, distance to river, distance to highway, population density, sheep unit density, and fencing policy, were evaluated on their impact on observed patterns of degradation. The results indicate that all of these factors had a significant influence on the process of steppe degradation. During the first 10 years, from 1991 to 2000, steppe degradation increased, but after 2000, the degradation trend has, to some extent, reversed. The analysis indicates that the measures taken by the government, such as fencing vulnerable areas, played an important role in this change. The results advance the understanding of grassland degradation and contribute to constructing an empirical and theoretical base for grassland management and planning.

Keywords Steppe degradation · Grassland · Degradation · Driving factors · Spatial analysis

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Introduction

Grassland degradation has become a major environmental and economic problem in large parts of the world. The problem is especially serious in Inner Mongolia, China, which has one of the world largest grassland regions. Grassland degradation leads to desertification, reduces grassland productivity and biodiversity, and accelerates the occurrence of dust storms (Wu and Loucks 1992; Li 1997; Liu et al. 2002; Chen and Jiang 2003; Li et al. 2003; Tong et al. 2004). The problem has been widely discussed in both the academic and policy environment (Abel and Blaikie 1989; Quinlan 1995; English 2002; Jiang 2005; Li et al. 2005; Schleuning et al. 2009; Anthony et al. 2008; Hijaba et al. 2004; Paulo and Caterina 2009). However, there is still insufficient knowledge available on the degradation process and its driving factors at the landscape or regional scale (Tong et al. 2004).

Steppes are the primary natural resource in both northern China and the vast semiarid region of the Eurasian continent. The term "steppe degradation" is often referred to as a process in which grassland production decreases and ecosystem conditions deteriorate because of poor management, overgrazing, and the changing physical environment (Li 1997; Liu et al. 2002; Chen and Jiang 2003; Li et al. 2003). The attributes of steppe degradation include the declining conditions of vegetation for multiple uses (grazing, biodiversity conservation, and recreation), the increasing proportion of less palatable plants, the decreasing resistance to topsoil erosion, and the decreasing root-zone moisture holding capacity (Tong et al. 2004). The vegetation pattern is a good indicator of steppe degradation, and therefore, remote sensing and spatial information technologies have been widely utilized in monitoring vegetation dynamics, including grassland degradation (Bastin et al. 1995; Tanser and Palmer 1999; Wang et al. 2001; Geerken and Ilaiwi 2004; Tong et al. 2004; Cao et al. 2006; Liu et al. 2006, 2008; Li and Liu 2007; Gao et al. 2009; Carrion et al. 2010). Steppe degradation in arid, semiarid, and dry subhumid areas is the result of various factors. Most frequently mentioned are variability in climatic conditions and human activities that lead to increased pressure on the vegetation (Li 1997; Li et al. 2003; Evans and Geerken 2004; Geerken and Ilaiwi 2004). A series of natural controlling factors, including altitude, slope gradient, climate conditions, and soil conditions, affect the growing season, pasture output, and the community structure of pastures (Bai et al. 2004; Liu et al. 2006; Fu et al. 2007; Yue et al. 2007; Shao et al. 2008; Shao and Cai 2008). Human factors, such as overpopulation, overstocking with livestock, and uneven grazing, further aggravate eco-functional degeneration of natural pasture land (Ludwig et al. 2000; Liu et al. 2006; Fu et al. 2007; Zang et al. 2007; Yue et al. 2007; Zhao 2007; Bian et al. 2008). The eco-environment in grassland regions has been improved in a number of cases after the introduction of policies to protect grasslands. The ecological effects reported include the restoration of grassland production, vegetation coverage, grass height, and soil organic matter (Su et al. 2005; Lu and Zhao 2008; Cheng et al. 2011). Nevertheless, most of these studies concentrate on a single factor or experimental treatment at the local scale (e.g. Liu et al. 2002; Li et al. 2003) and are still unconcerned with the more complex spatially diverse interaction of factors that are driving steppe degradation at landscape and regional scales (Yu et al. 2010).

While most of the current studies of grassland degradation focus on the local scale, this paper adds empirical evidence of the spatial and temporal variations in degradation at the scale of a large region. The regional scale impacts of biophysical and human factors are analyzed for a degraded steppe region in Xilinhot, one of the most representative areas of the Inner Mongolia steppe region. The objective of the paper is both to present an inventory of the spatio-temporal patterns of steppe degradation at the regional scale and to explore which factors affected the degree of degradation. The approach presented in this study combines remote sensing data (TM/ETM), data sets of natural and socio-economic variables, and additional field surveys. The combination of these data sets provided a unique opportunity to analyze both the role of the different factors separately and their combined effect in an econometric analysis.

In the next section, the study area and the development of the data set are described while "Methods" describes the methods for analysis of the driving factors of degradation. Results and discussion of the analysis of individual factors and the multivariate analysis are described in "Results." In the final section, we discuss the underlying processes explaining the empirical results. We conclude that the analysis has confirmed our hypothesis that spatial–temporal patterns of grassland degradation are the result of multiple, interacting, factors. The paper provides evidence for the role of policies in improving grassland. Based on the results, the implications of the findings for policy and further research are discussed.

Study area and data

Study area

The study area, Xilinhot, is located near the geometric center of Inner Mongolia autonomous region (IMAR) in northern China and covers about 15,000 km^2 (115°–118°E and 43°–45°N; Fig. 1). The eastern part of the study area is dominated by low mountains and hills, with an average elevation of approximately 1,300 m. The area gradually gets more flat to the west with a decrease in elevation from the south to the north. The area is located within the temperate climate zone with a continental monsoon climate, receiving an average annual precipitation of 250–350 mm. Seventy-five percent of the precipitation falls in the growing season of June to September. The annual temperature is around 1–4°C (at Xilinhot) with minimum monthly mean temperatures of −13.6°C in January and maximum 22.1°C in July. As one moves from the

