

Climate changes during the past 31 years and their contribution to the changes in the productivity of rangeland vegetation in the Inner Mongolian typical steppe

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Abstract. The objectives of this study were to explore the impact of climate change and human activities on the annual production of aboveground biomass of vegetation during the past 31 years at a county scale in the typical steppe region of Inner Mongolia. The changes in three banners in the region (Abag Banner, Xilinhaote City, and Xiuzhumuqin Banner) were analysed. The changes in the annual potential grassland production (net primary productivity) and in the annual production of vegetation, as the sum of aboveground biomass and consumption by livestock, were estimated for each year. A comparison of the changing rates in net primary productivity and aboveground biomass of vegetation over the 31 years was used to distinguish the effects of climate change on grassland production from human activities. The results showed that the climate had become warmer and drier during the past 31 years and thus net primary productivity and annual production of vegetation decreased significantly. Climate change was a major factor for these decreases, while human activities were a minor factor in the decrease of grassland production in Xiuzhumuqi Banner. The importance of human activities in reducing this decrease in grassland production during the last 31 years is in accordance with the changes in grassland-use policy that has encouraged destocking for grassland restoration in recent years.

Additional keywords: livestock consumption, net primary productivity, remote sensing, total grassland production.

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Introduction

Research on the effects of climate change on terrestrial ecosystems is still in the early stages, and most work to date has concentrated on forest and farmland ecological systems. Similar studies on grassland ecosystems are becoming more common together with the development of adaptive management strategies (Parton *et al.* 1995; Li *et al.* 2003; Peñuelas 2009; Steltzer and Post 2009; Kardol *et al.* 2010; Ma *et al.* 2010; Walther 2010; Wang and Shi 2010). Yin *et al.* (2011) has described some of these changes in northern China at the 41°07' northern latitude but further investigations are necessary in order to better understand the processes involved. These studies to date have mostly concerned the effects of rainfall, temperature and their interactions (Gao *et al.* 1996; Xiao *et al.* 1996; Wang *et al.* 2000; Zhou *et al.* 2000, 2002, 2012; Gao *et al.* 2003; Chuluun and Ojima 2012). However, there are very few reports about the use of grassland management models. Using the Savanna Model, Christensen *et al.* (2003) simulated the relationships among climate change, vegetation, and grazing ecology system at 14 stocking rates in the Inner Mongolian typical steppe. More recently, Tietjen and Jeltsch (2007) examined the potential of 71 grassland ecosystem models to better understand the relationship between grazing and grassland ecology.

Climate change and human activities interactively affect grassland productivity depending on the climate, topography and the types of land use in a region. To separate and understand the effects of these two drivers has been the focus of much recent attention in ecological and environmental science. The normalised difference vegetation index (NDVI) statistics model has been used to calculate the influences of climate change and human activities (Evans and Geerken 2004; Sun *et al.* 2008). However, most studies have been at a regional scale (Liang *et al.* 2002) and there have been few studies at a smaller scale, such as a county, which is more pertinent for grassland management. The objective of this study was to estimate the relative contributions of climate change and human activities on primary productivity of grasslands at a county scale in the typical steppe region of Inner Mongolia.

Materials and methods

Study area

Perennial bunch grasses are the dominant vegetation in the typical steppe region of Inner Mongolia, China. Shrub and semi-shrub vegetation are also present but at lower levels of cover (Chen and Wang 2000).

The study area extended across 43°04'–45°26'N and 113°27'–119°22'E and was administrated by three adjacent banners (Abag, Xilinhaote, and Xiwuzhumuqin). Xilinhaote is a banner-level city, so is included as a banner in this study. The rainfall increases from the relatively dry west to the moist east in the Xilingol region of Inner Mongolia. The total area is 65 357 km², of which ~61 101 km² are covered with grasslands of the typical steppe (Tong and Liu 1992). The mean annual precipitation varied between 244 and 345 mm, and annual mean temperature was 0.7–3.0°C and mean annual evaporation was 1500–2360 mm. The landscape consists of a high plain, low mountains and hills, dunes and sandy land, with elevation ranging from 1000 to 1400 m above sea level. The soil types include the castanozems, chernozems, aeolian sandy soils, grey meadow soils, and grey forest soils. The vegetation is mainly typical steppe, with small areas covered by meadow steppes, meadows and forest (Editorial Committee of Flora of Inner Mongolia 1994).

Experimental design

The changes in the annual production of vegetation in the three banners during the past 31 years were investigated. The annual production of vegetation was estimated as the amount of aboveground biomass plus the consumption of vegetation by grazing livestock in a year.

The effects of two factors, climate change and human activity, on the annual production of vegetation were studied using a NDVI statistical model (Evans and Geerken 2004; Sun *et al.* 2008).

