Land degradation of abandoned croplands in the Xilingol steppe region, Inner Mongolia, China

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Introduction

Steppe grasslands are distributed over vast areas in arid and semiarid regions of Eurasia (Walter 1973; Archibold 1995). The east Eurasian steppe has been used by pastoral nomads for long periods of time (Dulamsuren et al. 2005). However, steppe grasslands are facing desertification or degradation caused by human over-activity (He et al. 2005). In China, vast areas of grassland have been converted to cropland due to the increased human population during the last 50 years (Nan 2005), and many of the croplands have been abandoned subsequently due to the degradation caused by inappropriate agricultural management (Tong et al. 2004). The conversion of steppe grassland into cropland undoubtedly impacts steppe ecosystems (Laryea and Unger 1995). The destruction of steppe vegetation has caused increasing desertification in northern China (Chunru 1989). In Inner Mongolia, although many cases of desertification arise from overgrazing of livestock, desertification from abandoned cropland is also a serious problem. The restoration of vegetation cover following desertification is usually difficult (Zhang et al. 2004a; Jiao et al. 2007).

Croplands in semiarid regions are vulnerable to erosion (Mainguet 1991; Lopez 1998; Bärring et al. 2003; Nordstrom and Hotta 2004) because cultivation alters some environmental factors; the most important impact is the complete destruction of natural vegetation cover prior to cultivation. Soil erosion occurs easily when soil surfaces are not covered (Hupy 2004; Su et al. 2004a), whereas plant and litter coverage protects soil surfaces from erosion (Michels et al. 1995; Fearnehough et al. 1998; Liang et al. 2002). The frequency and intensity of dust storms are increasing because of the...
interactions between climate change and human disturbance (Li and Liu 2003). With global climate change, erosion will become a more serious problem because low-productivity cropland will be abandoned and exposed to wind and water (e.g. rainfall).

To avoid this outcome, sand movement must be carefully monitored, and early detection of soil degradation in abandoned croplands is critical. However, no useful countermeasures exist because there is no specific gauge for monitoring soil degradation. In addition, cost-effective indices of soil degradation are needed. To develop a specific gauge, we investigated the relationships between plant communities and soil degradation. This specific gauge was developed from observations and comparisons of plant species under various ecological conditions (Mitchell et al. 1999; Oba et al. 2001). Using plant indicators would be one of the easiest and least expensive ways to accomplish soil degradation monitoring. We believe that promoting and maintaining vegetation cover following agricultural abandonment are important aspects of steppe management. The restoration of steppe ecosystems requires an understanding of steppe degradation after cropland abandonment (Hölzel et al. 2002).

In this study, we examined land degradation after agricultural abandonment in Inner Mongolia, China. We focused on vegetation recovery after abandonment of farming and determined an indicative vegetation parameter to assess the effects of farming on grassland ecosystems. The objectives of this study were to (i) identify separate vegetation groups based on species composition and land use; (ii) determine indicator species for these groups; and (iii) analyze soil characteristics of different groups and make ecological interpretations.

**Materials and methods**

**Area descriptions**

The study area was the Xilingol steppe in Inner Mongolia, in the temperate monsoon climate region that is widely covered by arid and semiarid grassland (Chen and Wang 2000). This region, located about 600 km north of Beijing in the centre of the Inner Mongolia Plateau, is the most representative steppe grassland in northern China (He et al. 2005). The relief of the eastern area is 1300–1500 m, which is higher than the western area (<1000 m) because of the influence of the fold and rise of the Dashinganling Mountains to the east (Jiang and Li 1988). Inner Mongolia is characterized by strong winds; dust storms related to cyclone events in spring are common in northeastern China (Qian et al. 2004; Wang et al. 2004).