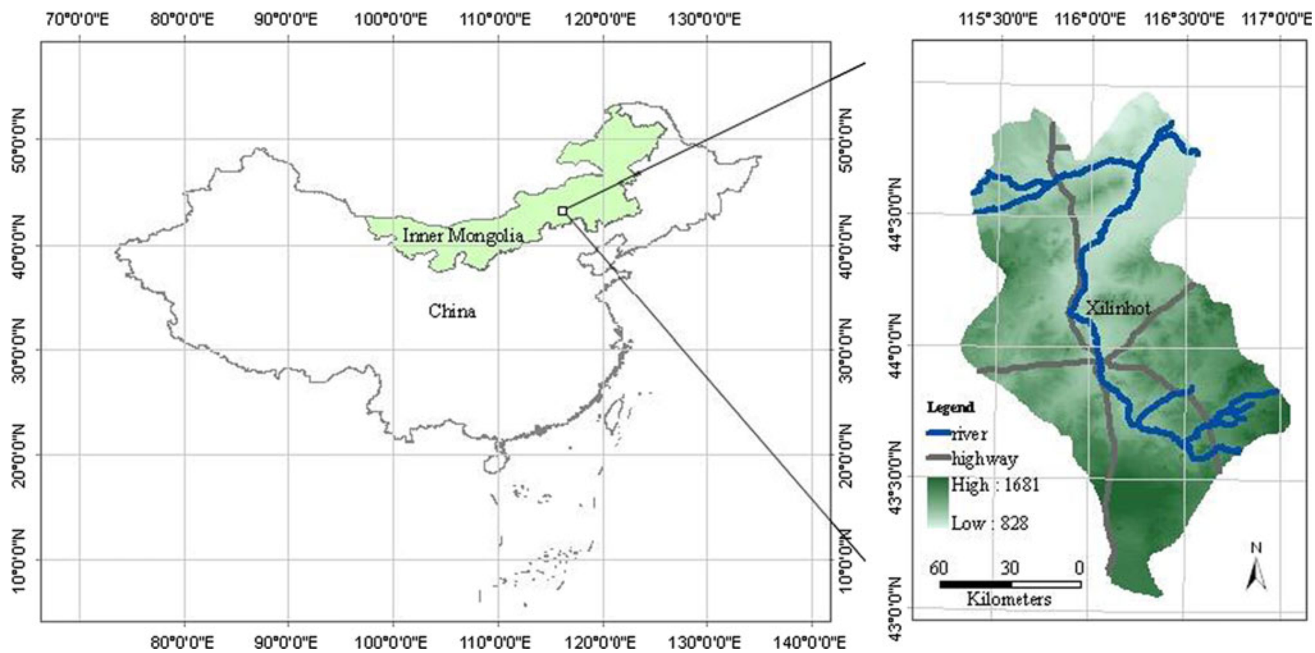


Fig. 1 Location of the study area

southeast to the northwest, both temperature and precipitation decrease gradually. The vegetation in Xilinhot has diverse plant communities that are found throughout much of the steppe region of northern China (Tong et al. 2004). This area serves as an important animal husbandry base for the Inner Mongolia autonomous region (IMAR). *Stipa grandis* steppe, *Stipa Krylovii* steppe, and *Leymus chinensis* steppe are the dominant (climax) plant communities in the region. However, overgrazing has introduced additional succession communities. Based on numerous studies carried out by Inner Mongolia University and the Inner Mongolia Grassland Ecosystem Research Station over the past several decades, Liu et al. (2002) developed a diagnostic model of steppe degradation which can be applied to estimate degradation grades according to the character of degradation. This study follows their classification system and adds more recent monitoring data.

Data

The data sets used in the paper were collected by three different approaches: (1) remote sensing images (TM/ETM) of three different years are used to assess and classify steppe degradation; (2) socio-economic and biophysical data sets from the government or related institutes are used to explain spatial and temporal patterns of steppe degradation, and (3) the data sets collected through field surveys are used to provide more detail in cases where regional-level variables were not available. All data are processed independently and are listed in Table 1.

Grassland degradation was based on remote sensing data derived from three Landsat TM/ETM images, respectively originating from 1991, 2000, and 2005, each having a spatial resolution of 30 m. Section "Mapping of grassland degradation" describes the procedure for interpreting these data in more detail.

A selection of biophysical and socio-economic variables that were assumed to be indicators for the process of grassland degradation was made based on their importance for the grassland ecosystem. The selection was based on frequently mentioned (proximate) drivers of spatial patterns of grassland degradation (Geist and Lambin 2004) and the results of previous studies applicable to the region. Landform was chosen to describe the general configuration of the surface, which included altitude, slope, and aspect. Altitude and slope were derived from a regional DEM (Digital Elevation Model). The growth of grass in the region is easily restricted by water availability (Li et al. 2003; Bai et al. 2004). Research has shown that climatic factors, especially precipitation and temperature, have a large impact on the grassland vegetation (Li and Shi 2000; Bai et al. 2004; Liu et al. 2006). We selected the climatic records of weather stations around Xilinhot from 1961 to 2005 to analyze the influence of rainfall and temperature on steppe degradation. Spatial distributions of annual rainfall and annual temperature maps of the 3 years analyzed were created through spatial interpolation using distance weighted kriging. Soil conditions are also important for plant growth and water retention. At the same time, grassland degradation is likely to affect soil quality by

Table 1 Description of the variables used in the analysis

Variable	Units	Original data format	Data processing method	Source	Obs. in MNL
Annual rainfall	mm	Raster	Kriging interpolation	16 weather stations (National Weather Service of China)	400384
Annual temperature	°C	Raster	Kriging interpolation	16 weather stations (National Weather Service of China)	400384
Altitude	m	Raster	–	DEM (State Bureau of Surveying and Mapping of China)	400384
Slope	°	Raster	Calculated from DEM	DEM (State Bureau of Surveying and Mapping of China)	400384
Soil organic matter	%	Polygon	Digitization	Soil organic matter map (Chinese Academy of Agricultural Sciences)	400384
River	–	Polyline	Digitization	TM image (Institute of Remote Sensing Application Chinese Academy of Sciences)	400384
Highway	–	Polyline	Digitization	TM image (Institute of Remote Sensing Application Chinese Academy of Sciences)	400384
Villages	–	Polygon	Digitization	Administrative Map (Xilinhot Government)	400384
Population density	Persons/km^2	Polygon	Digitization	Census Data (Local Bureau of Statistics in Xilinhot)	400384
Sheep unit density	Sheep unit/km^2	Polygon	Digitization	Animal Census Data (Local Bureau of Statistics in Xilinhot)	400384
Field survey	–	Points	GPS	Household investigation	400384
Fenced grasslands	–	Polygon	Digitization	Local map (Xilinhot Government)	400384

changing the physical and chemical properties of the soil (Liu et al. 2002). Soil organic matter was selected as an indicator of the soil conditions that affects grassland quality. Spatial accessibility to water resources, roads, and residential area was also hypothesized to influence degradation. Rivers inside Xilinhot region were interpreted from ETM images. Furthermore, the same method was used to obtain the location of the highway. Distance to highway is considered a driving factor of degradation as it provides access to these remote landscapes.