Sources of data

Average daily climate data from three meteorological stations were obtained from the national meteorological database of China from 1981 to 2011 (Chinese Meteorological Database 2012). Remotely sensed data consisted of NDVI data (from 1981 to 2006) which were generated by using the advanced very high resolution radiometer (AVHRR) that belongs to the National Oceanic and Atmospheric Administration (NOAA) family of polar orbiting platforms and MODIS NDVI data (from 2000 to 2011). The NOAA/AVHRR satellite records provide discrete information for individual 8 × 8-km areas. The temporal resolution is 15 days. The spatial resolution of MODIS NDVI is 1 × 1 km. Data from the NOAA/AVHRR satellite and MODIS NDVI were converted into monthly NDVI data using the maximum value composite procedure (van Leeuwen *et al.* 1999). Statistics on the numbers of livestock were obtained from the numbers of livestock present every year in the three banners, and were converted into sheep units (Ministry of Agriculture of the People's Republic of China 2002).

Description of variables used

Effective precipitation (P) is the sum of precipitation (p) from May to September (plant growing season); that is,

$$P = \sum p \quad (p > 0 \text{ mm}) \quad (1)$$

Mean annual daily temperature (BT) is the average of daily temperature (t) in every year (365 days) when $0 < t \leq 30^\circ\text{C}$. The BT was calculated based on the following equation:

$$BT = \frac{\sum t}{365} \quad (0 < t \leq 30^\circ\text{C}) \quad (2)$$

The aridity index (PER) describes the degree of dryness of the climate, and is the ratio of potential evaporation to precipitation. It was estimated by the CHIKUGO method (Zhou and Zhang 1996) according to the following equation:

$$PER = 58.92BT/P \quad (3)$$

The net primary production (NPP) is the amount of total organic matter produced by the vegetation during photosynthesis minus the amount of total organic matter the plants use during respiration. The NPP was calculated according to Eqn 5 given in Zhou and Zhang (1996). The unit is t MD ha⁻¹.

The radiation index of dryness corresponds to the water budgets for each year. The radiation dryness index (RDI) was estimated from Eqn 4:

$$RDI = (0.629 + 0.237PER - 0.00313PER^2)^2 \quad (4)$$

$$NPP = RDI^2 \times \frac{(1 + RDI + RDI^2)P}{(1 + RDI)(1 + RDI^2)} \times e^{-\sqrt{9.87+6.25RDI}} \quad (5)$$

The annual production of vegetation (GP) of every banner was estimated as the sum of the aboveground biomass from the remote sensing data (Y_R) and the amount of grazing utilisation (Y_G) every year (Eqn 6). The unit is t DM ha⁻¹.

$$GP = Y_R + Y_G \quad (6)$$

Y_R was estimated using the MODIS model of Zhang *et al.* (2006) (Eqn 7). The accuracy of this model was estimated to be 97%.

$$Y_R = 5.524X + 0.0446 \quad (7)$$

where X is NDVI.

The images of MODIS and NOAA overlapped from 2000 to 2006. The Y_R from NOAA was calculated according to the following equation:

$$Y_R = 5.358X - 0.11 \quad (8)$$

where X is NDVI.

The amount of grazing utilisation (Y_G) was calculated according to the following:

$$Y_G = U \cdot G \cdot D / 1000S \quad (9)$$

where U denotes the number of grazing livestock (sheep unit), G is the daily intake of a sheep unit [kg, dry matter (DM day⁻¹)], D is the number of grazing days, and S (ha) represents the area of available grassland. Before 2002, the number of grazing days for all three banners were 92 days from mid-May to mid-August and after 2002, the number of grazing days were 62 days from mid-June to mid-August.

The contribution of the two factors, climate change and human activity, on the changes in GP were estimated according to the following equations (Li *et al.* 2011, 2012; Sun *et al.* 2012):

$$V_{GP} = V_C + V_f \quad (10)$$

$$EC = \frac{V_C}{V_{GP}} \times 100 \quad (11)$$

$$E_f = \frac{V_f}{V_{GP}} = \frac{V_{GP} - V_C}{V_{GP}} \times 100 \quad (12)$$

where V_{GP} , V_C and V_f represent the annual rates of changes in GP, in NPP (climate determined), and the rate of change induced by human activities. The contribution of climate change and human activity, expressed as percentages, were denoted by E_C and E_f .

Data analyses

Statistical analyses were performed using SPSS version 13.0 and Microsoft Office Excel 2003. Analyses of general linear and curve linear models were used for ANOVA. Treatment means were compared to determine whether they were significantly different at $P < 0.05$.