The Xilingol steppe has a semiarid and continental temperate steppe climate with dry springs and moist summers. Topographically, this area, covering about 10 000 km², declines gradually from east (the highest elevation is 1505 m) to west (the lowest elevation is 902 m; Chen et al. 2005b). Chestnut and dark chestnut soils are the zonal soil types (Wang and Cai 1988). Climate data were collected at the Inner Mongolia Grassland Ecosystem Research Station (IMGERS), the Chinese Academy of Sciences, located about 60 km southeast of Xilinhot, the capital of the Xilingol League. The medium-term (1987–1999) average of annual mean temperature is 1.0°C, with the coldest and warmest mean monthly temperatures of −20.9°C in January and 19.2°C in July, respectively. Total annual precipitation averages 358.6 mm (1987–1999), ranging from 287.1 mm in 1989 to 507.0 mm in 1998. Rainfall is high between June and September during the summer monsoon season.

![Figure 1](image-url) Location of the study area (bottom) in Inner Mongolia, China (top). In the detailed map of the study area, gray shading indicates farmland, vertical stripes denote lakes and solid lines represent the Xilin River and its tributaries. The dotted line indicates National Highway 303.
The study site was at Taolintala Village in the Baiyinxile State Farm (43°54′ N, 116°19′ E), about 10 km southeast of Xilinhot (Figure 1). The villagers perform pasturage with sheep and goats around the village. Adjacent to Baiyinxile are extensive croplands that have been cultivated for over 30 years. Productive areas are used for wheat, corn, millet, potato and colza. Since 2000, extensive areas of unproductive croplands have been abandoned near this village.

Sample design and data collection

We established 115 study plots, which were considered sufficient to describe species composition at the study site. A plot consisted of a single 1 m × 1 m quadrat. We grouped these plots by land use into three types: typical steppe, abandoned cropland and yardang. Typical steppe was located in areas that had never been cultivated, and this is the control vegetation in this study. Abandoned cropland was located in areas that had been cultivated recently. The word yardang is of Turkish origin, meaning ‘steep bank’ (Hedin 1903). Yardangs were located in areas that were recently abandoned cropland plots, but in which bare sand dunes occurred. We recognized 41 typical steppe plots, 58 abandoned cropland plots and 16 yardang plots.

All vegetation data were collected in the summer of 2002. We recorded all plant species in a plot and estimated the cover of each species. From the ratio of species that appeared in study plots, we calculated the appearance frequency for each species. Coverage was estimated using the Key to Plants of the Xilin River Basin, Inner Mongolia (Liu 1993). Taxonomic nomenclature followed Flora Intramongolica (Ma et al. 1989, 1990, 1992, 1994, 1998).

We used Simpson’s diversity index and the Shannon diversity index to assess multilateral species diversity. Simpson’s diversity index (1 − D) is sensitive to the diversity of dominant species (Simpson 1949):

\[1 - D = 1 - \sum p_i^2,\]

de where \(p_i\) denotes relative coverage of species \(i\). The Shannon diversity index \((H')\) is sensitive to the diversity of common species (Shannon 1948):

\[H' = - \sum p_i \ln p_i.\]

To measure evenness, we used Pielou’s equitability index \((J; Pielou 1969):\)

\[J = H'/ \ln S,\]

where \(S\) denotes the total number of species.

We collected soil samples to determine soil nutrient concentrations and particle size distributions. We collected samples at a representative land use site for each of the three types. Samples (5 cm long × 5 cm wide × 1 cm deep) were collected from the soil surface at the centre of the vegetation survey plot. In total, 24 soil samples were air-dried and sifted through a 0.21 mm mesh sieve to remove litter, roots and stones. The percentages of total carbon (C) and total nitrogen (N) were measured with a total organic C analyzer (NC analyzer; SUMIGRAPH NC–900; Sumika Chemical Analysis Service, Osaka, Japan). Soil particle size was measured using a laser diffraction particle size analyzer (SALD–3100; Shimadzu Co. Ltd., Kyoto, Japan).

