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Journal of Arid Environments 59 (2004) 133–149
Journal of Arid Environments
www.elsevier.com/locate/jnlabr/yjare

A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China

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Received 14 October 2002; received in revised form 3 September 2003; accepted 14 January 2004

Abstract

Steppe degradation is a major ecological and economic problem in the Inner Mongolia steppe region, China because it reduces grassland productivity and leads to desertification. The objective of this study was to assess the spatial extent and severity of steppe degradation in the Xilin River Basin, Inner Mongolia using a landscape-scale approach. Our approach combined information from field survey records, existing vegetation maps, and remote sensing data to determine the different degrees of degradation for diverse steppe communities at the local scale and their spatial pattern at the landscape scale. We also developed a steppe degradation index (SDI) that integrates the information on the spatial extent and severity of steppe degradation. Our results showed that the total area of degraded steppe in this region increased from 7191.3 km^2 in 1985 to 7689.3 km^2 (72% of the total basin) in 1999. We used SDI to quantify the degree of degradation and its changes in space and time. The SDI maps revealed that large-scale patterns of steppe degradation were related to landform types. For both 1985 and 1999, the four landforms exhibited increasing degrees of degradation in the following order: low mountains > lava tablelands > hills > high plains. Several seriously degraded regions in the Xilin River Basin were identified. This study demonstrates the effectiveness of combining remote sensing data and synoptic ecological indices in assessing ecosystem degradation, and provides useful information for improving

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doi:10.1016/j.jaridenv.2004.01.004

grassland management practices and restoring the degraded steppe vegetation in the Xilin River Basin, Inner Mongolia.

Keywords: Grassland ecology; Ecosystem degradation; Steppe degradation index (SDI); Remote sensing; GIS; Xilin river basin; Inner Mongolia grassland

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1. Introduction

Steppe degradation has become a major environmental and economic problem in Inner Mongolia because it leads to desertification, reduces grassland productivity and biodiversity, and accelerates the occurrence of dust storms (Wu and Loucks, 1992; Liu and Wang, 1997, pp. 1–19; Wu and Overton, 2002). However, there is an insufficient amount of data at the landscape or regional scale to fully evaluate this problem. Landscape- and regional-scale assessments are urgently needed to accurately determine the spatial distribution and severity of the degraded steppe ecosystems in the Inner Mongolia steppe region.

Steppes are the primary natural resources in northern China and the vast semi-arid region of the Eurasian continent as a whole. The term "steppe degradation" often refers to a process in which grassland production decreases and ecosystem conditions deteriorate because of poor management, overgrazing, and changing physical environments (Li et al., 1988, pp. 84–183; Liu and Wang, 1997; Li, 1999, pp. 383–391; Chen and Zhao, 2002, pp. 1–12). The attributes of steppe degradation include the declining conditions of vegetation for multiple uses (e.g. grazing, biodiversity conservation, recreation), increasing proportion of less palatable plants, decreasing topsoil erosion resistance and root-zone moisture holding capacity. While steppe degradation essentially involves the deterioration of the entire steppe ecosystem, vegetation change is one of the most important indicators of steppe degradation that can be relatively readily studied on broad scales.

A number of local-scale studies of the steppe degradation in Inner Mongolia have been done (e.g. Bao and Chen, 1994, pp. 1254–1261; Wang et al., 1996), but landscape- and regional-scale investigations with adequate ecological details are still scarce. Worldwide, research at landscape and regional scales has now become feasible largely because of the development of remote sensing and spatial information technologies (Wu and Hobbs, 2002). Remote sensing has been widely utilized in monitoring vegetation dynamics, including grassland degradation (Yong et al., 1987, pp. 101–110; Pei and Pan, 1993, pp. 203–207; Bastin et al., 1995; Tong et al., 1996; Boyle et al., 1997; Xiao et al., 1997, pp. 130–138; Tanser and Palmer, 1999; Schmidt and Karnieli, 2000). Many, if not most, of these studies, however, evaluated the conditions of vegetation degradation based only on above-ground biomass estimated using the Normalized Difference Vegetation Index (NDVI) derived from the coarse-resolution satellite data (i.e. AVHRR with a spatial resolution of 1.1×1.1 km).

The major objective of this study was to accomplish a more detailed, landscape-scale assessment of steppe degradation in the Xilin River Basin—one of the most representative geographic areas of the Inner Mongolia steppe region. Our approach was to combine remote satellite data (i.e. Landsat Thematic Mapper or TM), existing vegetation maps, and additional field surveys. We were also interested in developing a synoptic index of steppe degradation that can be used to quantify steppe degradation in terms of both its spatial distribution and severity. By assessing the spatial extent, pattern, and severity of the steppe degradation in the Xilin River Basin, the project was intended to provide useful information for large-scale management and planning of the grassland resources in this region.