Results

Changes in precipitation, temperature and climate aridity over the past 31 years

The mean values of total effective precipitation for the Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner were 204 ± 63 mm, 227 ± 77 mm and 281 ± 80 mm, respectively. The effective precipitation during the past 31 years showed no significant change in Abag Banner and Xinlinhaote City ($P > 0.1$) but showed a significant decline in Xiwuzhumuqin Banner ($V_P = -3.58$ mm year⁻¹, $P < 0.01$), (Fig. 1).

Mean annual daily temperatures (BT) of the Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner were $7.1 \pm 0.41^\circ\text{C}$, $7.3 \pm 0.37^\circ\text{C}$ and $6.7 \pm 0.35^\circ\text{C}$, respectively. Mean annual daily temperatures increased significantly in all three banners during the past 31 years (Fig. 2).

Annual PER values of the Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner were 2.27 ± 0.77 , 2.14 ± 0.79 and 1.56 ± 0.61 , respectively. This index also showed a significant increase ($P < 0.05$) in all three banners during the past 31 years (Fig. 3).

Changes in NPP over the past 31 years

Annual NPP values in the Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner were 2.95 ± 0.56 t ha⁻¹, 3.17 ± 0.63 t ha⁻¹ and 3.46 ± 0.49 t ha⁻¹, respectively. There were significant decreases in NPP in all three banners during the past 31 years (Fig. 4); the annual percentage decreases (V_{NPP}) were -0.023 , -0.023 , and -0.018 , respectively, for Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner.

Changes in vegetation production and grazing utilisation of the rangelands over the past 31 years

Annual GP values of the Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner were 1.51 ± 0.23 t DM ha⁻¹, 1.82 ± 0.32 t DM ha⁻¹ and 2.28 ± 0.37 t DM ha⁻¹, respectively. The GP values in the three banners declined during the 31-year period (Fig. 5); the percentage rates of decline (V_{GP}) were -0.009 , -0.014 , and -0.022 in Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner, respectively.

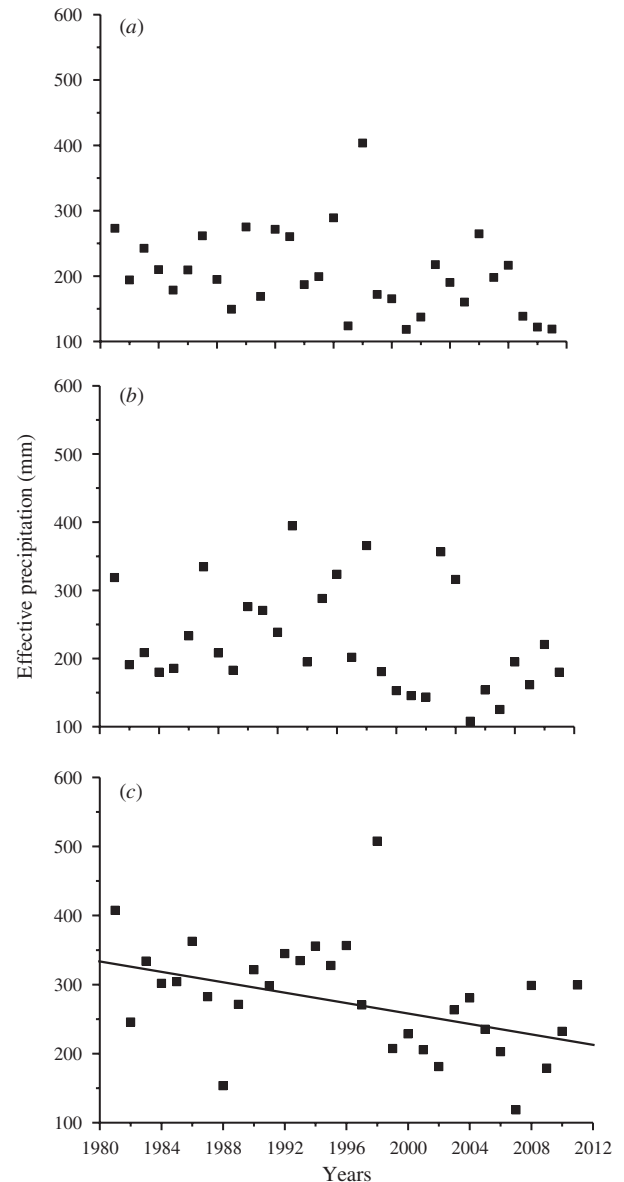


Fig. 1. Changes in effective precipitation (P, mm) over the past 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between P and years are described by the following linear equations: (a) $P = -2.304(\text{Year}) + 240.4$, $R^2 = 0.11$, $P = 0.07$; (b) $P = -2.286(\text{Year}) + 263.5$, $R^2 = 0.07$, $P = 0.14$; (c) $P = -3.579(\text{Year}) + 338.3$, $R^2 = 0.17$, $P = 0.022$.