Data analysis

We classified plant community types using two-way indicator species analysis (twinSPAN; Hill 1979). We divided the vegetation data until the second cut level (three divisions as a dendrogram) and decided endpoints of divisional standards using a \(\chi^2\) test \((P < 0.05)\). Then we determined indicator species for each group using indicator species analysis (insPAN; Hill et al. 1975). We set indicator criteria of \(P < 0.01\) in this analysis. The 24 soil samples were divided into groups based on the twinSPAN results. The twinSPAN and insPAN analyses were performed using PC–ORD for Windows version 4.25 (MJM Software Design, Gleneden Beach, OR, USA). SPSS for Windows version 11.0.1 (SPSS Inc., Chicago, IL, USA) was used for other statistical analyses. We conducted a multiple comparison test using a Wilcoxon test with a Bonferroni adjustment to compare differences in vegetation parameters and soil nutrient contents. We used a Friedman test to confirm differences in soil particle size distributions.

Results

Species composition

We found 70 species (including 11 unknowns) in the 115 plots. The unknown species were unidentifiable because they were very small seedlings and/or had been browsed by animals. The plant communities were dominated by Stipa
krylovii Roshev. Species with high frequencies were Cleistogenes squarrosa (Trin.) Keng (77.4%), Stipa krylovii (73.0%), Carex korshinskii Kom. (65.2%), Leymus chinensis (Trin.) Tzvel. (61.7%), Chenopodium acuminatum L. (55.7%), Salsola collina Pall. (50.4%) and Chenopodium aristatum L. (47.8%). The other 63 species had frequencies of <25% (mean 6.3% ± 0.7 standard error [SE]).

Classification of plots

We classified all plots into three groups based on the TWINSPAN results (Figure 2). We found 53 species (including seven unknowns) in group 1. L. chinensis had the highest frequency in these plots (97.1%). C. acuminatum and S. collina were also common (91.4%). Group 2 included 44 species (including seven unknowns), with C. squarrosa having the highest frequency in these plots (100.0%). S. krylovii was also common (90.6%). These species tended to appear in both groups 1 and 2. Group 3 included 21 species, with S. collina having the highest frequency (75.0%). Elymus dahuricus Turcz. ex Griseb. (50.0%), Digitaria ischaemum (Schreber) Muhl. (43.8%) and Polygonum aviculare L. (43.8%) also occurred at high frequencies.

Five vegetation parameters were calculated for each group: species richness, total plant coverage, Simpson’s diversity index, Shannon diversity index and Pielou’s equitability index (Table 2). Total cover differed significantly among the groups; the vegetation cover of group 1 was higher than that of group 2, which was higher than that of group 3. Species richness and species diversity of group 1 were significantly higher than those of the other two groups, but we did not observe significant differences in species richness and species diversity between groups 2 and 3.

Table 3 Field-recognized land-use patterns and statistically different groups

| Land use               | Group 1 (n = 35) | Group 2 (n = 64) | Group 3 (n = 16) |
|------------------------|------------------|------------------|------------------|
| Typical steppe         | 29               | 12               | 0                |
| Abandoned cropland     | 6                | 52               | 0                |
| Yardang                | 0                | 0                | 16               |

We examined the relationship between land-use history and group (Table 3). Group 1 comprised 29 typical steppe plots (82.86%) and six abandoned cropland plots (17.14%). Group 2 comprised 12 typical steppe plots (18.75%) and 52 abandoned cropland plots (81.25%). All group 3 plots were yardangs.

Indicator species of each group

We determined indicator species for each of the three groups based on the INSPAN analysis. The indicator species for group 1 were L. chinensis, C. acuminatum, S. collina, Allium tenuissimum L., Serratula centaureoides (L.) P. Fourn., Achnatherum sibiricum (L.) Keng., Saposnikovia divaricata (Turcz.) Schischk., Artemisia frigida Willd., Allium senescens L., Cymbaria dahurica L., Lappula myosotis Moench., Anemarrhena asphodeloides Bunge and Bupleurum scorzonerifolium Willd. The indicator species for group 2 were C. squarrosa and S. krylovii. The indicator species for group 3 were E. dahuricus.
Comparison of soil properties
The 24 soil samples were divided into group 1 \((n = 11)\), group 2 \((n = 7)\) and group 3 \((n = 6)\). The three soil properties (total C percentage, total N percentage and C/N ratio) varied among the groups (Table 4). Total C and N percentages were ranked group 1 > group 2 > group 3, with significantly higher values in group 1 than in the other groups. The C/N ratio of group 3 was significantly lower than that of the other groups. The soil particle size distribution differed significantly among the groups \((P < 0.05; \text{Figure 3})\). The largest particle size percentage of group 3 was 110.6 \(\mu\)m; 47.4\% of the soil was composed of particles 88.7–137.9 \(\mu\)m in size. The largest particle size percentage of groups 1 and 2 was 57.1 \(\mu\)m.

