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Grassland dynamics in response to climate change and human activities in Inner Mongolia, China between 1985 and 2009

S. J. Mu[A], *Y. Z. Chen*[A], *J. L. Li*[A,D], *W. M. Ju*[B], *I. O. A. Odeh*[C] *and X. L. Zou*[C]

[A]School of Life Science, Nanjing University, Nanjing 210093, People's Republic of China.
[B]International Institute of Earth System Science, Nanjing University, Nanjing 210093, People's Republic of China.
[C]Faculty of Agriculture, Food and Natural Resources, The University of Sydney, Sydney, NSW 2006, Australia.
[D]Corresponding author. Email: jianlongli@gmail.com

Abstract. China's grassland has been undergoing rapid changes in the recent past owing to increased climate variability and a shift in grassland management strategy driven by a series of ecological restoration projects. This study investigated the spatio-temporal dynamics of Inner Mongolia grassland, the main grassland region in China and part of the Eurasia Steppe, to detect the interactive nature of climate, ecosystems and society. Land-use and landscape patterns for the period from 1985 to 2009 were analysed based on TM- and MODIS-derived land-use data. Net Primary Productivity (NPP) estimated by using the Carnegie-Ames-Stanford Approach model was used to assess the growth status of grassland. Furthermore, the factors related to the dynamics of grassland were analysed from the perspectives of two driving factors, climate change and human activities. The results indicated that higher temperatures and lower precipitation may generally have contributed to grassland desertification, particularly in arid regions. During the period from 1985 to 2000, a higher human population and an increase in livestock numbers were the major driving forces responsible for the consistent decrease in NPP and a relatively fragmented landscape. From 2000 to 2009, the implementation of effective ecological restoration projects has arrested the grassland deterioration in some ecologically fragile regions. However, a rapid growth of livestock numbers has sparked new degradation onnon-degraded or lightly degraded grassland, which was initially neglected by these projects. In spite of some achievement in grassland restoration, China should take further steps to develop sustainable management practices for climate adaptation and economic development to bring lasting benefits.

Additional keywords: climate change, Grain to Green Project, Grazing Withdraw Project, livestock numbers, Inner Mongolia, net primary productivity.

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Introduction

Grassland is one of the most widespread land cover types worldwide, which covers ~25% of the natural land surface and accounts for ~16% of the terrestrial global net annual primary production (Conant *et al*. 2001; Zhou *et al*. 2002). Thus it has a major influence on the functioning of the terrestrial biosphere. China has 400 million hectares of grassland, accounting for 41.7% of the national land area (Ren *et al*. 2008) and 11.8% of the world's total grassland (Zhao *et al*. 2005*a*). China's grassland plays a pertinent role for ecosystem conservation and socioeconomic development, and is regarded as the country's most important natural resource by the central government and many scientists (Wei *et al*. 2004; Nan 2005; Han *et al*. 2008). Specifically, the grassland of China is not only the home to rich plant and animal diversity, but also the major source of animal products such as meat, milk, wool and pelts (Kang *et al*. 2007; Han *et al*. 2008). In addition, a social function, in terms of maintaining cultural diversity and social stability, has also been a critical component of the China's grassland, which is home to the majority of the ethnic people (Kang *et al*. 2007).

However, the grassland ecosystem in China has experienced large-scale degradation and desertification during the past decades, which has caused severe environmental issues and posed a challenge to food security (Jiang *et al*. 2006; Akiyama and Kawamura 2007). This has come largely by overgrazing and large-scale conversion to cropland to cope with the increasing demand for animal products and food resources following the sharply rising human populations (Li *et al*. 2008). Moreover, the situation has been further exacerbated by the adverse effects of droughts possibly due to climate change (Zhou *et al*. 2002; Han *et al*. 2008). A recent survey revealed that ~90% of total usable grassland in China has been degraded to various extents, with significant regional variation (Nan 2005). About 27.3% of the grassland in China is subjected to desertification (Lu 2006), and this area is increasing by 2460 km^2 per year (Akiyama and Kawamura 2007). No less than 400 million people are likely to be affected and the direct economic losses amount to 54 billion yuan per year (Akiyama and Kawamura 2007).

Grassland deterioration in China and the frequently occurring dust storms, as the direct consequence, have attracted world attention. Since 2000, China has invested heavily to restore degraded and dysfunctional grassland and seek effective management practices for sustainable development of China's grasslands (Kang *et al*. 2007). With this end in view, a series of ecological restoration projects (e.g. the Three-North Shelterbelt Forest project, the Beijing-Tianjin Sandstorm Controlling project, the Grain to Green Project and the Grazing Withdraw Project) were successively initiated by the Central Government (Tong *et al*. 2004; Liu *et al*. 2008; Hu *et al*. 2012). The implementation of these projects has caused drastic alternation of land-use patterns, exerting profound influences on the vegetation dynamics of grassland. In addition, climate change is taking place at an unparalleled rate in recent years. In some areas of East Asia, the frequency of extreme events has increased by as much as 5% over the past 30 years as compared with the average from 1961 to 2010, which has resulted in the frequent occurrence of extreme low/high temperatures and precipitation intensity, and the duration of events such as drought and severe winter storms (Qi *et al*. 2012). Lu *et al*. (2009), who investigated climate change in Inner Mongolia from 1955 to 2005, found that the inter-decadal increases in annual mean temperature was only significant in the last two decades, and the regional vapour pressure deficit showed insignificant increases in the first four decades but has increased significantly in the last decade.

Grassland in China is undergoing rapid changes in response to alternations in land-use practices and climate change, and it is a great challenge but an urgent task to understand the nature of these interactions coupled with climate, ecosystems and society. The present study selected Inner Mongolia grasslands, which constitutes the main grassland region of China and a significant part of the Europe-Asia Steppe, as a case to explore the grassland dynamics under cumulative effects of climate and human factors. This paper aims to analyse the pattern of land-use change using a geographic information system (GIS) and patch analysis methods, and to estimate the variation in growth status of grassland through simulating the Net Primary Productivities (NPP) using the Carnegie-Ames-Stanford Approach (CASA) model. The corresponding driving forces in this process are discussed based on climate change and human activities, which has important implications for decision-makers to balance environmental conservation and economic development on the grasslands under rapid climate change.

Study area

The Inner Mongolia Autonomous Region is located between 37°24′–53°23′N and 97°12′–126°04′E with a mean elevation of 1014 m, ranking it as the third largest region in China (Fig. 1). Inner Mongolia lies along the south-eastern fringes of the Northern Eurasian Earth Science Partnership Initiative (NEESPI, http://neespi.org/, accessed 20 May 2013) study area, whose domain of ~28.6×10^6 km^2 accounts for 60% of the terrestrial land area north of 40°N. During the past century, dramatic climatic, environmental and socioeconomic changes

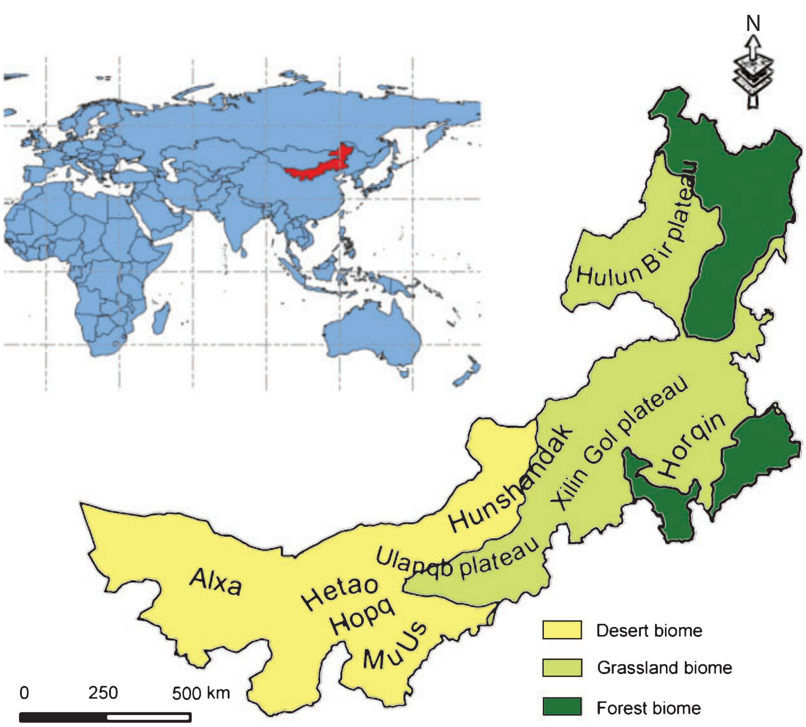

Fig. 1. Location map of study region, province of Inner Mongolia, People's Republic of China, overlaid with biomes derived from World Wildlife Fund terrestrial eco-region boundaries.

have occurred within northern Eurasia, and the NEESPI was formed to better understand and quantify the nature of global climate change impacts on land processes and anthropogenic activities in the region.