Annual Y_R values of the Abag Banner, Xinlinhaote City and Xiwu Banner were 1.38 ± 0.21 t DM ha⁻¹, 1.65 ± 0.30 t DM ha⁻¹ and 2.05 ± 0.32 t DM ha⁻¹, respectively. The annual Y_R values in the three banners declined during the 31-year period (Fig. 6); the percentage rates of decline (V_{YR}) were -0.008 , -0.013 , and -0.021 in Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner, respectively.

Annual Y_G values of the Abag Banner, Xinlinhaote City and Xiwu Banner were 0.14 ± 0.05 t ha⁻¹, 0.17 ± 0.06 t ha⁻¹ and 0.23 ± 0.08 t ha⁻¹, respectively. The annual Y_G values in the three

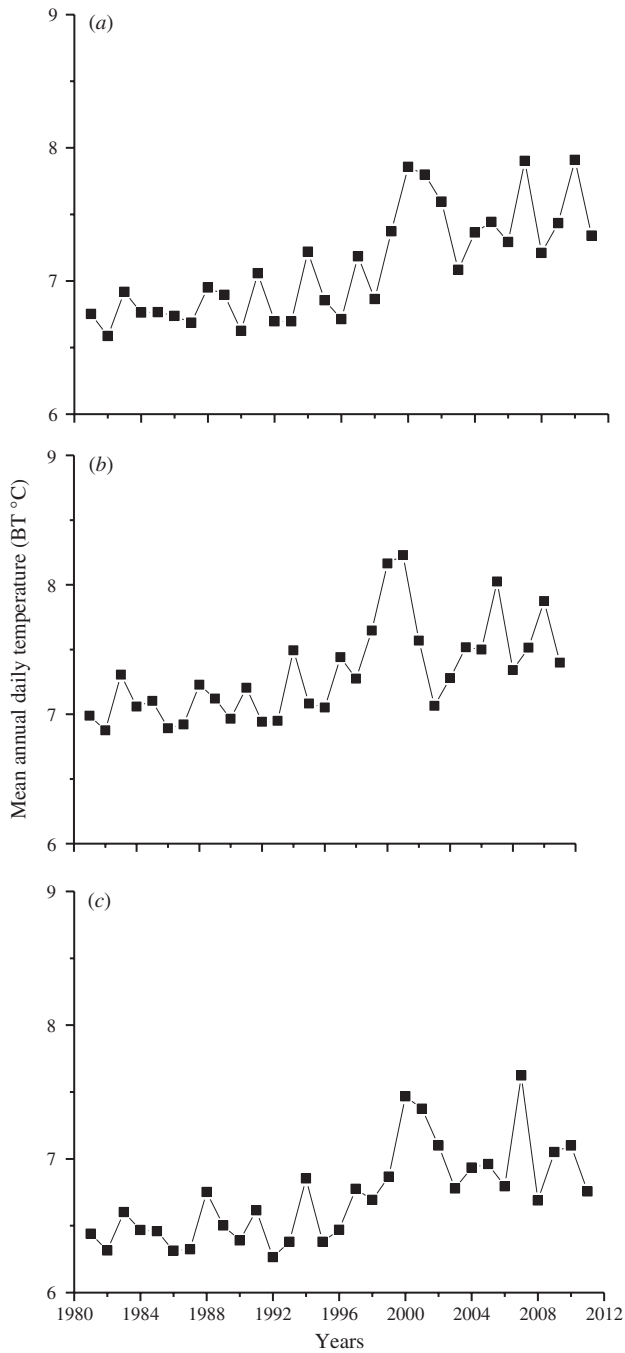


Fig. 2. Changes in mean annual daily temperature (BT, °C) over 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between BT and years are described by the following linear equations: (a) $BT = 0.034 (\text{Year}) + 6.6$, $R^2 = 0.59$, $P < 0.001$; (b) $BT = 0.026 (\text{Year}) + 6.9$, $R^2 = 0.40$, $P < 0.01$; (c) $BT = 0.026 (\text{Year}) + 6.3$, $R^2 = 0.46$, $P < 0.001$.

banners increased from 1981 to 1999 and then declined from 2000 to 2011 (Fig. 7); the percentage rates of increase (V_{YG}) were 0.007, 0.010, and 0.011 in the Abag Banner, Xinlinhaote City and Xiwuzhumuqin Banner, respectively, and the percentage rates of decline (V_{YG}) were -0.013 , -0.013 , and -0.024 , respectively.