Discussion
We divided the study plots into three vegetation groups that corresponded to land use history. Species diversity and cover-age was highest in group 1, and plants grew relatively well in group 1 plots. In this study, we found 13 indicator species for group 1. In previous investigations in the Xilingol steppe, most of these species were recognized as typical steppe species (Nakamura et al. 1998, 2000; Yiruhan et al. 2001). In particular, L. chinensis is a dominant species that is endemic to the steppes of northern China (Chen et al. 2005a). Therefore, we considered group 1 to represent typical steppe with L. chinensis as the most responsive indicator species (Table 5).

*Ceistogenes squarrosa* and *S. krylovii* were the indicator species for group 2. *C. squarrosa* is a perennial grass genus that is endemic to the steppes of northern China. It is a perennial C4 grass species and is often seen in degraded grasslands (Liang et al. 2002). In addition, *L. chinensis* (group 1 indicator species) and *C. squarrosa* (group 2 indicator species) grow well under different soil water regimes (Ping et al. 2002). We consider that the species dominant in abandoned croplands should differ from those in typical steppe. *S. krylovii* grows in the relatively dry conditions of typical steppe. We observed *S. krylovii* in group 1. We considered *C. squarrosa* a more responsive indicator species of abandoned croplands (Table 5).

In addition, our results imply that cultivation in steppe in semiarid regions promotes grassland degradation. Group 3 did not represent a natural steppe condition because the species number, species composition and vegetation cover differed from those of groups 1 and 2. We found six indicator species for yardang vegetation. *E. dahuricus, D. ischaemum* and *T. mongolicum* only occurred in group 3. *E. dahuricus* is widespread in steppe and has a strong tolerance for dry and saline soils, cold and erosion (Ma et al. 1994). It is thought that this species can survive in challenging environments such as yardangs. Other species are typical weeds in croplands, and we observed these species regardless of yardang presence. Therefore, *E. dahuricus* is the most responsive indicator species for yardangs (Table 5). *S. collina* had the highest frequency in yardangs, but this species was not an indicator of this habitat type. *S. collina* can grow in a wide range of environmental conditions because of its high tolerance to ecological stress (Pyankov et al. 2000).

The percentages of total C and total N were lower in abandoned croplands (group 2) than in steps (group 1), which could represent direct or indirect consequences of

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**Table 4** Total C, total N and C/N ratio in soil (0–1 cm depth) by group

| Parameter      | Group 1 \((n = 11)\) | Group 2 \((n = 7)\) | Group 3 \((n = 6)\) |
|----------------|-----------------------|----------------------|----------------------|
| Total N (%)    | 0.63 (0.04)a          | 0.40 (0.01)b         | 0.25 (0.05)c         |
| Total C (%)    | 5.70 (0.34)a          | 3.46 (0.30)b         | 1.90 (0.51)b         |
| C/N ratio      | 8.99 (0.08)a          | 8.67 (0.57)b         | 6.91 (0.71)b         |

Means with different superscripts within a row differ \((P < 0.05)\) based on multiple comparisons using a Wilcoxon test with a Bonferroni adjustment. Numerical values in parentheses indicate the standard error.