Inner Mongolia is characterised by an arid to semiarid continental climate with strong climatic gradients and varied land-use practices. The region can be divided into three biomes: the arid desert in the west, grassland in the centre and forest in the north-eastern region. Grassland is the dominant vegetation type in Inner Mongolia comprising more than 20% of China's total grassland. A strong east-to-west precipitation gradient results in a decrease in annual precipitation from more than 500 mm in eastern Inner Mongolia to less than 100 mm in the western part. With this large range in precipitation, three major zonal grassland types – meadow steppe, typical steppe and desert steppe – are distributed along the north-east to south-west axis in Inner Mongolia. Typical steppe, developed under semiarid conditions with annual precipitation from 200 to 400 mm and annual mean temperature from 0 to 8°C in central Inner Mongolia, is the most widely spread type (Piao *et al*. 2006). Meadow steppe, which is more productive than typical steppe, is developed in areas with moist fertile soils rich in organic matter in north-eastern Inner Mongolia, with annual average precipitation ranging from 300 to 600 mm and annual mean temperature from 2 to 5°C. The desert steppe found in areas with annual precipitation between 150 and 200 mm and annual mean temperature between 5 and 10°C has the least biomass (John *et al*. 2008).

Data and methods

Land-use data

To characterise the spatial and temporal patterns of land-use changes across China, the Chinese Academy of Sciences built a data platform supported by the National Resources and Environment Database (NRED) in the late 1990s. Land-use datasets for 1985, 1995 and 2000 with a mapping scale of 1 : 100 000 were originally derived from Landsat images of corresponding years, and then a 1-km raster database was generated. According to the land-use classification system for the NRED dataset, the land use was categorised into six types: cropland, forest, grassland, water bodies, built-up land and unused land including desert. In this study, the land-use data for 1985, 1995 and 2000 with a 1-km resolution were downloaded from Data Sharing Infrastructure of Earth System Science (http://wdcrre.geodata.cn/, accessed 20 May 2013).

MODIS-derived land-use data for 2009 with a 500-m resolution (MCD12Q1) were downloaded from the EOS data gateway (http://modis.gsfc.nasa.gov/), and were resampled to a 1-km resolution using a nearest neighbour method. MCD12Q1 data were based on the IGBP global vegetation classification scheme, which has 17 land-use classes. In this paper, the land-use map for 2009 was reclassified into six dominant categories in accordance with the maps of 1985, 1995 and 2000 to make them comparable. Evergreen needle-leaf, deciduous needle-leaf, deciduous broad-leaf, mixed forests and closed shrublands were recoded to forest; open shrublands, woody savannas, savannas, grasslands and permanent wetlands were recoded to grassland, whereas crop/natural vegetation was recoded to cropland.

These data were projected to the Albers equal area projection with datum WGS 84, for an easy overlay and inter-comparison of the two datasets. In addition, the land-use maps were overlaid with forest, grassland and desert biomes obtained from the World Wildlife Fund's terrestrial eco-region dataset (www.worldwildlife.org/science/data/terreco.cfm, accessed 20 May 2013).

Accuracy estimates of land-use data

The accuracy of the NRED dataset was evaluated from an extensive field survey and random sample check covering line survey of 70 000 km and 13 300 patches across China. The average interpretation accuracy is 92.9% for land use and 97.6% for land-use change interpretation (Liu *et al*. 2003). The accuracy for grassland, cropland, forest and built-up land were 88.1, 90.1, 94.9 and 96.3%, respectively (Yan *et al*. 2009).

The MODIS global land-use product was derived from the MODIS 500-m resolution data using a state-of-the-art supervised classification system based on the decision-tree classifier (Friedl *et al*. 2002). The accuracy of the International Geosphere and Biosphere Programme (IGBP) layer of MCD12Q1 was estimated to be 74.8% globally, with a 95% confidence interval of 72.3–77.4% (Friedl *et al*. 2010). Estimates of accuracy for the dominant IGBP classes in Inner Mongolia were 66% for grassland, 58% for cropland, 85% for open shrubland, 65% for mixed forest and 74.5% for barren land. A separate analysis of the urban land-use class in the MCD12Q1 product, based on Landsat data, indicates an overall accuracy of 93% (John *et al*. 2009).

A recent study compared four land-use datasets (UMD, IGBP-DISCover, MODIS and GLC2000) at a 1-km resolution across China with the NRED dataset for 2000. The analysis found that the MODIS land-use dataset was most representative of cropland cover in China with a bias of 2.9% from the NRED dataset (Wu *et al*. 2008). Furthermore, the Kappa coefficient was computed to assess the agreement between NRED dataset and reclassified MODIS dataset (six land-use types) of Inner Mongolia for 2000, in which year both of the two datasets were available. The Kappa coefficient was 0.723, which showed good agreement.

Landscape metrics

The concept of fragmentation refers to the transformation of landscape pattern, which is often driven by human disturbance, from a uniform to a more heterogeneous and patchy situation (Kouki and Löfman 1998). Such transformations include both changes in area and patch configuration. Landscape patterns produced as a result of the fragmentation and loss of natural habitat might affect the water and carbon fluxes and impose devastating and irreversible consequences on the biodiversity of ecosystems (Herkert *et al*. 2003). Land managers have long been aware of the link between the spatial pattern of landscapes and the ecological processes at varying scales (Lindenmayer *et al*. 2002), and sought out measures of landscape transformation in order to predict the ecological sustainability and aid their decisions (John *et al*. 2009). Landscape metrics, which can be defined as a quantitative indices to describe structures and patterns of a landscape (O'Neill *et al*. 1988), have been widely used for this purpose (Wang *et al*. 2008; Zhou *et al*. 2008; Yu *et al*. 2011). Landscape metrics cannot only frame the management plans but also track changes in ecological or socioeconomic variables (Herzog *et al*. 2001). Therefore, the analysis of landscape metrics is useful to characterise the process of grassland fragmentation in Inner Mongolia and help landscape managers to sustainable landscape planning and management.

In this study, the Patch Analyst module was used to calculate the landscape metrics, which is an extension to the ArcView GIS system that facilitates the spatial analysis of landscape patches, and modelling of attributes associated with patches (Rempel and Carr 2003). Two levels of landscape metrics were computed: (1) the patch-type level, which means each patch type (land-use type) in the landscape mosaic. In this study, the focus was on the grassland without concerning about other patch types, such as cropland, barren land and forest; (2) the landscape level, which means the landscape mosaic as a whole (Wang *et al*. 2008). The various patch metrics follow the definitions in FRAGSTATS (McGarigal and Marks 1994). Patch Analyst is capable of calculating a large number of landscape metrics but many of them can be highly correlated. In this analysis of the change in landscape metrics at the patch-type level, six metrics were selected: number of patches, mean patch size, largest patch index, edge density, area-weighted mean shape index and interspersion juxtaposition index. In addition, the Shannon's diversity and evenness indices were calculated to measure heterogeneity at the landscape level. The selected metrics are described in Table 1. The land-use maps were imported to ArcGIS Version 9.3 to obtain the attribute information of each land-use type in order to calculate the patch type and landscape metrics.