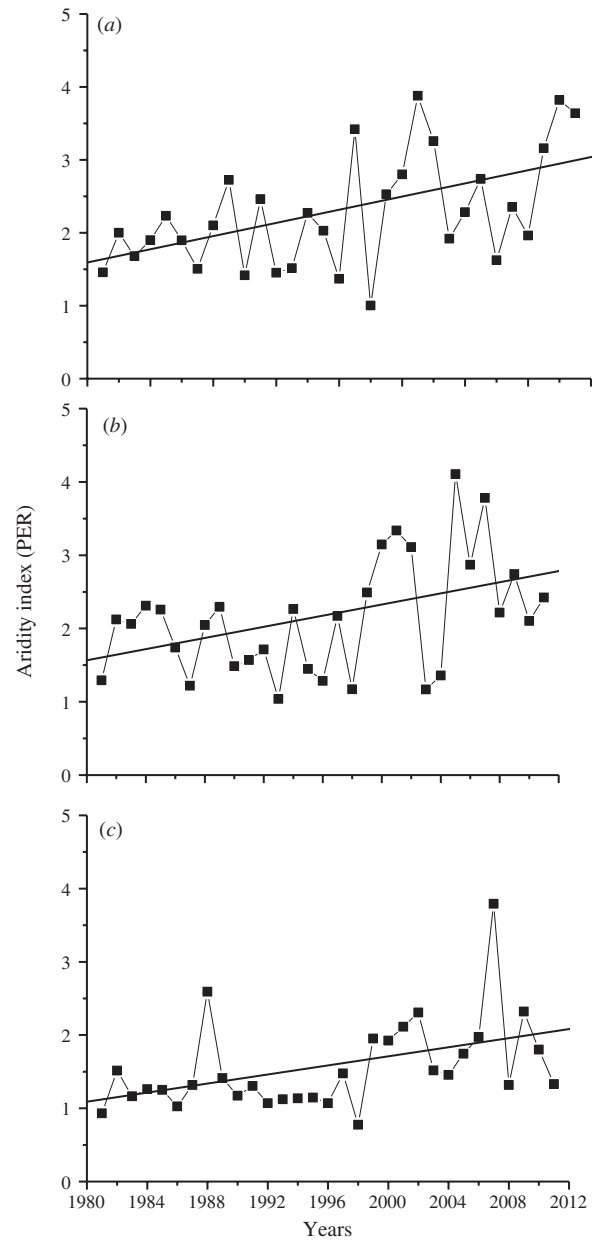


Fig. 3. Changes in aridity index (PER) over 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between PER and years are described by the following linear equations: (a) $PER = 0.044 (\text{Year}) + 1.57$, $R^2 = 0.27$, $P < 0.01$; (b) $PER = 0.037 (\text{Year}) + 1.54$, $R^2 = 0.18$, $P < 0.05$; (c) $PER = 0.030 (\text{Year}) + 1.07$, $R^2 = 0.20$, $P < 0.01$.

Contribution of climate change and human activity to vegetation production of rangelands over the past 31 years

The contribution (%) of climate change and human activity to productivity changes were calculated for the decrease in GP values over the 31-year period (Table 1). Both climate change and human activity significantly ($P < 0.05$) affected the GP in all three banners.