Socio-economic data were obtained from population and stockbreeding censuses for the 3 years considered, including population density and livestock density. These data are available at the level of village administrative units (locally called Gacha) and can be spatially represented by a polygon. More detailed socio-economic data were collected through interviews: 90 herd families were interviewed in 2005 to get more details about the spatio-temporal distribution of degradation and its perceived causes.

Degradation issues have received attention from the local and the central government, and several regulations to protect the grasslands were enacted and implemented. A policy was implemented through fencing and enclosing some serious degraded grassland in order to restore their original vegetation. Since 2001, these measures were introduced step by step. Maps of the fenced areas were used to compare the grasslands inside the fence with the grasslands outside the fence for the 3 years considered in order to explain the effect of the fencing policy on degradation.

Methods

Mapping of grassland degradation

The Landsat ETM/TM images of 1991, 2000, and 2005 were interpreted by their pseudo-color composition and mosaic in ERDAS software. The spatial resolution of the images is 30 by 30 m. Using a 1:100,000 topographic map, the images were rectified by geometric rectification and transformed into UTM projection. Both land use and degradation status were classified in these images. Following general practice in China (Liu et al. 2002), this study applies the diagnostic character of steppe degradation (Liu et al. 2002) and categorizes grasslands into four grades or types of degradation. After testing for error by field samples, the Gutman model was applied to estimate the regional vegetation fractional coverage (VFC). The Gutman model is one of the most commonly used methods to estimate VFC based on observed NDVI data (Gutman 1987). The four grades of steppe degradation determined by VFC are the following: light degradation (LD, vegetation coverage >55 ± 3%), moderate degradation (MD, vegetation coverage 40–55% ± 3%), heavy degradation (HD, vegetation coverage 25–40% ± 3%), and extreme degradation (ED, vegetation coverage <25 ± 3%). A field survey in the study area was conducted to check and validate the accuracy of the interpreted images (Li et al. 2007). Based on 86 field observations and a number of additional observations through detailed aerial photographs, the overall classification accuracy of the grassland degradation classification was 69% in 1991, 61% in 2000, and 63% in 2005 respectively.

Spatial and temporal analysis of driving factors

The possible association between grassland degradation and each of the factors was investigated for all factors separately followed by a multivariable approach.

Some reclassification of the data was made to facilitate the analysis. The annual rainfall was classified into six classes: 100–150, 150–200, 200–250, 250–300, 300–350, and 350–400 mm. The spatial distribution of these classes was compared with the degradation classes. For temperature data, a similar approach was followed. The range of mean annual temperature was subdivided into 6 classes: 1–1.5, 1.5–2, 2–2.5, 2.5–3, 3–3.5, and 3.5–4°C. For both landform and climate, a spatial analysis was preformed to calculate the prevalence of the different degradation classes within each of the classes of climate and/or landform.

This study used soil information at two different levels. Soil maps representing soil organic matter were used in the multivariate analysis. However, since soil maps often do not represent the fine-scale results of interactions between vegetation and soil conditions, this study also used soil samples collected in field surveys during 2005 to get more information on the relationship between the soil properties and degradation. ANOVA analysis was applied to understand the relationship between soil organic matter and the different degradation classes.

The proximity of a river is also supposed to influence the degree of degradation of the grasslands. The average degradation index of buffers of 150 m wide at incremental distance from the rivers was calculated. A similar method was used for the proximity to highways.

Ninety herd families were interviewed in 2005. The rangelands surrounding the village houses were analyzed with buffers at 150 m distance up to 3 km from the house. The degradation status of grasslands within these buffers was extracted. At the Gacha level, correlation analysis was applied to analyze the relationship between the population density/sheep unit density and an index of the steppe degradation calculated following:

$$\text{Degradation index} = (\text{HD} + \text{ED})/(\text{LD} + \text{MD}) \quad (1)$$

where HD is heavy degradation and ED is extreme degradation, LD is light degradation, and MD is moderate degradation.

Multivariate analysis

A multivariate analysis was carried out for the variables that were shown to have an influence on the spatial and temporal patterns of grassland degradation. This analysis was performed in order to see to what extent the variables together can explain spatial and temporal patterns of grassland degradation in the region. Such multivariate analysis is common in land science and follows the conceptual model specified by Chomitz and Gray (1996). Chomitz and Gray base their conceptual model on the Von Thünen model in which land cover is allocated according to land rent. The assumptions of this model do not fully apply to grassland degradation classes. In the case of grassland degradation classes, it is assumed that the likelihood of finding a specific degradation class is a result of the interplay between biophysical, socio-economic, and policy processes. Therefore, we assumed that the variables included in the analysis can be used as predictors of the occurrence of the different degradation types.

A multinomial logistic regression model was used to explain the occurrence of the different degradation types. Multinomial logistic regression models are used to predict the probabilities of the different possible outcomes of a categorically distributed dependent variable, given a set of independent variables.

A 1% sample of the spatial data across the 3 years of observation was used to create a panel data set. This data set contains observations of grassland quality and potential explanatory variables for 3 years. One of the choices to analyze such data is the panel data logit model which brings unobserved effects explicitly in the model, the form of which is:

$$\log\left(\frac{p_{itk}}{1 - p_{itk}}\right) = \beta_0 + \beta_n X_{nit} + v_t + \varepsilon_{it} \quad (2)$$

where p_{itk} is the probability of finding degradation class k relative to the reference class (moderate degradation), v_t refers to as unobserved heterogeneity, ε_{it} is error, and $\log(\cdot)$ denotes the natural logarithm.

There are two methods for estimating unobserved effects panel data namely fixed-effects model and random-effects model, and the former assumes that the unobserved heterogeneity v_t is correlated with each explanatory variable, whereas the latter assumes that v_t is uncorrelated with each explanatory variable. The fixed-effects panel model basically investigates how time affects the intercept using $t - 1$ time dummy variables. Random-effects model assumptions are violated given that the unobserved effect is not fully independent of the explanatory variables given the temporal dependence of especially the climate variables.

Temporal autocorrelation may introduce a bias due to time-lagged temporal effects. The model does not include lagged values of grassland quality due to the relatively little variation in the overall land cover over time; therefore, the lagged values predict land use almost perfectly, making model estimation problematic.

Significant variables were selected using a stepwise procedure to explore what variables are explanatory for the observed grassland degradation classes. A random sample of 1% from the available grid cells, totally representing approx. 400,000 observations for 3 years, was drawn to reduce spatial autocorrelation through avoiding neighboring pixels in the sample. This approach does not fully correct for the possible bias due to spatial autocorrelation. However, it is commonly used and will minimize spatial autocorrelation to a level that it will not affect the results (Verburg et al. 2000). Different 1% samples were tested to ensure consistency in the estimation results.