2. Materials and methods

2.1. Study area

The Xilin River Basin is located near the geometric center of IMAR and covers about 10,000 km^2 in area (Fig. 1). The eastern part of the basin is dominated by low

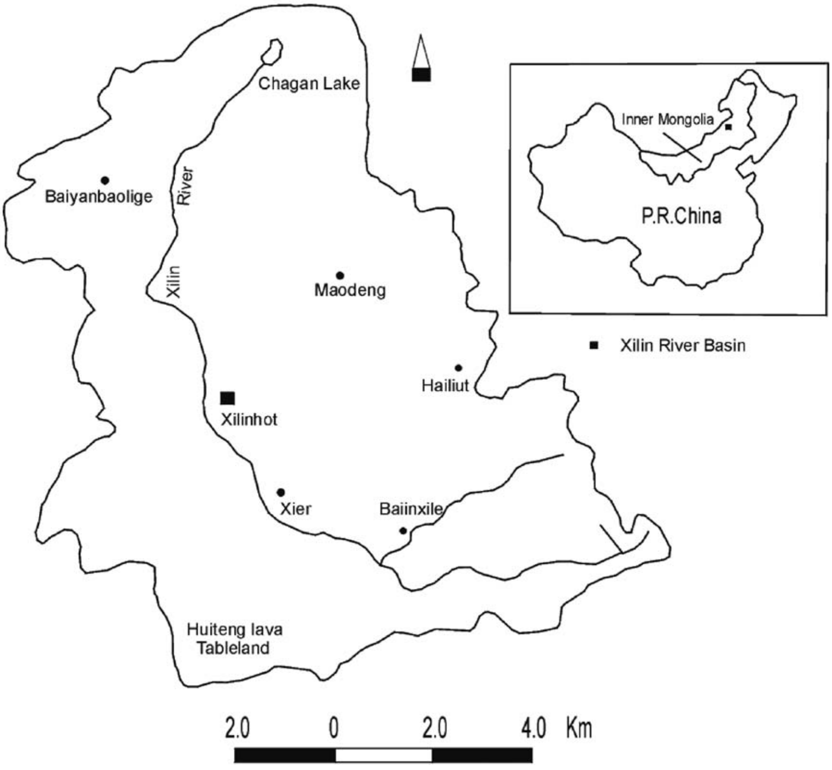


Fig. 1. Map of the Xilin River Basin, Inner Mongolia, China.

mountains and hills, with an average elevation of approximately 1500 m, bounded by the west side of the Daxing-An Mountain. The topography of the basin gradually gets flatter with a decrease in elevation from southeast to northeast. The lowest elevation within the basin, 902 m, is found at the lower reaches towards the western part of the Xilin River Basin. The landforms in the basin can be divided into several types: lava tablelands, low mountains, hills, high plateaus, and sandy lands. Large areas of lava tablelands exist in the southern part of the basin, whereas low mountains, hills and high plateaus are found in the middle and lower reaches of the Xilin River in the northern part of the basin. Between the two regions there are stretches of sandy lands.

The climate in the Xilin River Basin is typical of the temperate steppe region, with an average annual precipitation of 350 mm and average annual temperature of 1.7°C (at Xilinhaote). The highest monthly temperature, 20.8°C, occurs in July, and the lowest monthly temperature, −19.8°C, takes place in January (Chen, 1988, pp. 13–19). As one moves from the southeast to the northeast, temperature and frost-free periods increase, but precipitation decreases gradually.

The vegetation in the Xilin River Basin has diverse plant communities that are found throughout much of the steppe region of northern China (Li et al., 1988). This area serves as an important animal husbandry base for the Inner Mongolia Autonomous Region (IMAR), and is one of the Biosphere Reserves designated by the United Nations' Man and Biosphere Programme (UNESCO/MAB). *Stipa grandis* steppe and *Leymus chinensis* steppe are the dominant (climax) plant communities in the basin. But, overgrazing has introduced additional succession communities. Based on numerous studies carried out at Inner Mongolia University and the Inner Mongolia Grassland Ecosystem Research Station over the past several decades, Liu and Wang (1997) developed a diagnostic model of steppe degradation. Following up the work by Liu and Wang (1997) and with additional data from a field vegetation survey in July 2000, we have constructed a conceptual model of steppe degradation pathways for the *Stipa grandis* steppe in the Inner Mongolia region (Fig. 2). The degradation pathways of *Leymus chinensis* steppe is similar in that overgrazing has degraded the *Leymus chinensis* steppe to either the *Cleistogenes squarrosa*-*Artemisia frigida* steppe or the *Artemisia frigida* steppe in the Xilin River Basin (Liu and Wang, 1997).

2.2. Data acquisition and analysis

We used the TM images in 1985 and 1999 to produce the steppe vegetation maps. The images were all geo-referenced using a topographic map of the same area as a reference. Because some steppe community types in different stages of degradation (Table 1) were not distinguishable on the satellite images simply based on color differences, we interpreted the imageries visually using a combination of information sources, including the color and texture of satellite imagery, topographic features, the spatial extent of climax communities (e.g. *Leymus chinensis*-*Stipa grandis*- forbs steppe, *Stipa grandis*-*Leymus chinensis*- forbs steppe, *Stipa krylovii*-*Cleistogenes squarrosa* steppe), detailed field survey records, and published vegetation maps