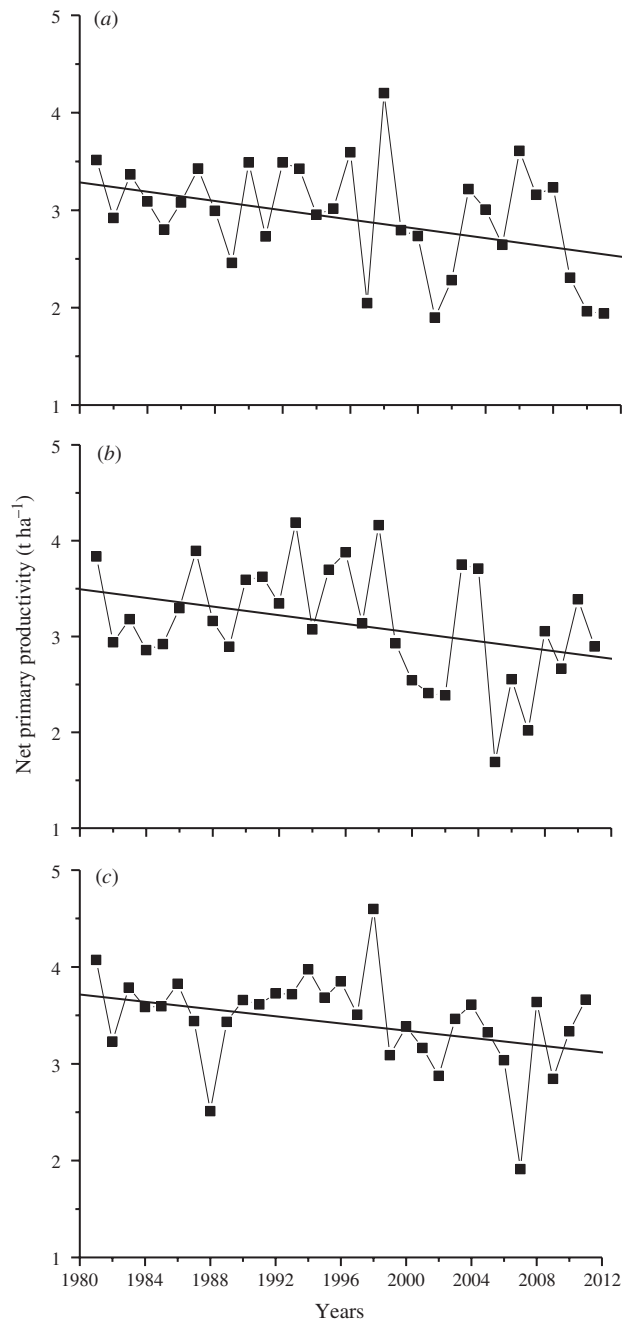


Fig. 4. Changes in net primary production (NPP) of steppe vegetation during 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between NPP and years are described by the following linear equations: (a) $NPP = -0.023 (\text{Year}) + 3.31$, $R^2 = 0.14$, $P < 0.05$; (b) $NPP = -0.023 (\text{Year}) + 3.52$, $R^2 = 0.12$, $P < 0.05$; (c) $NPP = -0.018 (\text{Year}) + 3.74$, $R^2 = 0.11$, $P < 0.05$.

The contribution of climate change was higher (256%, 164%) in the Abag Banner and Xilinhaote City than in the Xiwuzhumuqin Banner (82%) (Table 1). The effect of human activities was much greater in reducing the productivity in the Abag Banner than in the other two banners (−156% compared with −64% and 18%, Table 1).

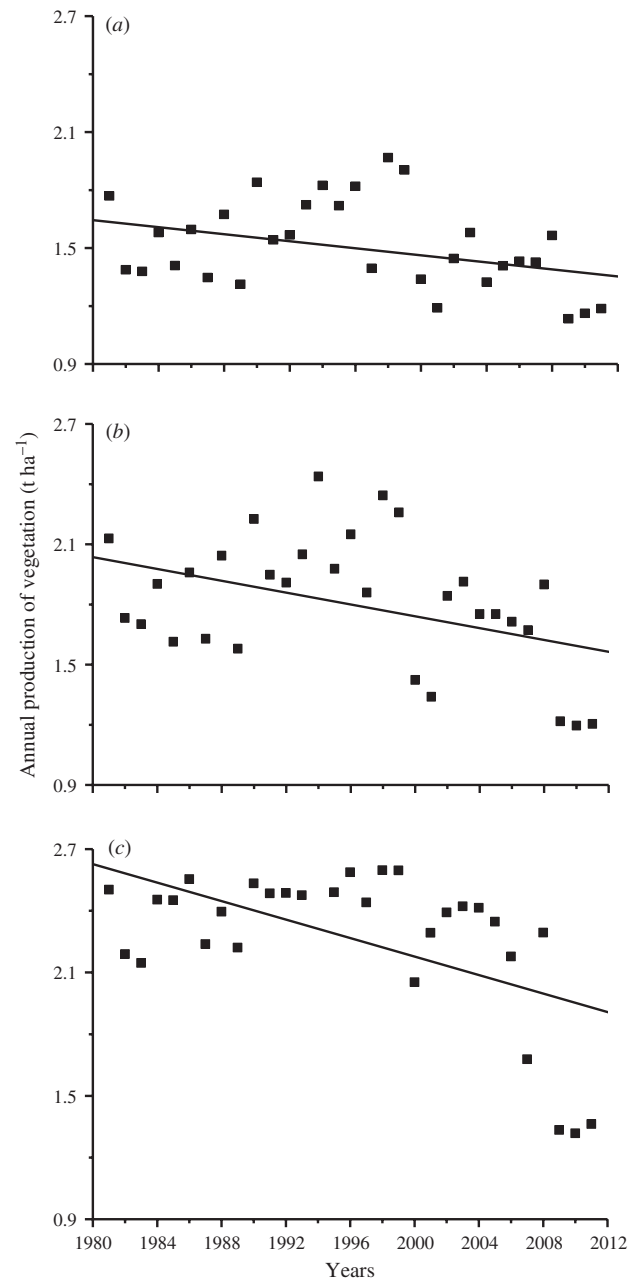


Fig. 5. Changes in annual production of vegetation (GP) of grassland over the 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between GP and years are described by the following linear equations: (a) $GP = -0.009 (\text{Year}) + 1.654$, $R^2 = 0.12$, $P < 0.05$; (b) $GP = -0.014 (\text{Year}) + 2.047$, $R^2 = 0.16$, $P < 0.05$; (c) $GP = -0.022 (\text{Year}) + 2.634$, $R^2 = 0.30$, $P < 0.01$.