Model to estimate Net Primary Productivity

Numerous models have been developed to estimate NPP at global or regional scales, which mainly include statistical models, parameter models and process-based models (Ruimy and Saugier 1994). The CASA model employed in this study is a process-based model developed on the resource-balance theory, which postulates that plants regulate their physiological, biochemical and morphological characteristics when the resources available to the plants change in response to changes in environmental conditions (Field *et al*. 1995). The proportion of photosynthetically-active radiation (PAR) that is absorbed by vegetation is both the driving potential for photosynthesis and influences the availability of whatever resource limits growth, which implies that NPP can be modelled using a relationship with absorbed photosynthetically-active radiation (APAR). The effects of environmental factors, such as temperature and water stress, on light-use efficiency are also considered to estimate NPP (Potter *et al*. 1993). As it is possible to make an estimation of

Table 1. Description of landscape metrics calculated for grassland landscape pattern

Metrics	Algorithm[A]	Description
SHDI	$SHDI = -\sum_{i=1}^{m}(P_i \ln P_i)$	Measure of relative patch diversity. Shannon's diversity index is a relative measure of patch diversity. The index will equal zero when there is only one patch in the landscape and increases as the number of patch types or proportional distribution of patch types increases
SHEI	$SHEI = -\sum_{i=1}^{m}(P_i \ln P_i)/\ln m$	Measure of patch distribution and abundance. Shannon's evenness index is equal to zero when the observed patch distribution is low and approaches one when the distribution of patch types becomes more even
NP	$NP_i = n_i$	The number of patches in the landscape. The number of patches is an intuitive and simple measure of the degree of subdivision of a land cover type
MPS	$MPS_i = \sum_{j=1}^{n} a_{ij}/n_i \times 10^{-3}$	Average size of patches is expected to decrease with increasing fragmentation
ED	$ED_i = E/A$	Amount of edge relative to the landscape area. The ED approaches 0 when there is no class edge in the landscape
LPI	$LPI_i = \max_{j=1}^{n}(a_{ij}) \times 100/A$	Percentage of the landscape composed of the largest patch. When the entire landscape is made up of a single patch, the LPI will equal 100. As the size of the largest patch decreases, the LPI approaches 0
AWMSI	$AWMSI_i = \sum_{j=1}^{n}\left[(0.25p_{ij}/\sqrt{a_{ij}})\left(a_{ij}/\sum_{j=1}^{n} a_{ij}\right)\right]$	Mean patch shape complexity, weighted by patch area. AWMSI is equal to 1 when all patches are circular (for polygons) or square [for rasters (grids)] and it increases with increasing patch shape irregularity
IJI	$IJI_i = -\sum_{k=1}^{m}\left[\left(e_{ik}/\sum_{k=1}^{m} e_{ik}\right)\ln\left(e_{ik}/\sum_{k=1}^{m} e_{ik}\right)\right] \times 100/\ln(m-1)$	A measure of interspersion over the maximum possible interspersion for the given number of classes, ranging from 0 to 100. Approaches 0 when the distribution of adjacencies among patch types becomes increasingly uneven and equals 100 when all patch types are equally adjacent to all other patch types. At the patch-type level interspersion is a measure of relative interspersion of each patch type

[A]In the above formulae, m and n_i represent the patch number of the land cover class i; E is total grassland edge; A is the total grassland area; a_{ij} means the area of jth patch of the land cover class i; P_{ij} means the perimeter of jth patch of the land cover class i; P_i is the proportion of area covered by land cover class i; e_{ik} is length of edge between class i and class k.

NPP based on satellite data and ground data at a large scale, the use of the CASA model has become widespread in recent years.

In the CASA model, NPP is the product of two modulated major driving variables, which are the APAR and light-use efficiency (ε). The basic principle of the model can be described by the following equation (Yu *et al*. 2011):

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \quad (1)$$

where x is spatial location (the pixel number), and t is time. $PAR(x, t)$ (MJ m^{-2} $month^{-1}$) represents the PAR absorbed by pixel x in t time while $\varepsilon(x, t)$ represents the actual light-use efficiency (g C MJ^{-1}) of pixel x in t time. $PAR(x, t)$ and $\varepsilon(x, t)$ are calculated from Eqns 2 and 3 (Zhu *et al*. 2005; Yu *et al*. 2011):

$$APAR(x,t) = SOL(x,t) \times FPAR(x,t) \times 0.5 \quad (2)$$

where $SOL(x, t)$ is the total solar radiation (MJ m^{-2}) of pixel x in t time and $FPAR(x, t)$ is the fraction of PAR absorbed by the vegetation canopy, and it can be determined by Normalised Difference Vegetation Index (NDVI). The value of 0.5 stands for the fraction of total solar radiation that can be used by vegetation (0.38–0.71 μm).

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{max} \quad (3)$$

where $T_{\varepsilon 1}(x, t)$ and $T_{\varepsilon 2}(x, t)$ are temperature stress coefficients, which reflect the reduction of light-use efficiency caused by a temperature factor. $W_{\varepsilon}(x, t)$ is the moisture stress coefficient, which indicates the reduction in light-use efficiency caused by moisture factor. ε_{max} is the maximum light-use efficiency under ideal condition. A more detailed description of the model has been given by Yu *et al*. (2011).

Input data for the CASA model

Global Inventory Modeling and Mapping Studies (GIMMS) Advanced Very High Resolution Radiometer (AVHRR)-based 15-day NDVI with the resolution of 8 km was obtained from the Environment and Ecological Science Data Centre for West China (http://westdc.westgis.ac.cn/, accessed 20 May 2013) to calculate NPP in 1985 and 1995, while MODIS-based 16-day composite vegetation indices (MOD13A1) with the resolution of 500 m was downloaded from the EOS data gateway to calculate NPP in 2000 and 2009. Monthly composite products (GIMMS AVHRR-NDVI) and 32-day composite products (MODIS-NDVI) of the maximal values were produced for a time series based on these data. These data were re-projected to the Albers equal area projection with datum WGS 84. ε_{max} varied among the land-use classes and, therefore, the land-use map was also used in the estimation of NPP. The NDVI images of the two datasets were resampled to a resolution of 1 km with the same spatial resolution as the land-use data, and NPP was also produced at a resolution of 1 km. Previous studies showed that the continuity of NDVI time series from AVHRR to MODIS is satisfactory, but a linear transformation between the two sets is necessary (Ji *et al*. 2008). To eliminate errors between GIMMS AVHRR-NDVI and MODIS-NDVI due to different satellite sensors, the correlation between the maximum NDVI of the two datasets in Inner Mongolia for 2004, 2005 and 2006 was determined. The correlation coefficients were 0.93, 0.91 and 0.89, respectively, with a confidence level of $P < 0.001$. Then MODIS-NDVI ($NDVI_M$) in 2005 was considered as an independent variable and GIMMS AVHRR-NDVI ($NDVI_G$) in 2005 as a dependent variable to carry out a linear fit. The linear regression equation was $NDVI_G = 0.314 NDVI_M + 0.0298$ (sample number = 1 146 529, $RMS = 0.031$, Chi-square = 25.72). Based on this equation, the interpolated GIMMS AVHRR-NDVI in 2000 and 2009 using MODIS-NDVI was obtained.

Meteorological data including daily average temperature, daily total precipitation and daily total solar radiation for the study period came from the China Meteorological Data Sharing Service System. The data from 50 climate stations in Inner Mongolia was reduced to monthly composite meteorological data for 1985 and 1995 and 32-day composite meteorological data for 2000 and 2009, and interpolated through the kriging method to produce raster images with the same temporal and spatial resolution as the remote-sensing images.

Results

Dynamics of grassland in the period from 1985 to 2009

The land-use maps for 1985, 1995, 2000 and 2009 are presented in Fig. 2 and the grassland areas under each of the three biomes and the whole region are shown in Table 2. From Table 2, the cover of grassland at the regional level in 1985, 1995, 2000 and 2009 were 0.54, 0.57, 0.53 and 0.61 million km^2, respectively, which exhibited drastic temporal variation, especially between 2000 and 2009. At the biome level, the peak value for grassland area in the desert biome occurred in 1995 (47.1% of the biome's area), while that in the grassland biome was in 2009 (81.1% of the biome's area). In the forest biome, it changed minimally.

Between 1985 and 1995, the grassland of Inner Mongolia increased by 33 735 km^2, representing an increase of 6.3% of the total area in 1985. The newly developed grassland was largely concentrated in the desert biome, where the area increased by 35 132 km^2 from 1985 to 1995 (an increase of 18.9%). Figure 3 presents the areas of conversion between grassland and three major vegetation types. During the first period (1985–95), the increase of grassland area in the desert biome was primarily attributed to the conversion between grassland and barren land. The area converted from grassland to barren land was only 7645 km^2 in the period from 1985 to 1995, while the area of conversion from barren land to grassland was 41 605 km^2. In the grassland biome and the forest biome, the grassland area showed a slight decreasing trend over this period, which was mainly due to the conversion to cropland. The net losses, as the consequence of conversion between grassland and cropland, were 3545 km^2 in the grassland biome and 963 km^2 in the forest biome, respectively.