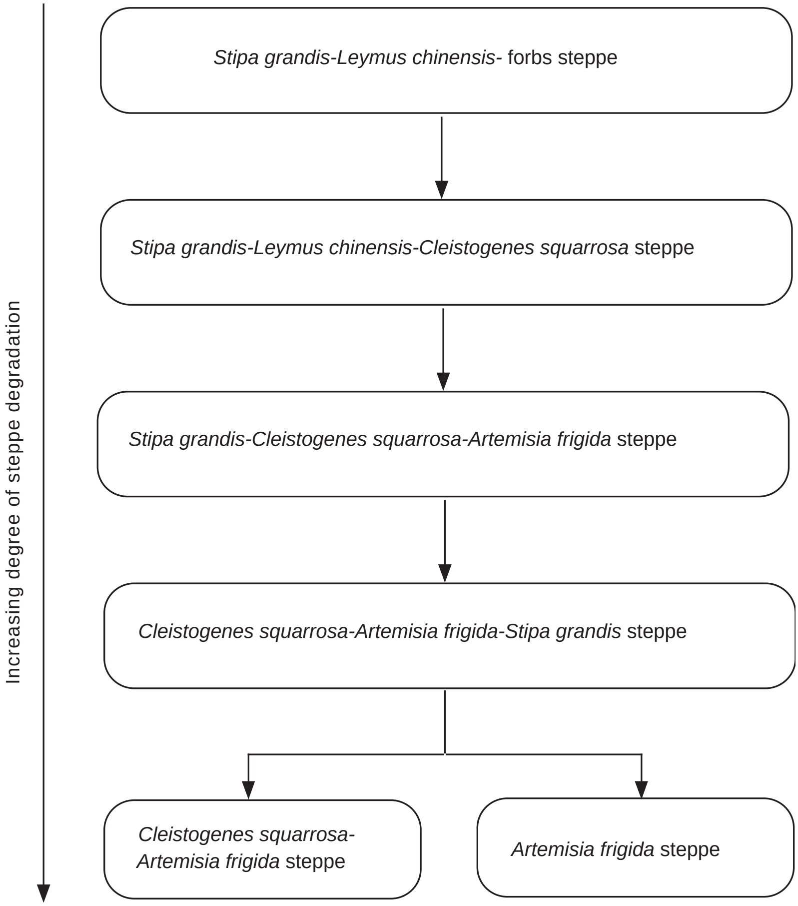


Fig. 2. A conceptual model of the degradation pathways of the *Stipa grandis* steppe.

(Cui and Yong, 1987, pp. 178–182; Yong and Cui, 1991). The imagery was used mainly to identify major vegetation types and their boundaries, while the detailed vegetation composition was determined according to field survey records obtained in July 2000. All the field records had geographic locations registered using a global positioning system (GPS). Figs. 3a and b are the resultant steppe vegetation maps of the Xilin River Basin in 1985 and 1999.

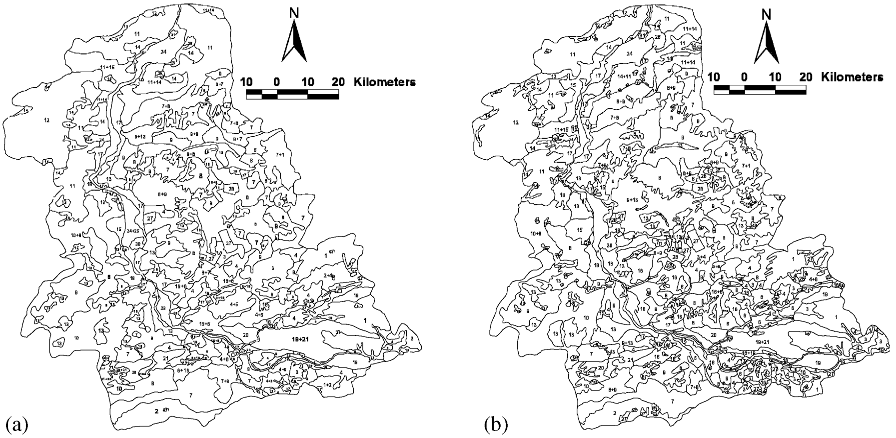
We constructed the steppe degradation map based on the dominant plant species in a community (Liu and Wang, 1997; Li, 1999) and its relative position in the steppe degradation pathway model (Fig. 2). In the Xilin River Basin, *Stipa baicalensis*, *S. grandis*, *S. krylovii*, *Leymus chinensis*, and some mesic forbs (e.g. *Sanguisorba officinalis*, *Saposhnikovia schischk*) are dominant species in different climax steppe communities. Thus, their relative abundance in a community tends to correlate with the degree of ecosystem degradation. On the other hand, *Artemisia frigida*, *Cleistogenes squarrosa*, *Caragana microphylly* (shrub), *Potentilla acaulis*, *Stellera*

Table 1
List of the steppe community types in the Xilin River Basin, Inner Mongolia, China and their degradation ranking (based on data in 1999)

Steppe community types	Degradation ranking
Stipa baicalensis-Filifolium sibiricum-Stipa grandis-forbs meadow steppe	Undegraded
Stipa baicalensis-Stipa grandis-Leymus chinensis-Filifolium sibiricum-forbs meadow steppe	Undegraded
Leymus chinensis-Stipa grandis-mesic-xeric forbs steppe	Undegraded
Leymus chinensis-Stipa grandis-Clesistogenes squarosa steppe	Slightly degraded
Leymus chinensis-Stipa grandis-Festuca ovina steppe	Undegraded
Leymus chinensis-Clesistogenes squarosa -Artemisia frigida steppe	Moderately degraded
Stipa grandis, *Leymus chinensis*-xeric forbs steppe	Undegraded
Stipa grandis, *Leymus chinensis-Clesistogenes squarosa* steppe	Slightly degraded
Stipa grandis-Agropyon cristatum-Clesistogenes squaros-Artemisa frigida steppe	Moderately degraded
Caragana microphylla-Stipa grandis-Leymus Chinensis-Cleisogense squarrosa steppe	Slightly degraded
Stipa krylovii-Cleistogenes squarrosa -Artemisia frigida steppe	Slightly degraded
Stipa krylovii-Artemisia frigida steppe	Slightly degraded
Caragana microphylla-Cleistogenes squarrosa-Artemisia frigida-Stipa grandis steppe	Heavily degraded
Cleistogenes squarrosa, *Artemisia frigida* steppe	Heavily degraded
Cleistogenes squarrosa, *Artemisia frigida* steppe	Heavily degraded
Artemisia frigida-Leymus chinensis-Cleistogenes squarrosa steppe	Heavily degraded
Artemisia frigida-Carex dwriscula steppe	Heavily degraded
Artemisia frigida-Cleistogenes squarrosa steppe	Heavily degraded