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**Table 5** Characteristic indicator species for each land type in the Xilingol steppe

| Land type          | Indicator species   |
|--------------------|---------------------|
| Typical steppe     | *Leymus chinensis*  |
| Abandoned cropland | *Ceistogenes squarrosa* |
| Yardang            | *Elymus dahuricus*  |
farming. The direct effect of ploughing cropland accounts for a decrease in soil nitrogen (Lobe et al. 2001). Ploughing results in large nutrient losses caused by reduced plant coverage. The indirect effects of farming lead to erosion through the removal of nutrient-rich topsoil, which can be a major cause of coarser surface soil texture and decreased soil quality in the Horqin Sandy Land of Inner Mongolia (Li et al. 2004). Topsoil includes important nutrient sources, but it is difficult for plants to establish on unstable substrates like sand. The percentages of total C and total N were further lower in yardangs (group 3) than in abandoned croplands (group 2), although there was no significant difference in total C because of the large variance among the samples within each group. These facts suggest that decreases in total C and total N are strongly related to erosion. Our results also suggest a high risk of decreased total C and total N due to farming.

In what type of sites will group 3 plots form? Because yardangs do not occur in normal grasslands, it is unlikely that they formed naturally. However, group 3 will occur naturally following abandonment of cropland and in areas of weak resistance to erosion. Soil erosion of abandoned croplands promotes the occurrence of yardangs. Group 3 was characterized by coarse soil particle size. An increasingly coarse sand ratio in surface soils results from erosion (Liu et al. 2003; Su et al. 2004b). Fine sand, which determines water-retention capacity, is lost easily by erosion (Scott 1995). The structure of loess soils does not vary, so differences in soil erodibility are attributable mainly to variation in particle size distributions, among which silt and clay content are the most important factors (Zhang et al. 2004b). Soil particle size affects soil moisture and strongly influences species composition in steppes. Therefore, how to control soil erosion and improve soil moisture for plant is a key issue of land management in this region (Fu et al. 2003). These findings imply that yardangs in steppe in semiarid regions represent an extremely severe state of grassland degradation.

Conclusions

Conversion of grassland into cropland promotes land degradation in arid and semiarid regions of steppe. In particular, abandoned croplands can be converted to yardangs by erosion; the extension of yardangs might then lead to desertification in steppe regions. Soil degradation inhibits plant growth and, as a result, most steppe plants cannot survive in abandoned croplands and very few can survive in highly degraded soils such as yardangs. We suggest that the indicator plant species (Table 5) serve as a means by which to evaluate the effects of farming in the Xilingol steppe. The degradation of steppe can be measured by monitoring these indicator species.

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References

Archibold OW (1995) Ecology of World Vegetation. Chapman & Hall, London.

Bärring L, Jonsson P, Mattsson JO, Åhman R (2003) Wind erosion on arable land in Scania, Sweden and the relation to the wind climate. Catena 52: 173–190.

Chen Z, Wang S (2000) The utilization and restoration of degradation grassland. In: The Ecosystem of Typical Grassland in China (Eds Chen Z, Wang S), The Science Press, Beijing, 307–317.

Chen S, Bai Y, Zhang L, Han X (2005a) Comparing physiological responses of two dominant grass species to nitrogen addition in Xilin River Basin of China. Environ Exp Bot 53: 65–75.

Chen SP, Bai YF, Lin GH, Liang Y, Han XG (2005b) Effects of grazing on photosynthetic characteristics of major steppe species in the Xilin River Basin, Inner Mongolia, China. Photosynthetica 43: 559–565.

Chunru H (1989) Recent changes in the rural environment in China. J Appl Ecol 26: 803–812.

Dulamsuren G, Hauck M, Mühlenberg M (2005) Ground vegetation in the Mongolian taiga forest–steppe ecotone does not offer evidence for the human origin of grasslands. Appl Veg Sci 8: 149–154.

Fearnehough W, Fullen MA, Mitchell DJ, Trueman IC, Zhang J (1998) Aeolian deposition and its effect on soil and vegetation changes on stabilized desert dunes in northern China. Geomorphology 23: 171–182.

Fu B, Wang J, Chen L, Qiu Y (2003) The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena 54: 197–213.