The increasing trend during the period from 1985 to 1995 was reversed during the second period (1995–2000). The area of grassland decreased by 41 407 km^2 (7.3%) at the regional level from 1995 to 2000. The most significant loss took place in the desert biome, with a loss in area of 37 017 km^2. Spatially (Fig. 2), the grassland that converted from barren land during period from 1985 to 1995 had reverted to barren land again during the period of 1995–2000 (Mu Us sandy land and Hopq desert), which reduced the grassland area by 35 790 km^2 in the desert biome. The conversion between grassland and barren land that had occurred

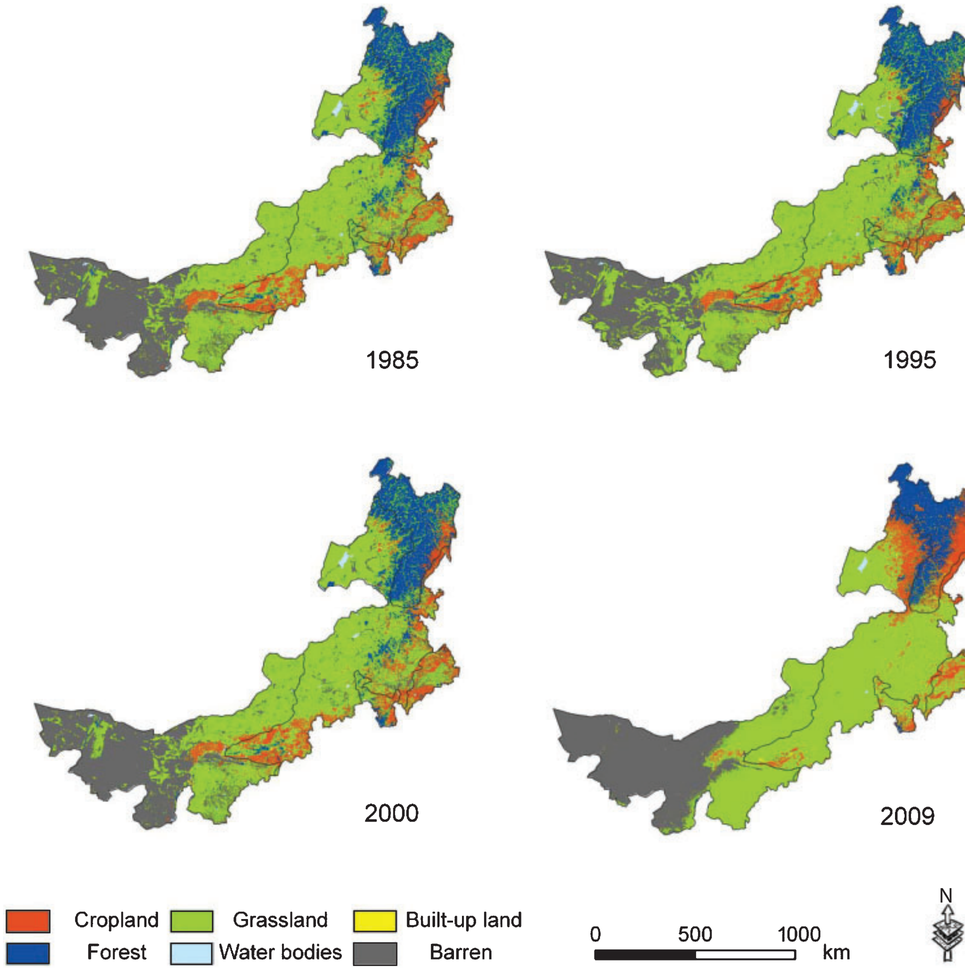

Fig. 2. Land-use maps of Inner Mongolia in 1985, 1995, 2000 and 2009.

Table 2. Area and percentage of grassland at biome and regional level during 1985–2009 in km^2

Biome section	1985		1995		2000		2009		Percentage change of grassland			
	Area	%	Area	%	Area	%	Area	%	1985–95	1995–2000	2000–09	1985–2009
Desert biome	186 181	39.65	221 313	47.13	184 296	39.25	187 663	39.97	18.87	–16.73	1.83	0.80
Grassland biome	298 666	65.42	297 817	65.23	295 361	64.69	370 265	81.10	–0.28	–0.82	25.36	23.97
Forest biome	51 991	25.09	51 443	24.83	49 509	23.90	50 808	24.53	–1.05	–3.76	2.62	–2.28
Whole region	536 838	43.39	570 573	46.12	529 166	42.77	608 736	49.20	6.28	–7.26	15.04	13.39

in the grassland biome, reached near equilibrium over the 5-year period and contributed minimally to the variation in grassland area (Fig. 3). The slight decrease found in the grassland biome was mainly because the areas, which converted from grassland to cropland and forest, were larger than that in the opposite direction. In the forest biome, 2921 km^2 of grassland was converted to cropland, contributing mostly to the loss of grassland at the biome level.

A large increase in grassland area was found at regional level during the third period (2000–09), with an increase of 79 570 km^2 or 15.0% of the total area in 2000. The increasing trend could be found in all the three biomes. The area in the grassland biome increased by 74 904 km^2 (25.4% in 2000), which was the largest increase among the biomes. In the grassland biome (Fig. 3), grassland areas converted from cropland, forest and barren land were 52 569, 21 275 and 29 753 km^2, respectively, which was considerably higher than the conversion to each corresponding vegetation type (31 686, 1368 and 192 km^2, respectively). In the desert biome, grassland experienced net gains of 11 004 and 1532 km^2 from the conversion of cropland and forest, respectively, while a net loss of 11 804 km^2 in grassland was found due to the conversion to barren land. In the forest biome, however, the conversion between grassland and cropland led to a net loss of 4509 km^2 in grassland area,

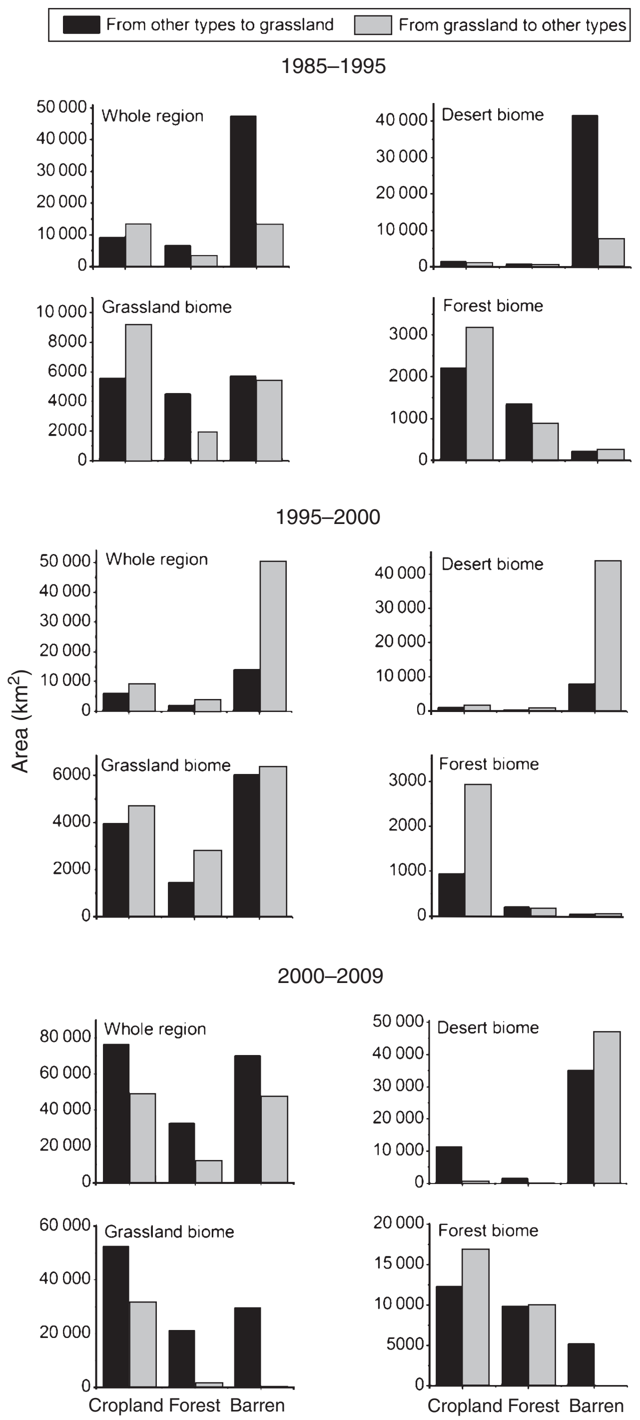

Fig. 3. The areas of main grassland transformation in Inner Mongolia during 1985–2009.

while 5211 km^2 of grassland was gained from the conversion of barren land.

The grassland of Inner Mongolia has increased by 71 898 km^2 in the past 24 years, an increase of 13.4% since 1985. The significant increase in the grassland biome during 2000–09 was the dominant contributor responsible for this change.

Changes in the pattern of grassland landscapes

The landscape metrics at landscape and patch-type level are shown in Fig. 4. Compared with the other two periods, both the Shannon's diversity index and the Shannon's evenness index decreased slightly during the third period (2000–09) at a regional scale, indicating decreasing landscape heterogeneity in Inner Mongolia. In the desert biome, the trend in the two landscape pattern metrics was consistent with the trend at the regional level. In the grassland biome, however, both of the metrics exhibited a sharp decrease over the period. In the forest biome, the Shannon's diversity index also decreased during 2000–09, but in the contrary, the Shannon's evenness index showed an increasing trend over the same period.