The ROC (relative operating characteristic) was used to indicate the goodness-of-fit of the models (Swets 1988). This measure is capable of assessing the quality of the predictor and can be compared between different models. The ROC summarizes the performance of a regression model over a range of cutoff values of the probabilities. The value of the ROC is defined as the area under the curve linking the relation between the proportion of true positives and the proportion of false positives for an infinite number of cutoff values. The ROC statistic varies between 0.5 (completely random) and 1 (perfect discrimination). Values above 0.7 are generally assumed to indicate a good model fit (Manel et al. 2001).

Results

Remote sensing interpretation of degradation

In all 3 years of the analysis, grasslands were found as the dominant land use type covering more than 80% of the area of Xilinhot (Fig. 2). In 1991, the more seriously degraded grasslands (heavy degradation and extreme degradation) covered 46.0% of the study area. Degraded grasslands were mainly found in the western and northwestern part of Xilinhot region. The better grasslands (light degradation and moderate degradation) were located in the southern and southeastern areas of the study region. Comparatively, strongly degraded areas increased from 46.0% in 1991 to 62.8% in 2000, and they consumedly expanded in the middle and north part of Xilinhot. In 2005, the extent of the strongly degraded classes decreased. During this stage, the better grasslands were scattered into bigger or smaller variform patches in the entire matrix of landscape. From the point, it was good to reflect the typical steppe displayed in the better status in 2005. The remote sensing results indicate that both the spatial and temporal dynamics of grassland degradation must be considered.

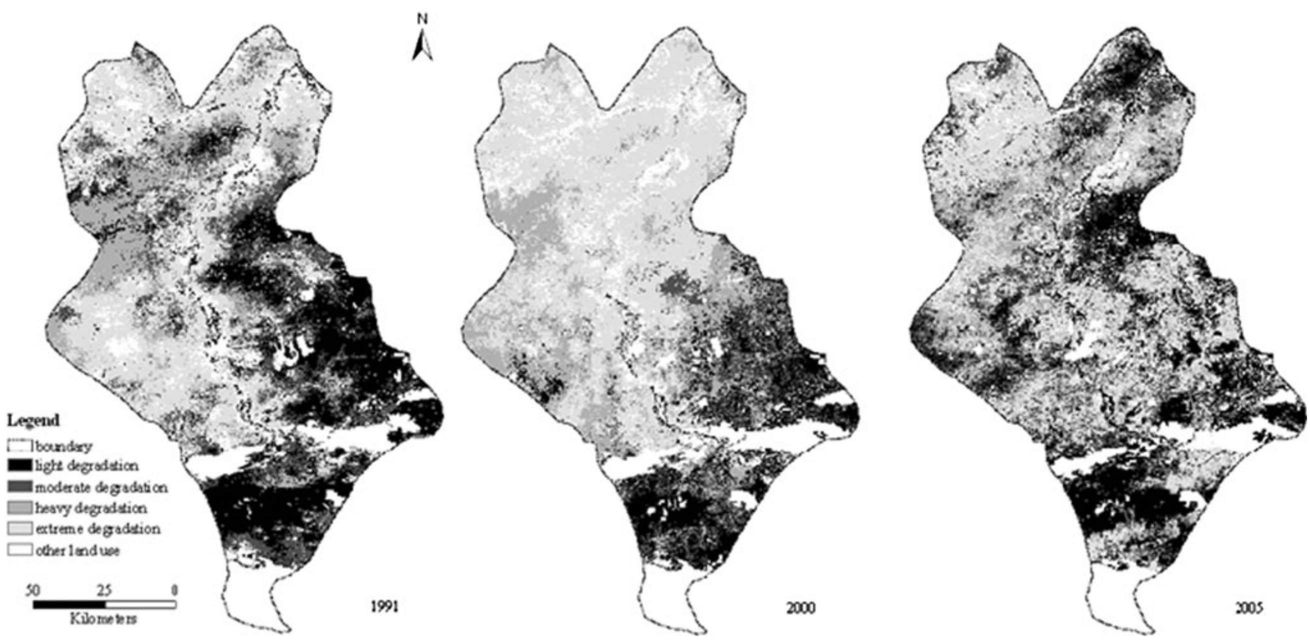


Fig. 2 Steppe degradation interpreted from remote sensing images in Xilinhot for 1991, 2000, and 2005

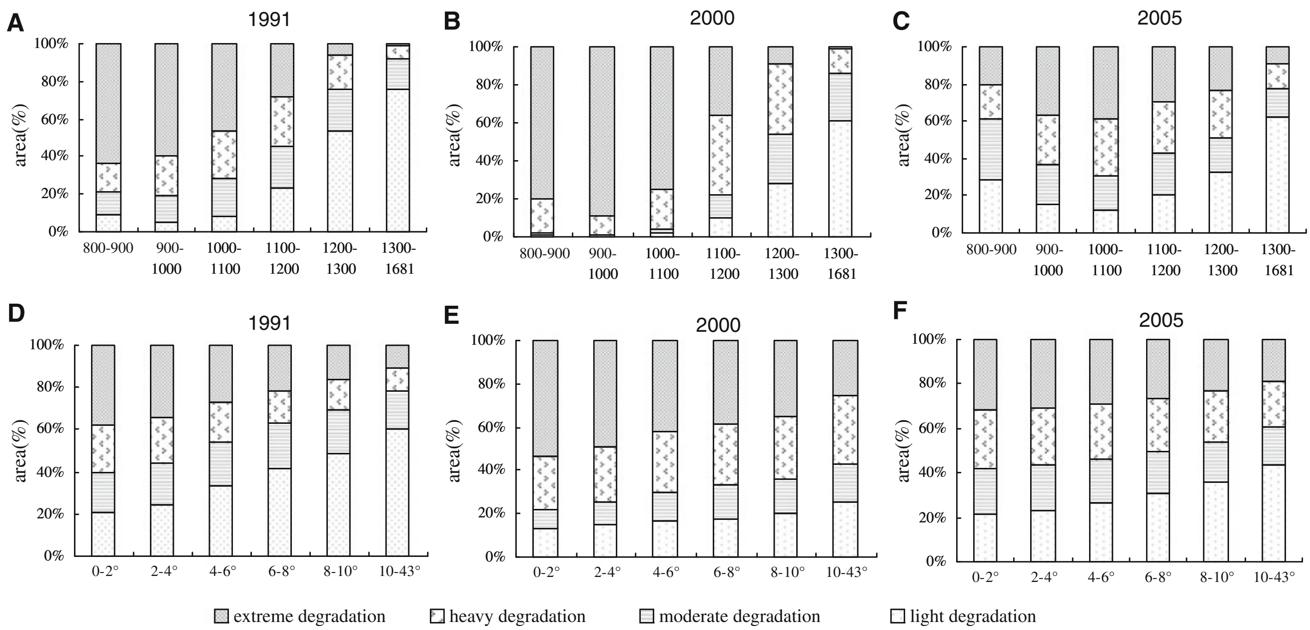


Fig. 3 Prevalence of degradation classes with altitude (**a**, **b**, **c**) and slope classes (**d**, **e**, **f**)