chamaejasme, *Salsola collina*, and *Convolvulus ammannii* tend to be common and even dominant species in degraded steppe communities. Therefore, the abundance of these species are indicative of steppe degradation. We divided all steppe communities in the Xilin River Basin into four categories in the order of increasing degradation: (1) un-degraded, (2) slightly degraded, (3) moderately degraded, and (4) heavily degraded. By applying these degradation classification criteria (Table 2) to the vegetation maps of 1985 and 1999, we were able to produce the steppe degradation maps for the corresponding years (Figs. 4A and B). Also included in the steppe degradation maps are several other land-cover types, including sandland vegetation, meadows, water, urban areas, and agricultural fields. Farmlands, if abandoned for multiple years, were regarded as heavily degraded steppe.

To examine the relationship between steppe degradation and geomorphology in the Xilin River Basin, we first compiled a landform map of the area based on a 1:250,000 topographic map and Landsat TM imagery of 1999 (Fig. 5). Then, we used Arc/Info, a geographic information system (GIS), to overlay the landform map with the corresponding steppe degradation map with a regular grid of 3 × 3 km cells. The value of the steppe degradation index (SDI; see details below) was also calculated for each grid cell. The spatial pattern of ecosystem conditions indicated by the steppe degradation index was depicted for 1985 and 1999 (Figs. 6A and B). We derived four classes of steppe degradation based on the values of SDI at the grid cell level: I: $0 \leqslant \mathrm{SDI} < 5$, II: $5 \leqslant \mathrm{SDI} < 10$, III: $10 \leqslant \mathrm{SDI} < 15$, and IV: $\mathrm{SDI} \geqslant 15$.



(a) (b)

Fig. 3. Vegetation maps of the Xilin River Basin in 1985 (a) and 1999 (b). Meadow steppe: (1) *Stipa baicalensis-Filifolium sibiricum-Stipa grandis*-forbs meadow steppe, (2) *Stipa baicalensis-Stipa grandis-Leymus chinensis-Filifolium sibiricum*-forbs meadow steppe. Typical steppe: (3) *Leymus chinensis-Stipa grandis*-mesic-xeric forbs steppe, (4) *Leymus chinensis-Stipa grandis-Clesistogenes* squarosa steppe, (5) *Leymus chinensis-Stipa grandis-Festuca ovina* steppe, (6) *Leymus chinensis-Clesistogenes squarosa-Artemisia frigida* steppe, (7) *Stipa grandis*, *Leymus chinensis*-xeric forbs steppe, (8) *Stipa grandis*, *Leymus chinensis-Clesistogenes squarosa* steppe, (9) *Stipa grandis-Agropyon cristatum-Clesistogenes squaros*, *Artemisa frigida* steppe, (10) *Caragana microphylla-Stipa grandis-Leymus Chinensis-Cleisogense squarrosa* steppe, (11) *Stipa krylovii-Cleistogenes squarrosa-Artemisia frigida* steppe, (12) *Stipa krylovii-Artemisia frigida* steppe, (13) *Cleistogenes squarrosa-Artemisia frigida-Stipa grandis* steppe, (14) *Cleistogenes squarrosa-Artemisia frigida-Stipa krylovii* steppe, (15) *Cleistogenes squarrosa*, *Artemisia frigida* steppe, (16) *Artemisia frigida-Leymus chinensis-Cleistogenes squarrosa* steppe, (17) *Artemisia frigida-Carex duriuscula* steppe, (18) *Artemisia frigida-Cleistogenes squarrosa* steppe. Sand land in Steppe: (19) *Ulmus pumila* open forest in fixed sandland, (20) *Ulmus pumila* open forest in fixed sandland with *Caragana microphylla* and *Artemisia intramongolia*, (21) *Ulmus pumila* open forest, with *Caragana microphylla*, *Artemisia intramongolia* and *Psammochloa mongolica* in fixed and semi-fixed sandland, (22) *Psammochloa mongolica-Agriophyllum squarrosum-Corispermum shinganicum* community on moving dunes. Meadow: (23) *Carex* spp.-*Sanguisorba officinalis* meadow, (24) *Achnatherum splendens* meadow, (25) *Phragmites australis* community, (26) *Nitraria sibirica-Kalidium foliatum* community. Others: (27) Farmland, (28) Abandoned cultivated steppe, (29) Bare land, (30) Urban or residential area, (31) Waters.

Table 2
Criteria used for ranking steppe communities in terms of the severity of degradation

	Slightly degraded	Moderately degraded	Heavily degraded
Decrease in plant biomass (%)	20–35	36–60	>60
Decrease in plant cover (%)	20–30	31–50	>50
Decrease in plant height (%)	20–30	31–45	>45
Severity of soil erosion	10–20	21–30	>30
Years needed for recovery	2–5	5–10	>10