Discussion

The contributions (%) of climate change and human activity to productivity changes over the past 31 years were significantly different ($P < 0.05$) in terms of the degree of change and the trend in the three banners studied. Therefore, these results would have important practical implications for grassland management

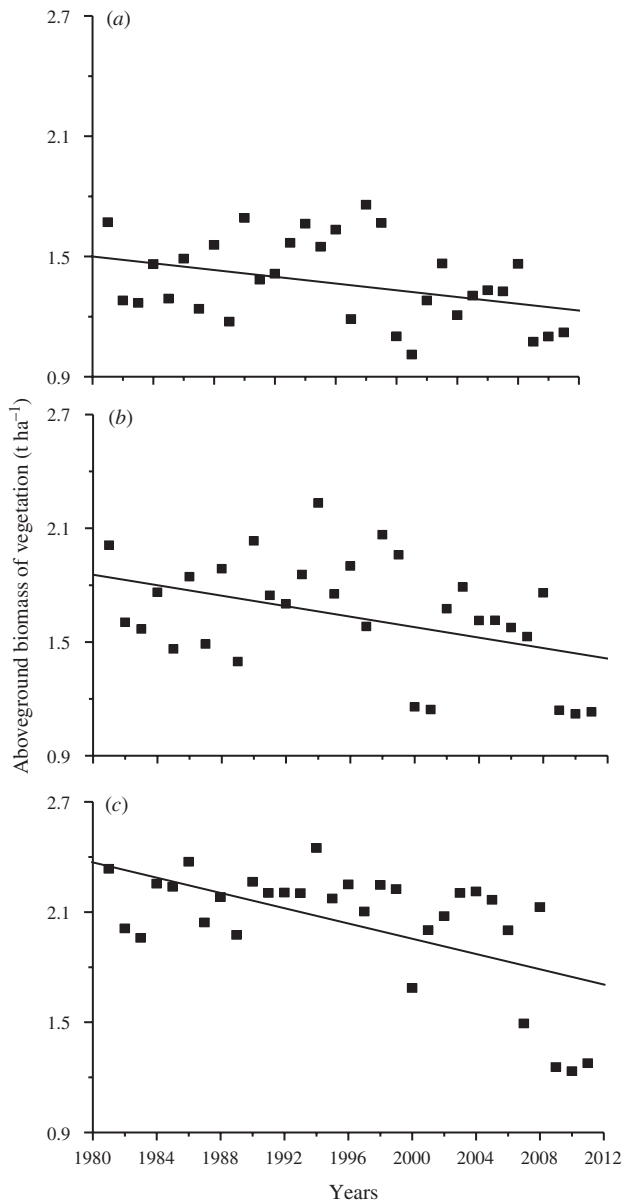


Fig. 6. Changes in the standing aboveground biomass (Y_R) of grassland over the 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between Y_R and years are described by the following linear equations: (a) $Y_R = -0.008 (\text{Year}) + 1.508$, $R^2 = 0.12$, $P < 0.05$; (b) $Y_R = -0.013 (\text{Year}) + 1.863$, $R^2 = 0.17$, $P < 0.05$; (c) $Y_R = -0.021 (\text{Year}) + 2.375$, $R^2 = 0.34$, $P < 0.001$.

change and so it would be important to perform similar studies for larger regions of the county.

The important elements of the changed climate over the past 31 years in the three banners studied were the decreased annual average effective precipitation (P), the increased mean annual daily temperature (BT) and the consequent changes in the aridity index (PER). This has resulted in the boundaries of the desert steppe extending to the east, whereas the boundaries of the typical steppe have been compressed in the eastern part of its range (Niu 2001).