Number of patches and mean patch size indicated that the fragmentation and discreteness of grassland reached its lowest in 2009 at the regional level, which was more obvious in the desert biome than in the grassland biome, and was not found in the forest biome. Due to less human disturbance during the third period, the changes in the large patch index indicated that grassland occupied a more dominant position in the regional and biome landscape in 2009. There was a decreasing trend in edge density for grassland during 1995–2009 at both regional and biome levels, implying that the grassland landscape was less isolated and the edge effect of grassland patches had decreased. At the regional level, the area-weighted mean shape index for grassland was relatively high in 1985 and 2000, and reached the lowest value in 2009, indicating that the shape of grassland patches was inclined to simplification and regularity in the period 2000–09. The trend in this shape index for the desert and grassland biome was consistent with the general characteristics at the regional scale. For the forest biome, however, the area-weighted mean shape index increased significantly during 2000–09, suggesting that the grassland patches tended to be more complex in this biome. Moreover, the large decrease in interspersion juxtaposition index at regional and biome levels in the period 2000–09 suggested an increased connectivity and cohesion for grassland patches.

Change in Net Primary Productivity

Table 3 shows the estimated values of mean and total NPP for Inner Mongolia grassland, which were simulated using the CASA model. The calculated NPP values were similar to those of Li and Ji (2004) who simulated the NPP base on the AVIMia model (consists of Atmosphere-Vegetation Interaction Model and an impact assessment model) for Inner Mongolia grassland and estimated that mean NPP in this region ranged between 222.6 and 315.0 g Cm^{-2} $year^{-1}$. To further verify the accuracy of the estimates of the CASA model, independently observed NPP data for grassland vegetation (33 data points) were collected in July 2009, and compared against the estimated values. Figure 5 presents the results of the correlation analysis between the observed and estimated NPP data. The correlation was significant ($R^2 = 0.48$, $P < 0.001$), which indicates that the model's accuracy was satisfactory and that the CASA model can be used to support research on changes in NPP in Inner Mongolia grasslands.

During the periods from 1985–1995 to 1995–2000, the mean grassland NPP for the whole region decreased by 4.3 and 7.2%, respectively. Contrary to this trend, it increased considerably during 2000–09 by ~36.6 g Cm^{-2} $year^{-1}$, i.e. an increase of 15.6%

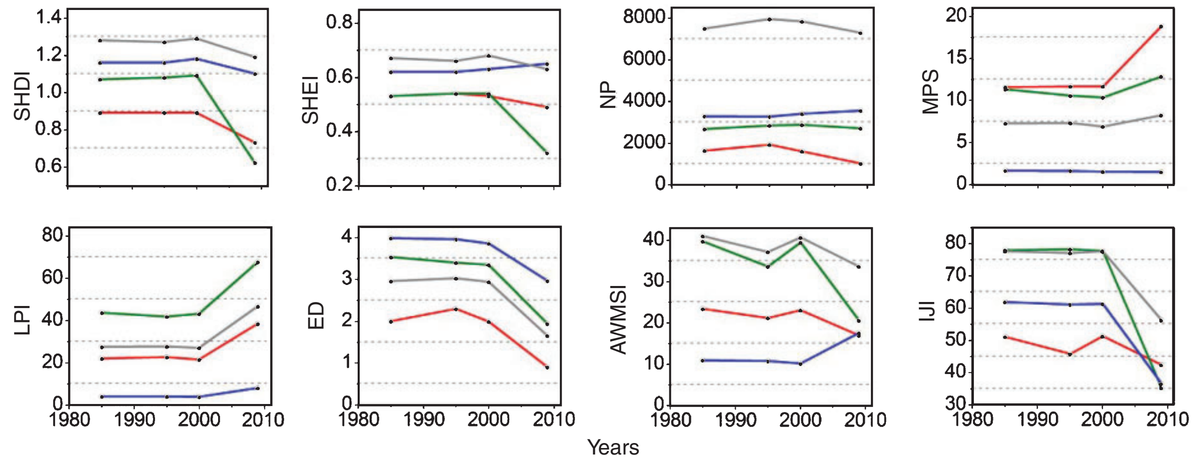

Fig. 4. Changes in landscape metrics at a regional scale (grey), and for desert biome (red), grassland biome (green), and forest biome (blue) in the period from 1985 to 2009. (SHDI: Shannon's diversity index, SHEI: Shannon's evenness index, NP: number of patches, MPS: mean patch size, LPI: largest patch index, ED: edge density, AWMSI: area-weighted mean shape index, IJI: interspersion juxtaposition index.)

Table 3. Estimated values of mean and total Net Primary Productivity (NPP) in 1985, 1995, 2000 and 2009 for Inner Mongolia grassland unit: mean NPP (g C m^{-2} year^{-1}), total NPP (Tg C)

Biome	Desert biome		Grassland biome		Forest biome		Whole region	
sections	Mean NPP	Total NPP	Mean NPP	Total NPP	Mean NPP	Total NPP	Mean NPP	Total NPP
1985	130.69	24.33	322.51	96.32	411.52	21.40	264.61	142.05
1995	137.13	30.35	307.34	91.53	438.48	22.56	253.14	144.44
2000	126.87	23.38	280.05	82.72	368.79	18.26	235.00	124.36
2009	180.20	33.82	299.29	110.82	406.63	20.66	271.55	165.29
Percentage change (%)								
1985–95	4.93	24.74	–4.70	–4.97	6.55	5.42	–4.33	1.68
1995–2000	–7.48	–22.97	–8.88	–9.63	–15.89	–19.06	–7.17	–13.90
2000–09	42.04	44.65	6.87	33.97	10.26	13.14	15.55	32.91

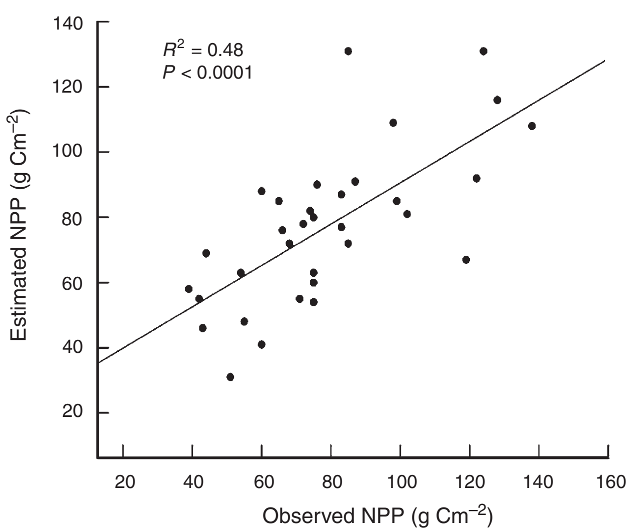

Fig. 5. Relationship between estimated Net Primary Productivity (NPP) and observed NPP for grasslands in July 2009.

of that in 2000, and reached the highest value in 2009 compared with the other two periods. In the desert biome, the mean NPP changed minimally from 1985 to 2000, while it increased considerably by 53.3 g Cm^{-2} year^{-1} from 2000 to 2009, being highest in 2009. In the grassland biome, although the mean NPP increased by 19.2 g Cm^{-2} year^{-1} (an increase of 6.9% from 2000) during the period from 2000 to 2009, it was lower in 2009 than in 1985 and 1995. A similar situation was found in the forest biome. The mean NPP in 2009 increased significantly compared with that in 2000 while still less than in 1985 and 1995.

The total NPP of grassland for the whole region reached the highest value in 2009, being 32.9% higher than in 2000 and 16.4% higher than in 1985. In the desert biome, total NPP was highest in 2009 due to the higher mean NPP than in the other periods. In the grassland biome, although mean NPP in 2009 was lower than that in 1985 and 1995, total NPP was highest in 2009 as a result of the larger grassland area. The total NPP in the forest biome was highest in 1995, while the lowest value occurred in 2000.

Discussion

Climate change and human activities are the two major factors affecting grasslands, especially in the arid and semiarid regions, which are characterised by extremely fragile ecosystems. This study shows that the dynamics of grassland in Inner Mongolia are based on slow changes in natural factors but with human activities exerting an increasing external influence.