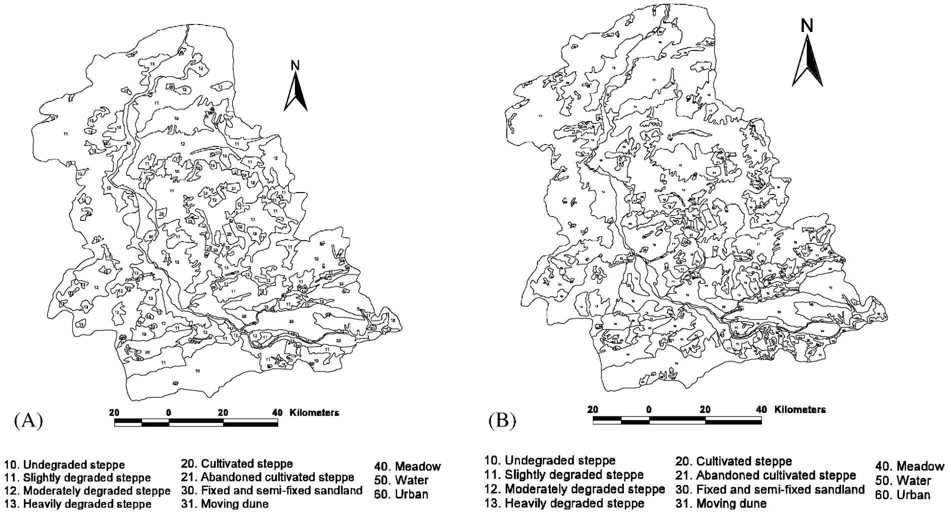


Fig. 4. Steppe degradation maps of the Xilin River Basin in 1985 (A) and 1999 (B).

3. Results

3.1. A synoptic index for quantifying steppe degradation

To study and restore degraded grassland ecosystems, synoptic indices or indicators would be desirable that can effectively combine multitudes of information and adequately characterize the status of steppe degradation (Hammond, 1995; Tanser and Palmer, 1999). Thus, a main objective of this study was to develop a steppe degradation index that integrates information on the spatial extent and severity of steppe degradation. Previous studies in the Inner Mongolia grassland have suggested several useful ranking criteria for the severity of steppe degradation (e.g. Liu and Wang, 1997; Li, 1999). These studies classified degraded steppes into four ranks (slightly, moderately, heavily, and extremely degraded) based mainly on changes in dominant species, plant biomass and vegetation cover. Based on these previous studies, we developed a more comprehensive set of criteria (Table 2), and merged the heavily and extremely degraded classes into one rank (heavily degraded).

To integrate the information on the current ecosystem condition (e.g. biomass) and the spatial extent of different steppe communities in a succinct manner, we developed the following formula as a synoptic measure of steppe degradation:

$$\mathrm{SDI} = \sum_{i=1}^{3} W_i \cdot A_i, \quad i = 0, 1, 2, 3, \tag{1}$$

where SDI is the steppe degradation index, i denote the 4 ranks of degradation (undegraded and slightly, moderately, and heavily degraded, respectively), W_i are the

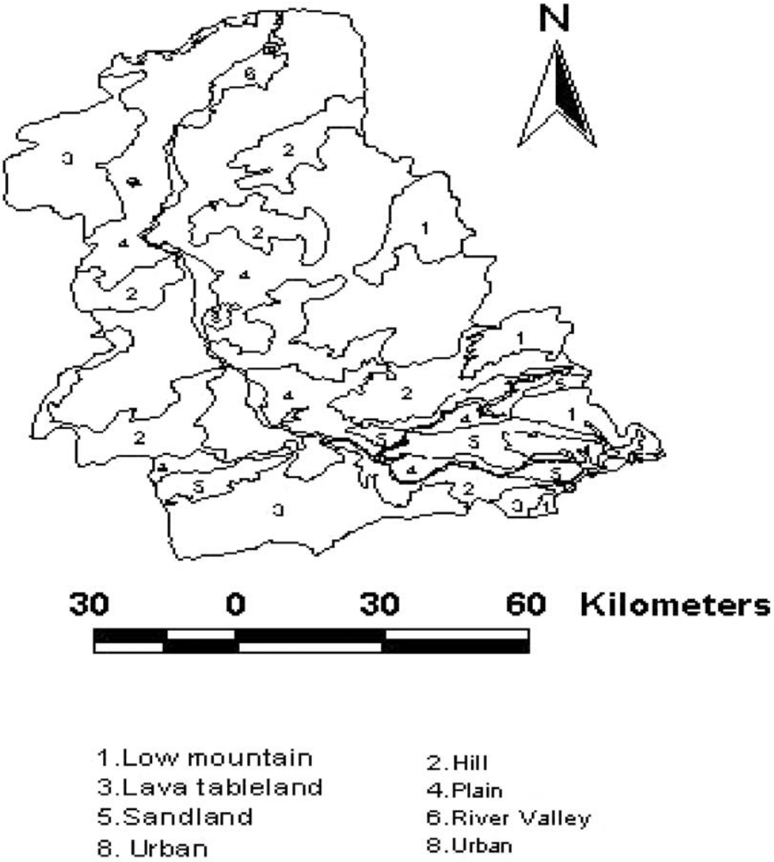


Fig. 5. Landform map of the Xilin River Basin.

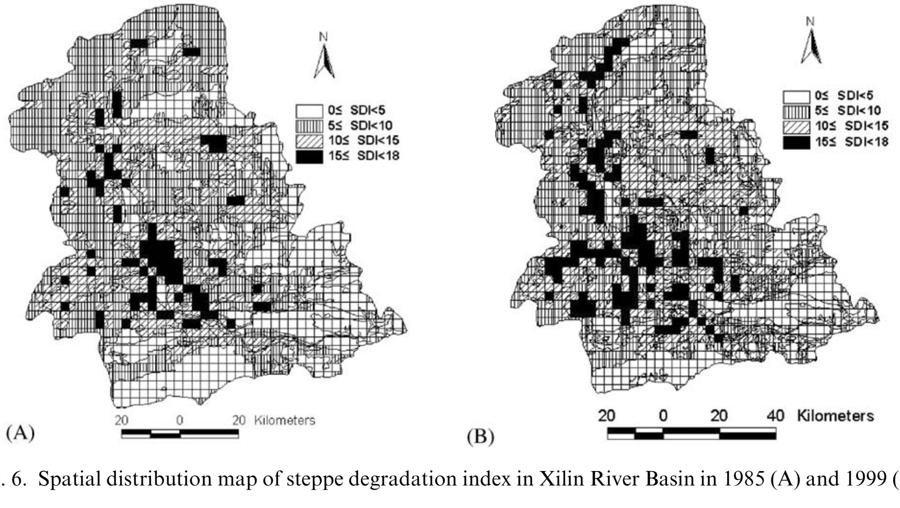


Fig. 6. Spatial distribution map of steppe degradation index in Xilin River Basin in 1985 (A) and 1999 (B).