He C, Zhang Q, Li Y, Li X, Shi P (2005) Zoning grassland protection areas using remote sensing and cellular automata mining – A case study in Xilingol steppe grassland in northern China. J Arid Environ 63: 814–826.

Hedin SA (1903) Central Asia and Tibet. C. Scribners Sons, New York.

Hill MO (1979) DECORANA. A Fortran Program for Detrended Correspondence Analysis and Reciprocal Averaging. Ecology and Systematics Department, Cornell University, Ithaca, NY.

Hill MO, Bunce RGH, Shaw MW (1975) Indicator species analysis: a divisive polythetic method of classification and its application to a survey of native pinewoods in Scotland. J Ecol 63: 597–613.

Holzel N, Haub C, Ingelfinger MP, Otte A, Pilipenko VN (2002) The return of the steppe – large-scale restoration of degraded land in southern Russia during the post-Soviet era. J Nat Conserv 10: 75–85.

Hupy JP (2004) Influence of vegetation cover and crust type on wind-blown sediment in a semi-arid climate. J Arid Environ 58: 166–178.
Jiang S, Li B (1988) *Natural Environments of Baiyinxile, Xilinhot, Inner Mongolia*, Bulletin of the Sugadaira Montane Research Center, University of Tsukuba, Ueda, 9: 1–8.

Jiao J, Tzanopoulos J, Xofis P, Bai W, Ma X, Mitchley J (2007) Can the study of natural vegetation succession assist in the control of soil erosion on abandoned croplands on the loess plateau, China? *Restor Ecol* 15: 391–399.

Laryea KB, Unger PW (1995) Grassland converted to cropland: soil conditions and sorghum yield. *Soil Tillage Res* 33: 29–45.

Li XY, Liu LY (2003) Effect of gravel mulch on aeolian dust accumulation in the semiarid region of northwest China. *Soil Tillage Res* 70: 73–81.

Li FR, Zhao LY, Zhang H, Zhang TH, Shirato Y (2004) Wind erosion and airborne dust deposition in farmland during spring in the Horqin Sandy Land of eastern Inner Mongolia, China. *Soil Tillage Res* 75: 121–130.

Liang C, Michalk DL, Millar GD (2002) The ecology and growth patterns of *Cleistogenes* species in degraded grasslands of eastern Inner Mongolia, China. *J Appl Ecol* 39: 584–594.

Liu S (1993) *Key to Plants of the Xilin River Basin, Inner Mongolia*. Inner Mongolia Grassland Ecosystem Research Station, Xilinhot, China.

Liu L, Shi P, Zou X et al. (2003) Short-term dynamics of wind erosion of three newly cultivated grassland soils in northern China. *Geoderma* 115: 55–64.

Lobe I, Amelung W, Dupreez CC (2001) Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. *Eur J Soil Sci* 52: 93–101.

Lopez MV (1998) Wind erosion in agricultural soils: an example of limited supply of particles available for erosion. *Catena* 33: 17–28.

Ma Y, Fu H, Chen S et al. (1989) *Flora Intramongolica 3*, 2nd edn. Typis Intramongolicae Popularis, Hohhot, China. (In Chinese.)

Ma Y, Fu H, Chen S et al. (1990) *Flora Intramongolica 2*, 2nd edn. Typis Intramongolicae Popularis, Hohhot, China. (In Chinese.)

Ma Y, Fu H, Chen S et al. (1992) *Flora Intramongolica 4*, 2nd edn. Typis Intramongolicae Popularis, Hohhot, China. (In Chinese.)

Ma Y, Fu H, Chen S et al. (1994) *Flora Intramongolica 5*, 2nd edn. Typis Intramongolicae Popularis, Hohhot, China. (In Chinese.)

Ma Y, Fu H, Chen S et al. (1998) *Flora Intramongolica 1*, 2nd edn. Typis Intramongolicae Popularis, Hohhot, China. (In Chinese.)

Mainouet M (1991) *Desertification: Natural Background and Human Mismanagement*. Springer–Verlag, Berlin, Germany.