Climate change affected grassland dynamics

Climate affects grassland mainly through the influence of changes in precipitation and temperature. It is generally recognised that increased precipitation is favourable for grassland development in arid regions (Yang *et al*. 2008). In contrast, higher temperatures mean more evaporation and, thus, less available water and more arid conditions (Shen *et al*. 2012). To detect the climate change, changes in annual precipitation and mean temperature during the period of 1951–2009 were calculated based on the climate data collected from 50 climate stations across Inner Mongolia.

As shown in Fig. 6 and Table 4, the mean temperature has increased by 0.4°C per decade from 1951 to 2009, which is much higher than global linear warming trend of 0.13°C per decade during the period of 1956–2005 (IPCC 2007). Inner Mongolia has become one of the most sensitive areas for global warming. The annual precipitation showed a linear decreasing trend (–9.9 mm per decade) over time, but this was not as obvious as that of temperature change. During the period from 1951 to 1960, the annual precipitation was higher than the multi-year average value (Table 4). The annual precipitation clearly decreased from 1961 to 1990, increased slightly from 1991 to 2000 and then decreased strongly from 2001 to 2009 (Table 4). From 2001 to 2009, the mean temperature increased by 2.09°C compared with the period of 1951–60, and the annual precipitation declined by 88.9 mm (Table 4). This implies that Inner Mongolia, as a region, has changed to a warmer and drier environment over the past 60 years (Lu *et al*. 2009; Liu and Wang 2012). The best evidence is the continuous heavy drought in recent years, which is obviously different from that in north-west China (Liu and Wang 2012).

Nevertheless, there was a steady wet period from 1990 to 1995 in Inner Mongolia, which is in agreement with the findings of Lu *et al*. (2004) and Liu and Wang (2012), because the annual precipitation anomaly percentages were positive and the temperatures were relatively low. The combined effects of precipitation and temperature should have promoted grassland development. And indeed, large areas of barren land in the desert and grassland biome were converted to grassland during 1985–95, leading to grassland expansion on the regional scale.

Since 1997, the short wet period has ended and the warming and drying trend seems to have accelerated. Over the 13-year period (1997–2009), the annual precipitation anomaly percentages of 10 of the years (excluding 1998, 2003 and 2008) were negative, while the annual temperature anomaly percentages were positive in all the years (Fig. 6). The annual precipitation decreased from 307.8 mm in the period of 1991–2000 to 263.3 mm in the period of 2001–09, while the mean temperature increased from 4.7°C in 1991–2000 to 5.0°C in 2001–09 (Table 4). According to the estimate of Le Houérou (1996), a 1°C increase in temperature would correspond with an annual potential evapo-transpiration (PET) increase of 5.25 ± 1.55% when evaluated using the Penman–Monteith formula. Along with the decrease in precipitation, the P/PET ratio would decrease and indicate a rise in aridity, leading to a reduction in effective soil moisture, a condition necessary for desertification and, indeed, a large area of grassland was converted to barren land during the second and the third periods of this study. Although human activities and anthropogenic pressures are widely thought to be one of the causes of grassland desertification in China (Zhao *et al*. 2005*b*; Zheng *et al*. 2006; Akiyama and Kawamura 2007), such a climate trend would exacerbate the desertification of grassland in arid and semiarid Inner Mongolia even if human impacts could be fully controlled (Wang *et al*. 2006; Yang 2010). Studies, focussed on the Ordos region, Horqin sandy land and Hunshandak sandy land in Inner Mongolia, have reconfirmed the important role of recent climate change in the desertification process (Tang *et al*. 2008; Xu *et al*. 2009; Yang 2010).

The conversion from grassland to barren land varied among biomes and through time. Spatially, the conversion was mainly

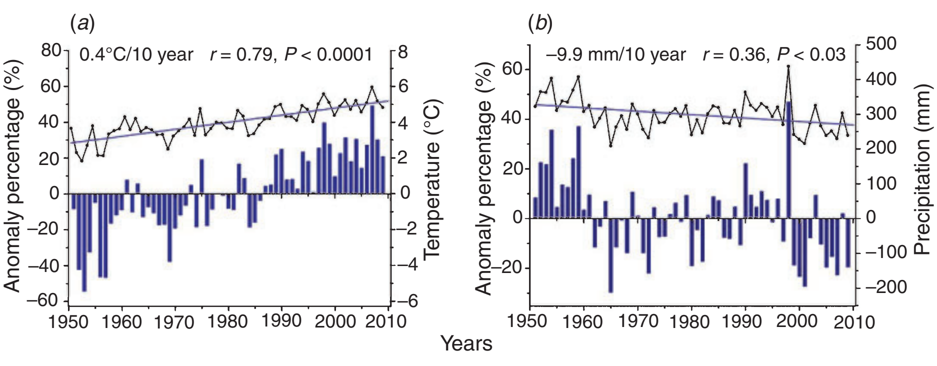

Fig. 6. Variations in climate from 1970 to 2009 in Inner Mongolia. (*a*) Annual mean precipitation and anomaly percentages of annual precipitation, and (*b*) annual mean temperature and anomaly percentages of annual temperature.

Table 4. Climate change for the Inner Mongolia region of China during six periods

Values are means ± s.e. Within rows, values followed by different letters are significantly different at $P < 0.05$. P, precipitation (mm); T, temperature, (°C)

Climate factors	1951–60	1961–70	1971–80	1981–90	1991–2000	2001–09
P	352.24 ± 11.24a	284.93 ± 11.86bc	282.9 ± 10.18bc	296.38 ± 10.86bc	307.79 ± 18.37b	263.31 ± 10.96c
T	2.90 ± 0.236a	3.52 ± 0.163b	3.80 ± 0.142bc	4.13 ± 0.188c	4.65 ± 0.102d	4.99 ± 0.151d

concentrated in the desert and grassland biomes. Temporally, continuous change could be found during the second and third period in the desert biome, while in the grassland biome, a drastic change occurred in 1995–2000 but not in 2000–09. This may have resulted for the following three reasons. First, climate change was more pronounced in the desert and grassland biomes, especially the former. From 1951 to 2009, the annual precipitation in the desert biome decreased significantly at a rate of –11.4 mm per decade, while the mean temperature in the biome increased significantly at a rate of 0.56°C per decade (Fig. 7). It is clear that global climate change has produced ecosystem- or region-dependent consequences (Lu *et al*. 2009), and forests and grasses may have had a moderating influence on climate, leading to lower rate of climate change (Bonan *et al*. 1992; Du 1996). Second, grasslands distributed in different regions may respond differently to alterations in precipitation and temperature. According to Yang *et al*. (2008), arid grasslands may be more sensitive to fluctuations in precipitation than those under more humid environments. Third, implementation of ecological restoration projects in early 2000s may have prevented grassland desertification in the grassland biome and eastern desert biome (Normile 2007), which may also be responsible for the increase in mean NPP at a regional and biome scale during 2000–09. However, in the western desert biome, which was not the focus area of the projects, the warming and drying climate promoted further grassland desertification.

Human activities spurred grassland dynamics

Overgrazing

Overgrazing is the primary problem from which China's grassland has suffered and it was particularly prevalent in Inner Mongolia (Kang *et al*. 2007; Schönbach *et al*. 2011). Ever since the intensive migration of the Han people into Inner Mongolia in the 1970s, the livestock numbers have increased sharply to meet the rapidly increasing regional demand for meat production (Jiang *et al*. 2006). From 1947 to 2009, the human population of Inner Mongolia increased from 5.6 to 24.7 million (Fig. 8*a*), with the livestock numbers increasing from 8.4 to 96.0 million (Fig. 8*b*). Accompanying these changes was a socio-cultural transition from the traditional nomadic lifestyle of the local people to modern settlement. In return, overgrazing became gradually more widespread with such a large breeding herd, and the grassland was consumed and tramped nearly constantly with little chance for recovery. In Xilinguole, the main grassland region in Inner Mongolia, one-third of grassland was degraded as a result of livestock numbers increasing from 2 million in 1977 to 18 million in 2000 (Han *et al*. 2008). By the end of 1999, 32% of the Inner Mongolia grassland was overgrazed and 60% was degraded (Lu 2006).

One direct consequence of grassland degradation was the reduction in productivity. According to the report by the Inner Mongolia Grassland Survey Institute, the grassland aboveground NPP of grasslands declined by 53% from 1961 to 2009, with overgrazing and climate change being identified as the important factors in this process (Qi *et al*. 2012). In this study, although the grassland area increased following a wetter period (1990–96), the mean NPP decreased in the grassland biome in which the major grazing land was located. Moreover, overgrazing should amplify the vulnerability of grassland to climate change, resulting in a cumulative effect that is more than the sum of the two individual factors.