Analysis of individual driving factors

Landform

The altitude of Xilinhot ranges between 828 and 1,681 m. In 1991, the better grasslands (light degradation and moderate degradation) were mainly found at higher altitudes, and there was a gradual decrease in degradation by altitude (Fig. 3). In 2000, an increase in the level of degradation was found in the grasslands between 900 and 1,100 m that cover about 44% of all grasslands. In 2005, the grasslands between 800- and 1,100-m elevation had been largely rehabilitated. In all 3 years, the flatter lands were dominated by strongly degraded grasslands. However, in 2000 also the sloping lands were more deteriorated than before.

Climate change

The annual temperature in the study area increased, based on data from Xilinhot weather station, between 1961 and 2005 by 1.9°C, mainly during winter. At the same time, the annual rainfall dropped down by 12.6 mm. The climatic trend in the region during the past 44 years is therefore clearly toward a warmer and drier climate (Fig. 4). Both temperature and precipitation in the region are decreasing from the southeast to the northwest. It means that the northwest part of Xilinhot is much cooler and drier than the southeast part.

The precipitation in 1991 was plentiful in the whole area with >250 mm rainfall (Fig. 5). Spatial patterns of degradation are clearly related to the spatial variation of rainfall. Irrespective of the different quantities of rainfall between 2000 and 2005, a very similar pattern of association between rainfall distribution and the location of degradation was found. On the contrary, the distribution of degradation types by temperature showed an unstable pattern (Fig. 5) most likely because grassland vegetation was mainly impacted by regional rainfall during the corresponding period. Year 2000 was the hottest year followed by 2005 and 1991.

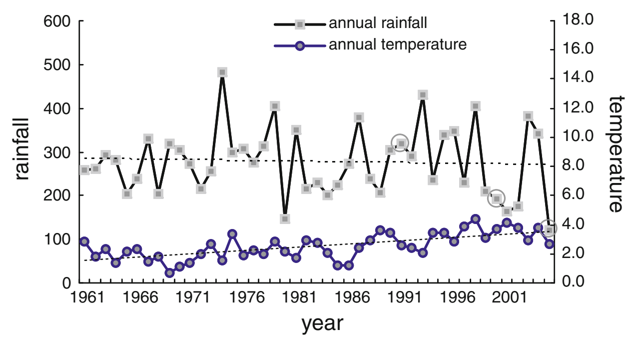


Fig. 4 Development of precipitation and temperature in Xilinhot between 1961 and 2005

Soil organic matter

An ANOVA was made for the soil organic content in the soil samples across the different degradation types. The result indicates that the difference of soil organic matter was significantly ($p < 0.01$) different between the

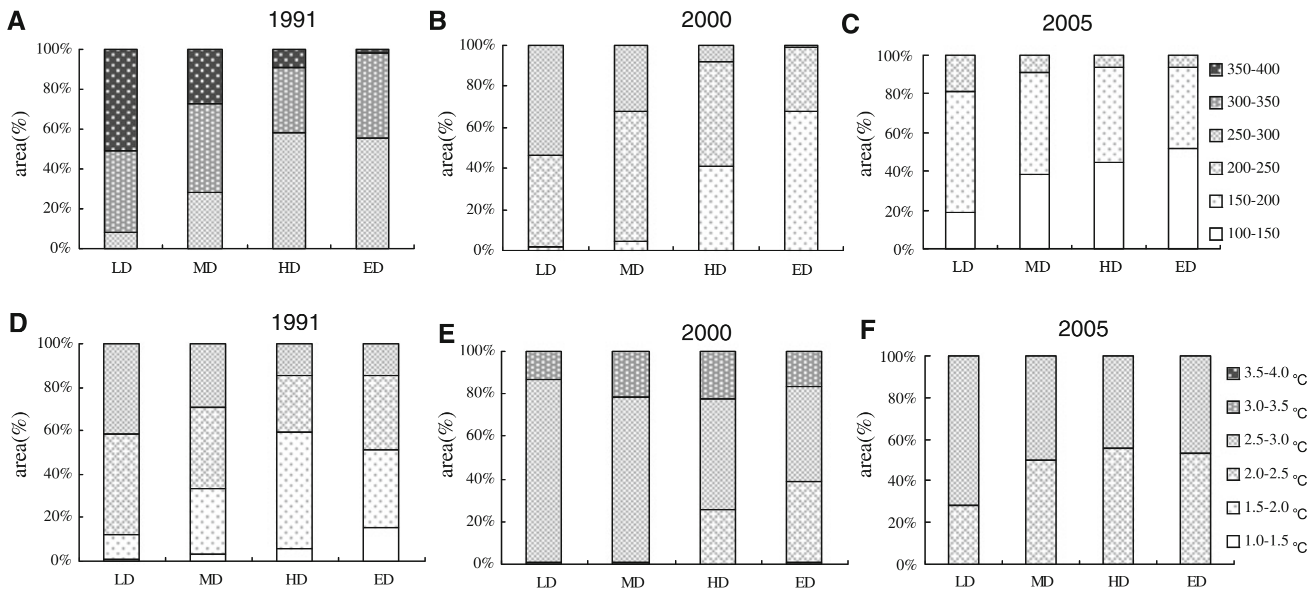


Fig. 5 Distribution of grassland degradation by zone of rainfall (**a**, **b**, **c**) or temperature (**d**, **e**, **f**)

degradation classes (Fig. 6). The soil organic matter in the light degradation class was much higher than in the other degradation classes because dead grass and litter decrease upon degradation due to a lower supply of organic matter to the soil. At the same time, low organic matter content can make grasslands more vulnerable to degradation. The analysis based on the soil maps shows a similar pattern, but the differences in the content of soil organic matter were less pronounced than those observed in the soil samples.