weights of steppe degradation rank i, and A_i are the areas of the degraded steppe of rank i. For un-degraded steppe, the weight was defined to zero, so the value of SDI was also zero. SDI has the unit of area (e.g. km^2).

For slightly, moderately, and heavily degraded steppes, the weights were assigned according to their relative biomass loss. Based on previous studies and additional analysis using vegetation indices derived from remote sensing (TM) data, we estimated that biomass decreased approximately by 1/3 for slightly degraded steppe, by 1/2 for moderately degraded steppe, and by 2/3 or more for heavily degraded steppe. Based on these biomass estimates, we defined the weight for the slightly degraded steppe as 1, and then determined those for moderately and heavily degraded according to their biomass loss relative to the slightly degraded steppe. Thus, W_i is equal to 0, 1, 1.5 and 2.0 for un-degraded, slightly degraded, moderately degraded, and heavily degraded steppes, respectively.

For comparing different geographic areas or landform types, we also developed the area-weighted SDI (AWSDI):

$$\mathrm{AWSDI} = \frac{\mathrm{SDI}}{A_k}, \tag{2}$$

where A_k is the spatial extent of the geographic areas under consideration. AWSDI is a dimensionless normalized index, and its value ranges between 0 and a maximum value ($\mathrm{AWSDI_{max}}$) that is exactly equal to the maximum weight in Eq. (1). In our case, $\mathrm{AWSDI_{max}} = 2$. These two features, dimensionless and bounded values, make AWSDI more preferable for comparative purposes.

3.2. Steppe degradation in the Xilin River Basin between 1985 and 1999

Figs. 4A and B show the spatial distribution of steppe degradation in 1985 and 1999. The total area of degraded steppe due to overgrazing (excluding abandoned farmland) was 7191.0 km^2 (67.19% of the Xilin River Basin) in 1985, and increased to 7689.3 km^2 (71.86% of the Xilin River Basin) in 1999. So, the degraded steppe area expanded by 498.3 km^2 from 1985 to 1999 at an annual rate of 33.2 km^2 yr^{-1}. The area of abandoned cultivated steppe increased from 31.79 km^2 to 84.30 km^2 from 1985 to 1999. Not only did the area of degraded steppe increase, the degree of

Table 3
Changes in the areas of steppe communities with different degrees of degradation in the Xilin River Basin, Inner Mongolia from 1985 to 1999

Year	Non-degraded		Slightly degraded		Moderately degraded		Heavily degraded	
	Area	% of steppe	Area	% of steppe	Area	% of steppe	Area	% of steppe
1985	2242.1	23.77	4377.6	46.41	1399.1	14.83	1414.2	14.99
1999	1722.8	18.30	3678.8	39.08	1933.6	20.54	2077.2	22.07

The spatial extent of each category is represented in terms of both the absolute area (km^2) and the percentage of the entire basin (%).

degradation worsened as well (Table 3). In 1985, 60.88% of degraded steppe was slightly degraded, and this percentage dropped to 47.84% in 1999. On the other hand, the total area of moderately and heavily degraded steppes increased from 2813.3 km^2 to 4010.8 km^2 during the same time period. The steppe degradation index seemed to be able to capture the information on both the extent and severity of steppe degradation. The value of SDI of the entire basin increased from 9304.7 km^2 in 1985 to 10,733.6 km^2 in 1999.

Different landforms in the Xilin River Basin—high plains, hills, lava tablelands and low mountains—have experienced different grazing intensities historically. Therefore, the extent and ranks of steppe degradation differed among the four landforms as well as over time for each landform (Figs. 7A and B). SDI and AWSDI both showed increasing degradation from low mountains, lava tablelands, hills to high plains in 1985 and 1999 (Table 4 and Figs. 7C and D). However, the exact patterns exhibited by the two indices were not the same because the difference between hills and high plains seemed to be exaggerated in the case of SDI. As mentioned above, for comparing different regions, it is more appropriate to use AWSDI, and thus we believe that the pattern shown by AWSDI is more accurate. These results indicate that steppe degradation caused by overgrazing in the Xilin