Cultivation

The increasing human population and livestock numbers also triggered a large conversion from grassland to cropland to meet

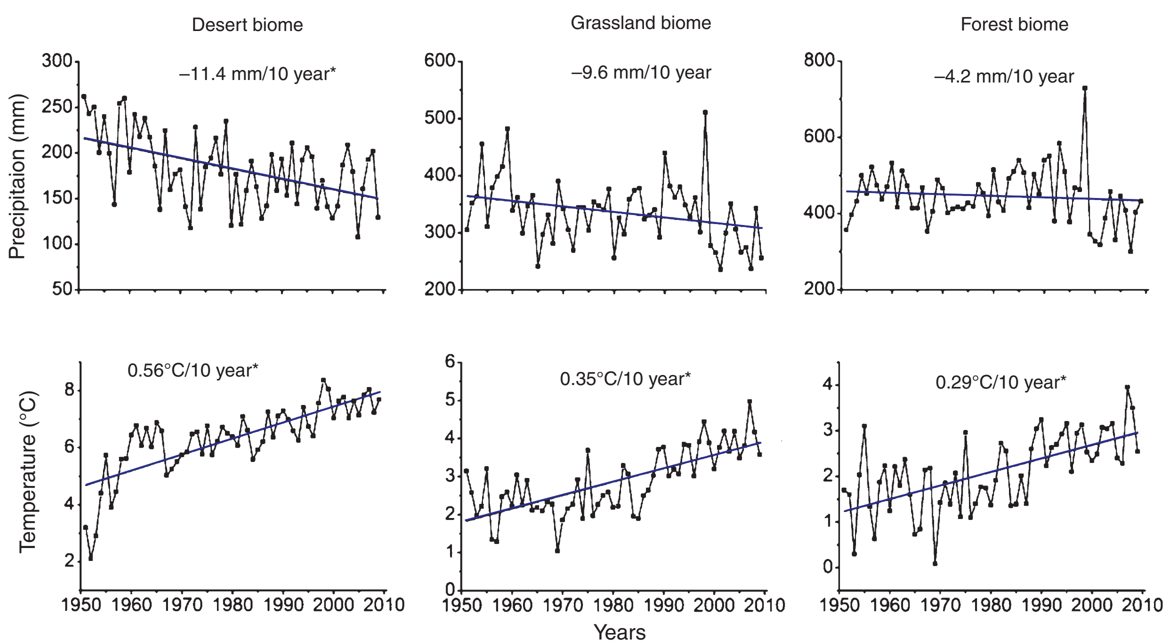

Fig. 7. Mean annual precipitation and temperatures for the period from 1950 to 2009 in Inner Mongolia for the desert, grassland and forest biomes. The number was the regression slope; and asterisk meant slopes were significant.

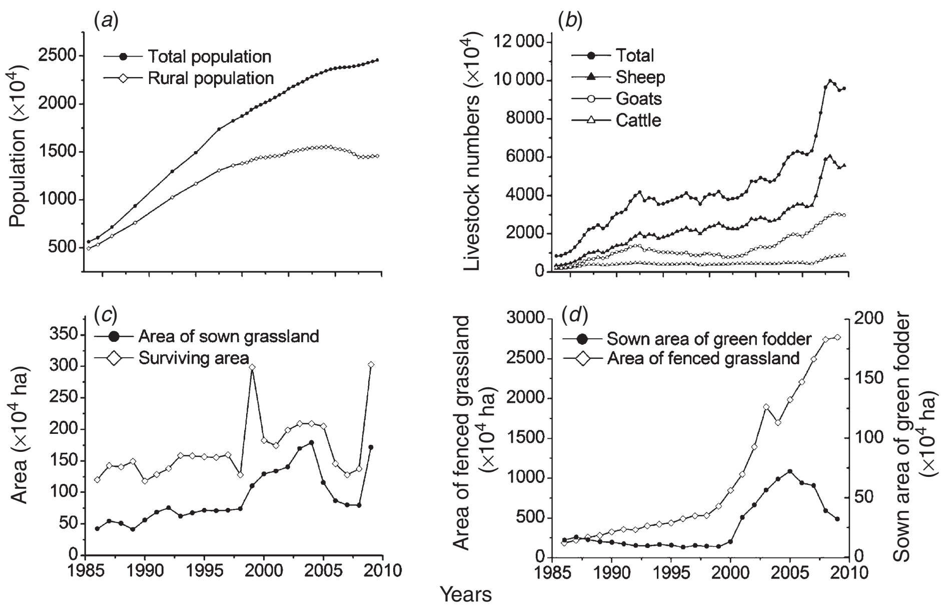

Fig. 8. (*a*) Total and rural population for the period from 1947 to 2009, (*b*) livestock numbers from 1947 to 2009, (*c*) area of sown grassland and surviving area of sown grassland from 1986 to 2009, and (*d*) area of fenced grassland and sown area of green fodder from 1986 to 2009. Data sources: Inner Mongolia Statistical Yearbook (1986–2010).

the increasing urban demand for food production (Jiang *et al*. 2006). For example, ~2 million ha of grassland was converted to cropland in Inner Mongolia during the period from 1958 to 1976 (Chuluun and Ojima 2002), which occurred primarily along the traditional boundaries between agricultural and grazing land (Qi *et al*. 2012). In discussions with local herders and farmers in Inner Mongolia, it has become clear that the agricultural land around major cities has expanded into grassland under urbanisation processes (Qi *et al*. 2012). However, the conversion often failed, especially in arid regions where 30–80% of the cropland degraded and was then abandoned (Han *et al*. 2008), resulting in increased soil erosion, the internal cause of potential land desertification.

Although the total area of grassland was not reduced significantly due to the conversion to cropland, which was shown in this study and in that of Qi *et al*. (2012), the quality of the grassland levelled off in the process. Most of the grassland converted to cropland was of high productivity, while the newly developed grassland from cropland was generally from area of poor land quality and with low productivity. This can be seen through comparing the changes in crop production resulting from the conversion between cropland and grassland. In the period of 1990–2000, newly cultivated cropland in China transformed from grassland caused an increase of 10.1 Mt in crop production, while the cropland transformed into grassland reduced crop production by 1.69 Mt (Yan *et al*. 2009). This conversion may have contributed to the relative low mean NPP in 1985, 1995 and 2000 as compared with that in 2009. Meanwhile, the relatively higher number of patches and mean patch size in the grassland and desert biomes showed that the fragmentation of grassland was higher in 1985, 1995 and 2000, which would have resulted from anthropogenic activities, especially agricultural activities. Such a high degree of fragmentation of natural vegetation could lead to a loss of biological diversity and deterioration of the ecosystem, exerting great impacts on regional climate change and carbon cycle (Tang *et al*. 2009).

Ecological restoration projects

In China, the first major attempt to protect the environment and resources of grassland occurred in 1985 with the enactment of the Rangeland Law (Han *et al*. 2008). However, it did not become a major government concern until the increase in desertification and the frequency of dust and sand storms observed in recent years (Zhang *et al*. 2012). In response, a series of ecological restoration projects were rapidly implemented at the national level on the west side of China. Two of them, the Grain to Green Project and the Grazing Withdraw Project, were of great importance, whose overall ecological effects were beneficial and generally observable (Tong *et al*. 2004; Liu *et al*. 2008).

The Grain to Green Project, initiated in 1999, included the implementation of returning cropland to forest and grassland, fencing hillsides to facilitate vegetation regeneration and planting trees and grasses on barren land and wasteland (Dai 2010). Based on this study, the achievement of the Grain to Green Project, implemented in Inner Mongolia, can be summarised into the following two aspects.

(1) This study found that the conversion between cropland and grassland shifted to facilitate grassland expansion at a regional level in 2000–09, which was in accordance with the study of Dong *et al*. (2011) conducted in a typical agro-pastoral transitional zone in the mid-eastern Inner Mongolia. According to the Inner Mongolia Statistics Yearbook (1986–2010), the rural population has shown a decreasing trend since 2000, while the growth of the local population has remained steady (Fig. 8*a*), implying decreasing intensity and frequency of impact from agricultural activities. Through ~10 years of returning cropland to grassland not only did the

grassland area expand but also the newly developed grassland tended to surround the old grassland and finally joined together to form strips. Consequently, the degree of fragmentation of grassland declined as evidenced by the decreased number of patches and increased mean patch size, thus resulting in the leading position of grassland in each biome and the whole region (indicated by the increased largest patch index). In addition, a reduced interspersion juxtaposition index also illustrated that the spatial distribution of grassland patches in the landscape became clumped, and the dominance of grassland patch type increased and had an even greater connectivity. Such a trend in the pattern of the landscape of grassland towards low fragmentation had significant ecological effects, e.g. facilitating improvement of biological diversity and ecosystem stability as well as the habitats of many species (Zhang *et al*. 2012).