Distance to river

The relation between the degradation index and the distance to the river shows a pattern that can be divided into three parts (Fig. 7). For the first part, between 150- and 900-m distance from the river, the degradation index sharply increased with increasing distance to the river. Between 900 and 3,000 m, the degradation state was slowly increasing or almost stable with distance to river. However, at distances >3,000 m, the degradation index decreased slightly. This pattern of degradation may be explained by water availability that favors grass growth near the river followed by overuse of the grasslands at relatively short distances to the river.

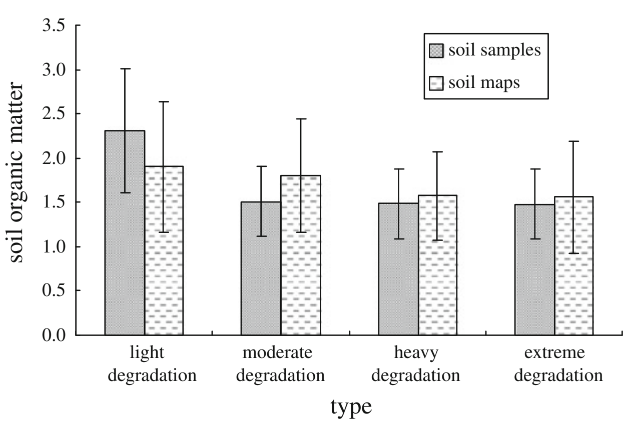


Fig. 6 Average soil organic content in grassland according to different degradation classes based on, respectively, field samples taken in 2005 and an analysis of the soil map

Distance to highway

The relation between the degradation index and distance to the main road can also be separated into three parts (Fig. 8). For areas within 450 m of the road, the degradation index decreased sharply with distance to the road. This means that grassland degradation near the road was more serious than that further from the road. Between 450 and 3,750 m, the degradation was stable with increasing distance. At distances >3,750 m, the degradation index increased slightly.

Distance to household residence

With increasing distance to the household residence, light degradation, moderate degradation, and heavy degradation increased steadily in 2005. The occurrence of extremely degraded grassland decreased after an increase at distances <300 m from the residence (Fig. 9). The level of degradation rapidly decreases at distances larger than 900 m from the household residence.

Fig. 7 Relation between distance to river and grassland degradation. High values of the degradation index indicate strong degradation

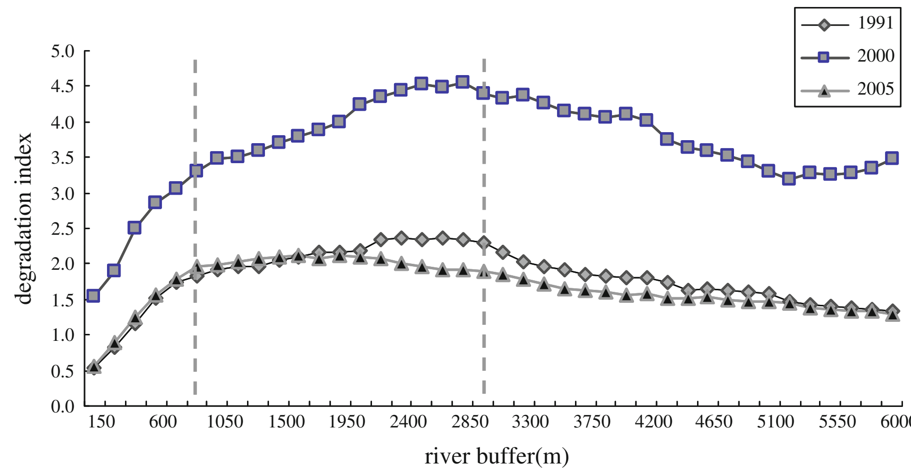
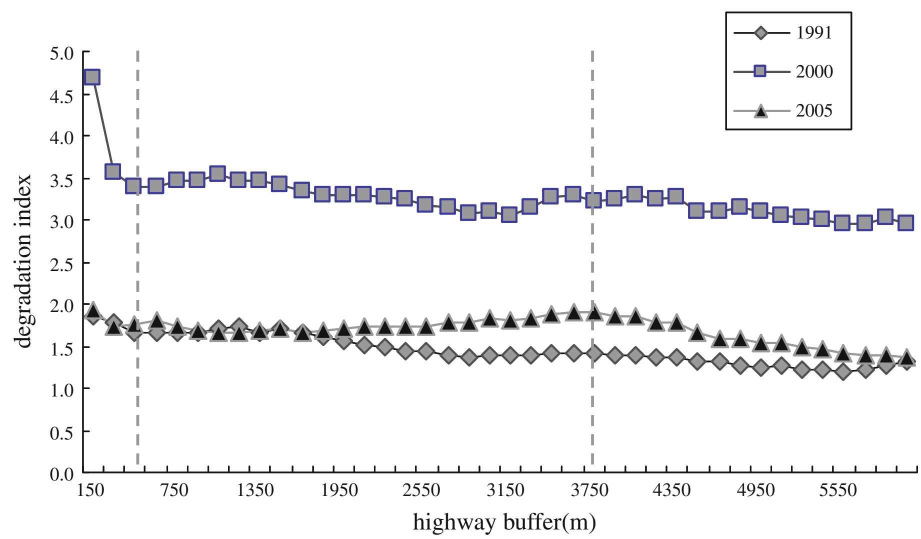


Fig. 8 Relation between distance to roads and grassland degradation. High values of the degradation index indicate strong degradation



Population density and sheep unit density

From the correlation analysis between the degradation index and the population density and sheep unit density, it can be seen that sheep unit density has a significant, positive, relation with the degradation index. The correlation coefficients were, respectively, 0.58 in 1991, 0.68 in 2000, and 0.75 in 2005. Correlations with population densities were not significant.

Fencing policy

In 1991, the share of the different degradation classes was nearly the same inside and outside the fenced areas (Table 2). In 2000, grasslands inside of fenced area were more degraded than outside of the fenced area. This is not surprising since the fencing policy was only implemented from 2001 onward. In 2005, the abundance of the light and moderate degradation classes was far higher within the fenced areas as compared to the unfenced situation, clearly indicating the beneficial effect of the fencing policy.