Michels K, Sivakumar MVK, Allison BE (1995) Wind erosion control using crop residue 1. Effect on soil flux and soil properties. *Field Crops Res* 40: 101–110.

Mitchell RJ, Marrs RH, Le Duc MG, Auld MHD (1999) A study of the restoration of heathland on successional sites: changes in vegetation and soil chemical properties. *J Appl Ecol* 36: 770–783.

Nakamura T, Go T, Wuyunna, Hayashi I (2000) Effects of grazing on the floristic composition of grasslands in Baiyinxile, Xilingole, Inner Mongolia. *Grassl Sci* 45: 342–350.

Nan Z (2005) The grassland farming system and sustainable agricultural development in China. *Grassl Sci* 51: 15–19.

Nordstrom KF, Hotta S (2004) Wind erosion from cropland in the USA: a review of problems, solutions and prospects. *Geoderma* 121: 157–167.

Oba G, Vetaas OR, Stenseth NC (2001) Relationships between biomass and plant species richness in arid-zone grazing lands. *J Appl Ecol* 38: 836–845.

Penfound WT, Howard JA (1940) A phytosociological study of an evergreen oak forest in the vicinity of New Orleans, Louisiana. *Ann Mo Bot Gard* 23: 165–174.

Pielou EC (1969) *An Introduction to Mathematical Ecology*. Wiley–Interscience, New York, NY.

Ping CS, Fei BY, Guo HX (2004) Variation of water-use efficiency of *Leymus chinenis* and *Cleistogenes squarrosa* in different plant communities in Xilin River Basin, Nei Mongol. *Acta Bot Sin* 44: 1484–1490.

Pyankov VI, Gunin PD, Tsoog S, Black CC (2000) C4 plants in the vegetation of Mongolia: their natural occurrence and geographical distribution in relation to climate. *Oecologia* 123: 15–31.

Qian W, Tang X, Quan L (2004) Regional characteristics of dust storms in China. *Atmos Environ* 38: 4895–4907.

Scott WD (1995) Measuring the erosivity of the wind. *Catena* 24: 163–175.

Shannon CE (1948) A mathematical theory of communication. *Bell Labs Tech J* 27: 379–423.

Simpson EH (1949) Measurement of diversity. *Nature* 163: 688.

Su Y, Zhao H, Zhang T, Zhao X (2004a) Soil properties following cultivation and non-grazing of a semi-arid sandy grassland in northern China. *Soil Tillage Res* 75: 27–36.

Su Y, Zhao H, Zhao W, Zhang T (2004b) Fractal features of soil particle size distribution and implications for indicating desertification. *Geoderma* 122: 43–49.

Tong C, Wu J, Yong S, Yang J, Yong W (2004) A landscape-scale assessment of steppe degradation in the Xilin River basin, Inner Mongolia, China. *J Arid Environ* 59: 133–149.

Walter H (1973) *Walter’s Vegetation of the Earth*. English University Press and Springer, Berlin, Germany.

Wang J, Cai Y (1988) Studies of genesis, types and characteristics of the soils of the Xilin River basin. In: *IMGERS, Research on Grassland Ecosystem (3)* (Eds Chen Z, Wang S), The Science Press, Beijing, 23–83.

Wang X, Dong Z, Zhang J, Liu L (2004) Modern dust storms in China: an overview. *J Arid Environ* 58: 559–574.

Yiruhan , Hayashi I, Nakamura T, Shiyomi M (2001) Changes in floristic composition of grasslands according to grazing intensity in Inner Mongolia, China. *Grassl Sci* 47: 362–369.

Zhang K, Li S, Peng W, Yu B (2004a) Erodibility of agricultural soils on the Loess Plateau of China. *Soil Tillage Res* 76: 157–165.

Zhang TH, Zhao HL, Li SG et al. (2004b) A comparison of different measures for stabilizing moving sand dunes in the Horqin Sandy Land of Inner Mongolia, China. *J Arid Environ* 58: 202–213.