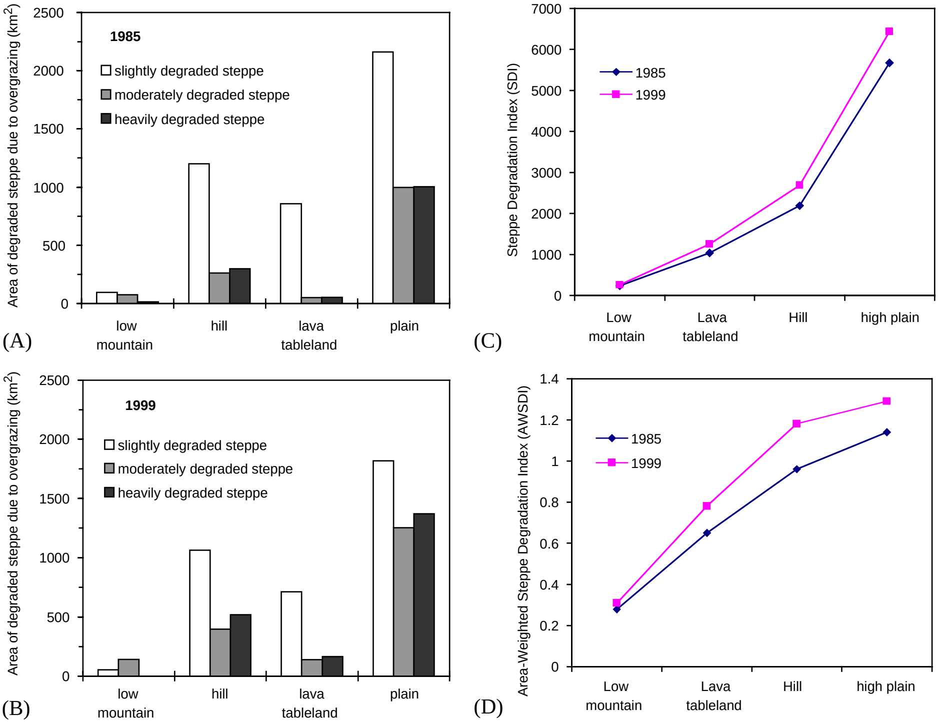


Fig. 7. Steppe degradation of the four landforms in the Xilin River Basin, Inner Mongolia in 1985 and 1999.

Table 4
Comparison of SDI and AWSDI between 1985 and 1999 for four different landforms in the Xilin River Basin, Inner Mongolia, China

	Low mountain		Hill		Lava tableland		Plain	
	SDI (km^2)	AWSDI	SDI (km^2)	AWSDI	SDI (km^2)	AWSDI	SDI (km^2)	AWSDI
1985	236.3	0.28	2190.6	0.96	1040.1	0.65	5669.5	1.14
1999	265.9	0.31	2695.9	1.18	1257.0	0.78	6434.1	1.29

River Basin was more serious on high plains and hills than lava tablelands and low mountains. Historically, high plains and hills have been the preferred areas for grazing practice and population settlement primarily because of the proximity to the Xilin River which serves as a critically important water source in the region and the feasibility and convenience for travel. These general trends seemed to hold for both 1985 and 1999.

3.3. Spatial distribution of steppe degradation in the Xilin River Basin

As discussed above, our results showed clearly that both the area and intensity of steppe degradation in the Xilin River Basin increased significantly within 15 years (1985–1999), and the spatial pattern of the degraded steppes, in general, seemed to correlate with landforms (Figs. 4 and 6). However, the details of the spatial distribution of steppe degradation, including the differences in the degree of degradation within and among landforms, may have been caused by a suite of factors, including geophysical, ecological, and land use practices. While exploring the exact causes is beyond the scope of this paper, our results allow for a closer examination of these detailed patterns themselves. For example, degradation was rather obvious in large areas of the Maoden Plain, the Hailiute Plain, the Xier Plain, and the Gong Plain (Figs. 4 and 6; use Fig. 1 to locate the places). In the east part of the Hailiute Plain steppe degradation exhibited a pattern of scattered patches, surrounded by residential areas. In the Xier Plain, the primary climax vegetation was supposed to be the *Stipa grandis*-*Leymus chinensis* community. But overgrazing has led to the dominance of *Artemisia frigida* steppe and *Cleistogenes spuarrosa* steppe in this area. Low mountains are primarily located in the east part of the Xilin River Basin, including the Hailiute Mountain and the Sirongwenduer Mountain.

In these low mountains, *Stipa baiclensis*-*Filifolium sibiricum*-*Stipa gradisis*-forbs steppe and *Stipa baiclensis*-*Stipa grandis*-*Leymus chinensis*-forbs steppe—the climax communities of the region—were still found dominant. Hills are distributed mainly in the upper and middle reaches of the Xilin River Basin where, in the past, grazing intensity was relatively light. However, the increasing grazing pressure driven by the soaring number of livestock in recent years has evidently accelerated the process of steppe degradation in these areas. The value of AWSDI has gone up from 0.96 in 1985 to 1.18 in 1999 in the hill areas. The Huitengliang Lava Tableland, located in the southwest part of the Xilin River Basin, is the largest lava tableland in Inner Mongolia. Twenty years ago, grazing intensity in this area was very low due partly to the lack of drinking water for humans and livestock, and the vegetation was dominated by *Stipa grandis*-*Leymus chinensis*-forbs steppe and *Stipa baicalensis*-*Stipa grandis*-*Leymus chinensis*-*Filifolium sibiricum*-forbs meadow steppe. In 1999, the native vegetation in this area remained in a much better condition than other places. However, because of the increasing human population, built-up of residential areas, and increased grazing pressure, the invasion of the shrub species, *Caragana microphlla*, and the decrease in the height, cover and biomass of the steppe communities were becoming evident.

4. Discussion and conclusions

4.1. Quantifying steppe degradation with an integrated approach

Although steppe degradation has been considered a serious environmental problem in Inner Mongolia for decades, droughts in recent years have brought increasing attention to the issue. However, a rigorous evaluation of the spatial extent and severity of steppe degradation is still lacking especially at broad scales. Due to the lack of funding and the complexity inherent in such assessments, progress has been slow and difficult. Successful assessment of steppe degradation requires the field survey-based documentation of the species composition, height, cover, and biomass of the steppe communities at the local scale and the use of remote sensing and synoptic indicators at the landscape and regional scales.