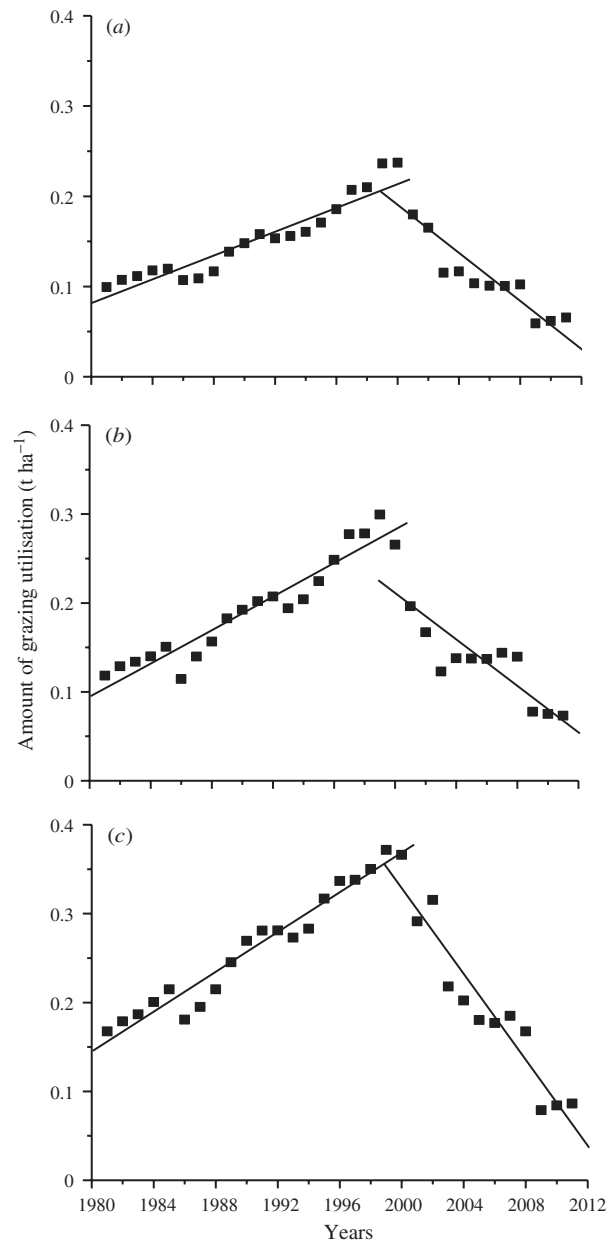


Fig. 7. Changes in the amount of grazing utilisation (Y_G) of grassland over the 31 years in (a) Abag Banner, (b) Xilinhaote City and (c) Xiwuzhumuqin Banner. The relationships between Y_G and years from 1981–1999 are described by the following linear equations: (a) $Y_G = 0.007 (\text{Year}) + 0.081$, $R^2 = 0.90$, $P < 0.001$; (b) $Y_G = 0.011 (\text{Year}) + 0.093$, $R^2 = 0.92$, $P < 0.001$; (c) $Y_G = 0.011 (\text{Year}) + 0.147$, $R^2 = 0.95$, $P < 0.001$; and, from 2000 to 2011, (a) $Y_G = -0.013 (\text{Year}) + 0.444$, $R^2 = 0.83$, $P < 0.001$; (b) $Y_G = -0.013 (\text{Year}) + 0.459$, $R^2 = 0.75$, $P < 0.01$; (c) $Y_G = -0.024 (\text{Year}) + 0.788$, $R^2 = 0.90$, $P < 0.001$.

The NPP significantly decreased ($P < 0.05$) by 19%, although the annual production of vegetation (GP) decreased by 21%. The impact of climate change on the annual production of vegetation was very strongly negative, whereas the effect of human activity was significant ($P < 0.05$) and positive after 2000. This change indicated that a series of important ecological

Table 1. The relative contribution of climate change and human activity (%) to the changes in annual production of vegetation (GP) for the Abag Banner, Xilinhaote City and Xiwuzhumuqin Banner in typical steppe vegetation in Inner Mongolia over 31 years from 1981 to 2011

Banners	Relative contribution to change in GP	
	Climate change	Human activity
Abag Banner	256	-156
Xilinhaote City	164	-64
Xiwuzhumuqin Banner	82	18
Mean	167	-67

protection and improvement projects, such as returning land to pasture implemented after 2002, and controlling the sandstorms, implemented after 2003 in Inner Mongolia have been successful (Liu 2007). However, the fluctuations in the weather associated with climate change were also important in their effect on the annual production of vegetation.

Sun *et al.* (2012) and Li *et al.* (2011) used similar methods to calculate the contribution of climate change and human activity on vegetation growth during the desertification processes in the Three-River Headwaters region in China. However, the present paper is the first occasion in which this method has been used to investigate the contribution of climate change and human activities on the annual production of vegetation of grassland. The importance of human activities in reducing this decrease in grassland production during the past 31 years is in accordance with the changes in grassland use policy that have encouraged destocking for grassland restoration. In order to balance grassland restoration with the livestock grazing industry, the central government has invested more than 10 billion RMB in grassland recovery including grass seed production, seedling establishment, grassland fencing, grazing bans on heavily degraded areas and sandstorm control from 2000 to 2007 (Liu *et al.* 2008). These projects have slowed down the degradation of the grasslands.

The equations for the NDVI statistics model are simpler than those for other models and fewer variables were used. The NDVI statistics model can clearly show the contributions of climate change and human activity on GP. Therefore, this method was selected in this paper. However, the resolution of the NOAA is lower than that of MODIS satellite, so that the effects of the other types of vegetation, such as farmland and forest, had not been eliminated in the data up until 2006. Using the higher resolution remote sensing data, it may be feasible to study in-depth and more accurately the relative contributions of climate change and human activity at the banner scale.

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