Multivariate analysis of driving factors

The resulting multinomial logistic regression model is shown in Table 3. Seven variables (altitude, slope, annual rainfall, distance to highway, soil organic matter, sheep unit density, and fencing policy) have a significant, positive influence in explaining the occurrence of the light degradation class. High values of these variables are related to the occurrence of the light degradation class. Population density, annual temperature, and distance to river showed a negative relation with light degradation. These results indicate that high values of these three variables reduce the likelihood for finding this class. For the models of heavy degradation and extreme degradation, the most notable results were that fencing policy had a significant negative effect. The results show that the degradation is lower in

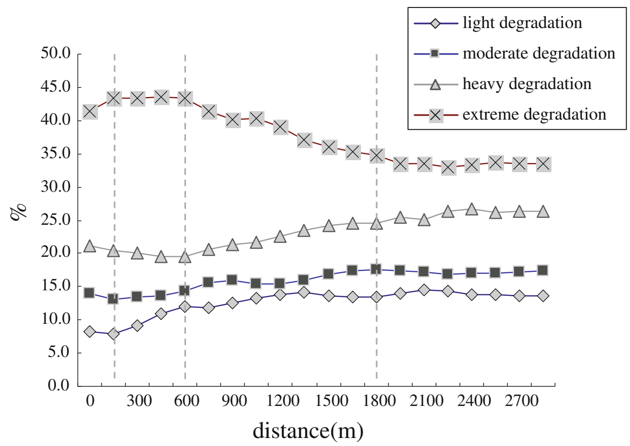


Fig. 9 Area covered by different degradation classes with distance to household residence

Table 2 Grassland degradation within fenced areas and in a 1 km buffer outside fenced areas (% of area)

Year	Light degradation (LD)	Moderate degradation (MD)	Heavy degradation (HD)	Extreme degradation (ED)
1991				
Inside fence	25.85	18.66	23.82	31.67
Outside fence	23.89	20.85	20.55	34.70
2000				
Inside fence	4.96	11.43	20.44	63.18
Outside fence	12.58	9.28	26.85	51.30
2005				
Inside fence	24.43	22.46	27.39	25.72
Outside fence	21.75	21.01	27.01	30.23

areas where fencing is implemented. In the model for heavy degradation, five driving factors, including altitude, distance to highway, distance to river, sheep unit density and annual temperature, showed a positive relation with the occurrence of heavy degradation, while the other factors have a negative effect on the probability for heavy degradation.

To test the goodness-of-fit of the models, ROC (relative operating characteristic) statistics were calculated. A ROC value of 0.84 was obtained in the light degradation model, indicating a good fit. The ROC statistic for the occurrence of heavy degradation was 0.68, indicating a reasonable model fit. In the extreme degradation model, a value of 0.81 was obtained indicating a good fit.

Estimates for the coefficient of the year dummies were significant for all three regression models. Year dummies for 1991 and 2000 were negative in the light degradation model while showing a positive value in both the heavy degradation and extreme degradation models. As the year 2005 was used as a reference (i.e. no dummy was included for 2005), these results indicate that, irrespective of the change in climatic the variables between the years, an overall lower degradation was found in 2005 as compared to 1991 and 2000.

Discussion

Xilinhot, with its continuous drought and overgrazing, has undergone strong degradation of the steppe landscape in the past decades. The maps indicate that the larger part of the region is moderately to strongly degrade. The changes observed are exemplary for many other regions in Inner Mongolia and the world (Ludwig et al. 2000; Chen and Jiang 2003; Abulea et al. 2005; Harris 2010). The result of the analysis of possible explanatory factors illustrates that there is no simple, single factor, causation in grassland degradation and that the spatial and temporal processes of degradation are the result of a combination of natural and socio-economic factors. Our results showed that altitude, slope, precipitation, temperature, soil organic matter, distance to river, distance to highway, population density, sheep unit density, and fencing policy all have a significant value in explaining the processes of grassland degradation. The result is consistent with other studies, supporting the conclusion that degradation is caused by multifactor causation, especially including regional drought and livestock pressure (Li 1997; Liu et al. 2002; Geist and Lambin 2004). The exact combination of factors influencing degradation is location specific and differences in the factors across the region cause spatial variation in degradation status.

Within the study region, the better grasslands were mainly found at locations with higher altitude mainly because livestock could not easily reach these higher places. In 2000, 44.2% of the total grasslands between 900 and 1,100 m have suffered strong degradation. Grasslands in this altitude range are used as the main rangelands to breed domestic animals explaining the degradation after heavy grazing. For each of the 3 years, the most serious steppe degradation was found on the plain, and gentle slopes since most of livestock were grazed on the flatter grasslands. Correspondingly, in 2000, these flatter locations were more degraded than in the other 2 years because these locations were used as primary pasture while infrequent rainfall during the same period aggravated the process of degradation. Our results respecting the role of topography in the degradation process are consistent with other studies (Yue

Table 3 Estimated coefficients and odds ratios of the multinomial logistic regression models (all coefficients significant at $p < 0.01$)

Variable	Light degradation (LD)		Heavy degradation (HD)		Extreme degradation (ED)	
	Coefficient	Odds ratio	Coefficient	Odds ratio	Coefficient	Odds ratio
Constant	−6.74		2.48		6.22	
Altitude (m)	5.02 E−3	1.01	1.25 E−3	1.001	−3.26 E−3	0.997
Fencing policy (0–1)	0.43	1.54	−0.13	0.87	−0.30	0.74
Dist. to highway (km)	1.37 E−2	1.01	6.49 E−3	1.01	−8.17 E−3	0.99
Population density (person/km^2)	−9.33 E−2	0.91	−0.50	0.61	−1.41	0.25
Rainfall (mm)	8.51 E−3	1.01	−2.22 E−2	0.98	−1.26 E−2	0.99
Dist. to river (km)	−1.08 E−2	0.99	2.41 E−3	1.002	−6.83 E−6	0.99
Sheep density (sheep unit/km^2)	2.24 E−3	1.002	3.01 E−3	1.003	1.53 E−2	1.02
Slope (°)	2.93 E−2	1.03	−2.81 E−2	0.97	−2.13 E−2	0.98
Soil organic matter (%)	4.18 E−2	1.04	−0.24	0.78	−0.11	0.89
Temperature (°C)	−0.28	0.75	0.25	1.29	9.40 E−2	1.10
Year91 dummy	−1.24	0.29	3.31	27.27	2.41	11.16
Year00 dummy	−0.44	0.64	2.29	9.91	2. 80	16.44
ROC statistic	0.84		0.68		0.81	

et al. 2007; Shao et al. 2008). In 2005, these grasslands have seen large improvements after the local and central governments implemented measures to lower the grazing pressure in these areas (Zhao 2007). However, during the same period, there was also strong variation in climatic conditions, favoring a recovery of the grasslands. It is, therefore, difficult to separate climatic and policy effects. By comparing the grassland conditions within and just outside the fenced areas, a clear effect of the fencing policy could be seen. In addition, both climatic variables and a variable indicating the fenced areas appeared significant in the regression model. However, the significant values for the year dummies indicated that structural differences between years could not solely be explained by climate and fencing policy. The analysis indicates generally lower levels of degradation in 2005 irrespective of the fencing and climate conditions. The year dummies may capture climatic conditions in preceding years and other policies aimed at reducing the overall grazing pressure not included in the analysis. In the analysis, we could only include the fencing policies directly. The fencing policy and other incentives with respect to grassland carrying capacities may have generated awareness among land users to more carefully manage grasslands and avoid further degradation. Otherwise, the heavy degradation in previous years and shortage of feed may also have caused the decrease in grazing intensity that explains the decline in degradation with time.