Changes in plant biomass may be an important measure of steppe degradation, and have been used to monitor grassland degradation (Hanan et al., 1991; Pei and Pan, 1993; Tachiiri et al., 1998, pp. 23–34; Tanser and Palmert, 1999). Vegetation indices derived from remote-sensing data, such as the normalized difference vegetation index (NDVI), have been often used to estimate grassland biomass and then to determine the degree of steppe degradation. However, changes in vegetation composition and ecosystem conditions are also important to consider in assessing steppe degradation (Ho, 2001). In this study, we attempted to combine the different kinds of information from field survey records, existing vegetation maps, and remote sensing. Our integrated approach allowed us to distinguish similar vegetation types that otherwise would not have been discernable only using remote sensing data, such as Landsat TM imagery. The steppe degradation index and the area-weighted steppe degradation index we developed during this study seemed effective in detecting steppe communities with different degrees of degradation, comparing different geographic areas, and monitor landscape changes over time.

4.2. Factors affecting steppe degradation in the Xilin River Basin

Many factors may have contributed to the steppe degradation in the Xilin River Basin, including land use change, overgrazing, and climatic fluctuations. Although it may still be debatable, the results of numerous studies since the 1950s have strongly suggested that anthropogenic factors (especially overgrazing) are primarily responsible for the steppe degradation of the basin (Li et al., 1988; Wu and Loucks, 1992; Liu and Wang, 1997; Li, 1999; Chen and Zhao, 2002). This has much to do with the rapidly growing human population in this region over the past several decades. For example, the City of Xilinhaote, which is located within the Xilin River Basin (Fig. 1), experienced a rapid growth in human population from 116,700 in 1985 to 136,900 in 1999 and an even faster increase in the number of livestock from 618,400 to 1.133 millions for the same time period (Inner Mongolia Statistics Bureau, 1986, 2000). This translates into a dramatic escalation in grazing intensity from 0.66 heads/acre in 1985 to 1.20 heads/acre in 1999.

The number of livestock in the Baiyinxile Livestock Farm, the biggest in the Xilin River Basin, was only 1023 in 1950 and rose to 252,248 in 1999, a 246-fold increase in 50 years (Chen and Zhao, 2002). The devastating effects of overgrazing on the structure and function of the steppe communities were most dramatically illustrated by the controlled experiments carried out at the Inner Mongolia Grassland Ecosystem Research Station of the Chinese Academy of Sciences (IMGERS), which is located near Baiyinxile. In the early 1980s, some degraded steppe communities were fenced by researchers to investigate how the removal of grazing would affect the community succession and ecosystem restoration. Significant differences between the fenced and the non-fenced became apparent after only several years. Now, the fenced community has completely restored to its climax stage, whereas the steppe community outside the fence has become even more severely degraded.

4.3. *Management and restoration of degraded steppe ecosystems*

To improve the grassland management practice and restore the degraded steppe ecosystems, the most obvious and essential solution is keeping the densities of humans and livestock under the carrying capacity of the steppe region. In other words, necessary measures must be taken to reduce the head counts of livestock to alleviate grazing pressure. It is important to recognize that the carrying capacity of the grassland, like any other ecosystems, changes in time and space, and these changes are often driven by a suite of interacting biophysical and socio-economic factors. Simple estimates of carrying capacity may be misleading, and new paradigms in range management that emphasize non-equilibrium dynamics, thresholds, and irreversible changes should be considered to guide the current and future practice (Wu and Loucks, 1995; Briske et al., 2003). In the same time, alternative economic mechanisms should be developed locally and through cooperations with entities outside the region. Creating more employment opportunities in the urban areas for the surplus labor force from rural areas, developing eco-tourism, and subsidizing the herders with funds and technology are some examples of such alternative measures.

The herders in the Xilin Rive Basin are still struggling to make a living out of the grassland resources. The current land tenure arrangements in the Xilin River Basin seem vulnerable to further steppe degradation (English, 2002, pp. 89–96), and the proper management and restoration of the steppe ecosystems require the involvement of governmental agencies and policy makers at different bureaucratic levels. To a large extent it is the economic pressures that drive these people to maximize their short-term benefits, regardless of the long-term steppe degradation (English, 2002). Therefore, any successful attempts of conserving and restoring the degraded steppe ecosystems must address the basic issues of feeding the people.

Steppe communities with different degrees of degradation require different measures for their restoration. For the heavily degraded steppe, the elimination of grazing by fencing may be necessary, and the herders should be resettled elsewhere. Examples of such "ecological migrations" now exist in the Inner Mongolia steppe region (Chen and Zhao, 2002). For slightly and moderately degraded steppes, ecologically sound, advanced rangeland management measures, including grazing rotation, seasonal enclosures, and constructing artificial and semi-artificial grasslands should be considered. In any case, scientific research is critically important for providing the necessary basis for actions. Hopefully, this study not only provides some useful insight into the problem of steppe degradation in the Xilin River Basin, but also a landscape-scale assessment approach that can be used for future studies throughout the Inner Mongolia grassland region.

This project was supported by the National Natural Science Foundation of China (No. 39960020). J. Wu's research in the landscape ecology of the Inner Mongolia grassland has also been supported by the National Natural Science Foundation of China (No. 30028002). We thank Zhao Liqing, Jiang Chao and Bao Yin for their help with the fieldwork and Prof. Han Nianyong for his advice and discussion on the concept of steppe degradation index. Special thanks are extended to two anonymous reviewers for their valuable comments.

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