This trend could only be found in the desert biome and grassland biome. In the forest biome, the new developed grassland converted from cropland could not compensate for the grassland loss in the opposite direction (Fig. 3). As illustrated by the higher number of patches and grater edge density, and lower mean patch size, largest patch index and area-weighted mean shape index for grassland in the forest biome as compared with the regional and other two biomes, it offered further proof that conversion from grassland to cropland still exerted a large impact on grassland in this biome. The Environmental Migration Project, a supplementary program, focussed on the households whose livelihood would be adversely affected by the Grain to Green Project, may play an important role in the process (Zhan 2010). Under the Grain to Green and Environmental Migration Projects, the cropland patches scattering in ecological fragile regions diminished, and most of cropland was concentrated in wetter regions where the ecosystem was relatively stable.

(2) A reverse of grassland desertification was also observed at a regional level during the last period of the study. The Grain to Green Project may have contributed much to this change. Large-scale grass seeding accelerated in 1999 and the annual mean area of sown grassland was 0.62 million ha in the period from 1986 to 1998 and 1.27 million ha in the period from 1999 to 2009 (Fig. 8*c*). The surviving area of sown grassland also showed an increasing trend since 1999, reaching 3.03 million ha by the end of the year 2009. It is suggested that the implementation of vegetation restoration programs was the possible intrinsic cause for grassland expansion. Our findings are in generally in accordance with Normile (2007) who suggested that artificially expanding oases at the desert's edge under the Grain to Green Project could successfully stop the process of grassland desertification and provide a chance to regenerate vegetation. Bagan *et al*. (2010) also reported that in Horqin sandy land, the implementation of the Grain to Green Project successfully suppressed the sand area and increased the sparse-grass area between 1999 and 2007. During the restoration process in desertified regions, vegetation patches formed by shrubs could create 'islands of fertility' with a less harsh micro-environment and facilitate the establishment and growth of a herbaceous community (Zhao *et al*. 2007). With increasing age of shrub plantations, herbaceous vegetation patches tended to expand and merged into larger patches, leading to a decrease in landscape heterogeneity. This is also indicated by the change in the Shannon's diversity and Shannon's evenness indices in the two biomes, both of which became smaller. Meanwhile, grassland patches became more regular (indicated by a decreased area-weighted mean shape index in the desert and grassland biome) and the edge effect of grassland patch type was decreased (indicated by decreased edge density). Increased large patch index indicated an enhancement of grassland's resistance to fragmentation (Batistella *et al*. 2003). Such a change in landscape pattern will improve the ecosystem stability of grassland, particularly in the desert-grassland ecotone, and combat desertification.

The Grazing Withdrawal Project initiated in 2003 aimed at alleviating grazing pressure in the degraded natural grassland in western China through banning of grazing, rotational grazing or converting grazing land to cultivated pasture. According to the data of Inner Mongolia Statistical Yearbook (1986–2010), the area of fenced grassland in Inner Mongolia accelerated significantly since the implementation of vegetation restoration programs in the late 1990s and early 2000s, and it had increased from 8.45 million ha in 2000 to 27.70 million ha in 2009 (Fig. 8*d*). Undisturbed mature grassland ecosystems seem to culminate with high biodiversity, productivity and ecosystem stability concurrently (Bai *et al*. 2004). For instance in a degraded Alxa desert steppe, with grazing exclusion for 6 years, the grass biomass increased by 56%, and the ground cover increased by a factor of 1.5, compared with the grazed area (Pei *et al*. 2008). Grazing rotation and seasonal enclosures were also widely implemented in Inner Mongolia. In Xilinguole, 88% of grassland was fenced off to allow the grass seed to germinate in the spring during 2002 and 2004 (Zhu *et al*. 2008). The increase in the sown area of green fodder implied that the pattern of use of grassland was shifting from grazing to indoor feeding. These changes undoubtedly contributed much to grassland restoration, specifically, the expansion of grassland area and the increase in mean NPP during 2000–09.

The ecological restoration projects, mentioned above, mainly focussed on seriously degraded grassland and the source area of sandstorm, such as Mu Us sandy land, Hobq desert, Hunshandak sandy land and Horqin sandy land (Jiang *et al*. 2006; Dai 2010; Zhang *et al*. 2012). Indeed, the mean NPP in these regions increased to some extent in the period of 2000–09 (Fig. 9). On the other hand, the total number of livestock in Inner Mongolia has increased significantly from 62.1 million head in 2000 to 96.0 million head in 2009, with the number of sheep (the major grazing animal) increasing from 34.1 to 57.8 million. Production of livestock in Inner Mongolia traditionally depends on the natural grass in Inner Mongolia, with little feed imported. The increase in the number of livestock meant increased feed or consumption of herbage from grasslands in Inner Mongolia. Consequently, given the increasing area of fenced grassland in these ecologically fragile regions, the increasing livestock numbers in the whole region could lead to a large increase in grazing intensity in the original non-degraded or lightly-degraded grassland, which was neglected by the ecological restoration projects. For the whole region, grazing pressure has shifted and become more concentrated, triggering new degradation. In the period of 2000–09 (Fig. 9), the mean NPP decreased in the central

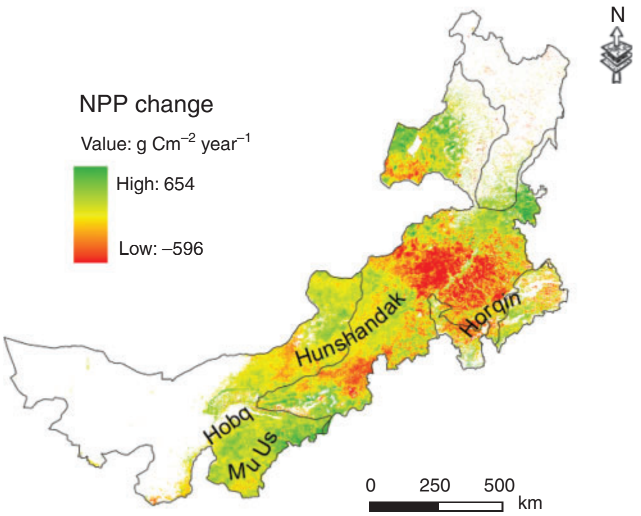

Fig. 9. Map of change in Net Primary Productivity (NPP) in Inner Mongolia grasslands between 2000 and 2009.

grassland biome, which was at least partially caused by the increased grazing intensity.

In spite of some achievements in grassland restoration induced by these ecological projects, grassland in Inner Mongolia, as well as in the rest of China, still face the ever-increasing pressure stemming from the growth of human population and livestock numbers. Our study implies that a large area of grassland was converted to cropland in the forest biome from 2000 to 2009. This conversion should be controlled strictly at a reasonable level to prevent the further loss of grassland to grain cultivation. Furthermore, our study revealed that the original non-degraded or light degraded grassland tended to degrade from 2000 to 2009. Restoration projects should be more concerned with these types of grassland. Looking forward, China should make further steps towards sustainable grassland development. It is necessary to shift the focus for grassland from economic development to the provision of ecosystem services that grasslands provide for people and nature, such as conserving water resources, reducing wind speed and dust in the air, improving biodiversity and sequestrating carbon from the atmosphere (Nan 2005; Li *et al.* 2008).

Conclusions

Grassland dynamics in China have been shaped by a range of factors. In this paper, carried out in Inner Mongolia grassland as a key component of China's grasslands, three indicators, i.e. grassland area, landscape metrics and NPP, were employed for regional vegetation assessment. The factors related to grassland dynamics were analysed from the perspectives of two driving factors, climate change and human activities. This study may provide decision-making support for rational grassland use and environmental protection.

The results demonstrated that, although grassland has expanded due to a steady wet period during 1985–95, the warming and drying climate has led to consistent desertification since 1995, especially in arid regions. During 1985–2000, overgrazing and large-scale conversion from grassland to cropland contributed much to a decrease in NPP as well as a fragmented landscape. Since the implementation of ecological restoration projects in the late 1990s and early 2000s, the regional grassland ecosystem has recovered to a certain extent. However, these recoveries were mainly concentrated in ecologically fragile regions. While large areas of grassland were fenced off for restoration of the existing degraded grassland, rapid growth of livestock numbers poses a great threat to the grassland, which was initially non-degraded or lightly degraded, and neglected by these projects. Looking forward, the grassland restoration projects, whose effectiveness has been evaluated to be positive at some local levels, should be further adjusted to balance environmental conservation and economic development. More plausible adaptation strategies to cope with both climate change and socioeconomic changes are needed for this purpose.

Acknowledgements

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