Climatic conditions in the study region changed to an overall warmer and drier climate during the past 44 years. This is unfavorable for grass growth in the region, especially the palatable grasses which require more humidity during the growing process (Liu et al. 2006). In general, soil moisture was hardly absorbed in the plants due to the high evapotranspiration. Thereby, the drought had enormously aggravated the regional degradation and caused changes in the ecosystem functions. In addition, our study showed that both the regional precipitation and temperature in Xilinhot decreased from southeast to northwest. The results indicate that areas with more plentiful rainfall show less degradation: the degradation in the northwestern part was most serious because of the infrequent rainfall in the area. Similar relations with climate were found by other researchers (Ringrose et al. 1990; Bai et al. 2002; Zhang et al. 2008).

The ANOVA analysis of soil organic content and the different degradation grades showed that the soil organic matter in the area with light degradation was significantly different from the soil organic content of the other three degradation classes. It is likely that the physical and chemical characteristics of the soil were affected by the changes in vegetation cover (Simon et al. 2007). Generally, the resistance of topsoil to erosion and the root-zone moisture-holding capacity decrease with continuous degradation. This results in insufficient supply of soil nutrients and moisture for grass growth (Martin et al. 2009). This process may lead to a positive feedback: soil degradation causes more grassland degradation while reduced grass production leads to further degradation of the soil. To some extent, the differences in soil conditions can also be explained by the variation in climatic conditions in the area. However, in the multivariate analysis, both soil and climatic factors were significant.

Better grasslands are found near to the river, and the degree of degradation increased with the distance from the river. The degradation near the river was clearly less serious as a result of the higher soil moisture. A similar result was found in other research in which light degradation was mostly located around lakes, riversides, or bottomland (Shao et al. 2008).

Also, distance to highway had an influence on accelerating the regional degradation. Our results showed that the more serious degradation was found near the highway, while with increasing distance from the highway, the grasslands became less degraded. By local custom, the grasslands near highway do not belong to any herd family so that livestock can freely graze on the sides of the highways.

With the distance from the residence, the occurrence of extreme degradation decreased after a short sharp increase. This fluctuation of degradation with distance can be explained by the behavior of the livestock. Nearby the houses, the domestic animals immediately browse the grasses regardless of the quality of the palatable grass. Therefore, the grasslands around the herd houses are always seriously degraded.

High sheep unit density and population density are usually considered as the key driving forces of degradation in the Eurasian steppe region (Li 1997; Liu et al. 2002). In our study area, the degradation was positively related to the sheep unit density in the region, meaning that the degradation status was easily affected by the grazing pressure. So, corresponding to earlier studies, also in this region, the decline in vegetation coverage is related to overgrazing (Liu et al. 2002; Li et al. 2005; Zang et al. 2007). The relation with population is less clear. In the single factor analysis, there is no significant relation with population, while in the multivariate analysis, the relation is negative for all classes. This result is not corresponding with the general notion that areas with high population densities are subject to more intense degradation. This result may be due to multicollinearity and may also be explained by the fact that the population numbers used did not distinguish rural and urban population. Recently, efforts were made to control the number of domestic animals in China according to the theoretical livestock carrying capacity, but in most regions, livestock numbers still exceed the proper theoretical livestock carrying capacity (Verburg and van Keulen 1999; Yu et al. 2010). Continuous grazing in the steppe landscape is very detrimental to the vegetation because it results in less vegetation coverage and litter accumulation, exposed ground surface, and soil coarseness (Abel and Blaikie 1989; Su et al. 2005). At the same time, grassland degradation and desertification will accelerate the regional overstocking. Grassland degradation reduces the livestock-carrying capacity in the region, which will trigger a vicious circle between the degradation and overstocking (Ludwig et al. 2000; Ding et al. 2007; Zang et al. 2007).

Since 2001, the local governments began to enclose the seriously degraded grasslands. After nearly 2–5 years, the fenced grasslands inside the enclosure were in a better state than the unfenced grasslands. Commonly, most fenced grasslands could be restored after several years, which would bring more vegetation coverage, increasing the proportion of palatable plants, lower exposure of the ground surface, increasing the soil moisture holding capacity, and higher soil nutrient accumulation (Hijaba et al. 2004; Lu and Zhao 2008). This effect was also supported by 2 years of plentiful precipitation before 2005.

The results of the multivariate analysis are exemplary for the complexity in land management in the region. Spatial variation in environmental and infrastructural conditions, temporal variation in climate, and the trend toward a drying climate need to be understood in relation to the behavior of land managers that respond to these spatial and temporal dynamics. At the same time, the positive trend in recent years and the success of the fencing policies indicate that when land management accounts for the spatial and temporal variations, a more sustainable use of this landscape is possible. The large spatial variation within the region indicates that policies should be adapted to the local conditions that provide options and constraints to the livestock capabilities and appropriate land management schemes.

Conclusion

In this study, we have successfully analyzed spatial and temporal variations in the grassland degradation processes in a typical steppe region. Besides analyzing the hypothesized driving factors separately, a multivariate model was estimated to link the pattern of degradation in time and space to its biophysical and social-economic driving factors. Interpretations of the empirical results were supported with information obtained by interviews in the area. The methodology accounts for the multifactor effect on steppe degradation at the level of a larger region. By combining monitoring data of land cover based on remote sensing techniques with spatial data on biophysical and socio-economic conditions, the methodology has the ability to reflect the complex dynamics of the land use in grassland systems. Our results indicate that higher values of the variables, altitude, slope, annual rainfall, soil organic matter, distance to highway and fencing policy, were supportive for the occurrence of less degraded grasslands. These results indicate that a lot of processes reported in literature for other grassland regions worldwide, also hold in this specific region. The paper shows that both spatial and temporal variations are high and significant for understanding the dynamics in steppe ecosystems.

Therefore, this study encourages future research on grassland use dynamics to account for the interaction of degradation across time and space. The methodology adopted in the study could be used as a tool for understanding the possible impacts of degradation on terrestrial ecosystems and providing scientific support for effective grassland planning and management.

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