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RESEARCH ARTICLE

Distinguishing between human-induced and climate-driven vegetation changes: a critical application of RESTREND in inner Mongolia

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Abstract Changes in the spatiotemporal pattern of vegetation alter the structure and function of landscapes, consequently affecting biodiversity and ecological processes. Distinguishing human-induced vegetation changes from those driven by environmental variations is critically important for ecological understanding and management of landscapes. The main objectives of this study were to detect human-induced vegetation changes and evaluate the impacts of land use policies in the Xilingol grassland region of Inner Mongolia, using the NDVI-based residual trend (RESTREND) method. Our results show that human activity (livestock grazing) was the primary driver for the observed vegetation changes during the period of 1981–2006. Specifically, vegetation became increasingly degraded from the early 1980s when the land use policy—the Household Production Responsibility System—led to soaring stocking rates for about two decades. Since 2000, new institutional arrangements for grassland restoration and conservation helped curb and even reverse the increasing trend in stocking rates, resulting in large-scale vegetation improvements in the region. These results suggest that most of the degraded grasslands in the Xilingol region can recover through ecologically sound land use policies or institutional arrangements that keep stocking rates under control. Our study has also demonstrated that the RESTREND method is a useful tool to help identify human-induced vegetation changes in arid and semiarid landscapes where plant cover and production are highly coupled with precipitation. To effectively use the method, however, one needs to carefully deal with the problems of heterogeneity and scale in space and time, both of which may lead to erroneous results and misleading interpretations.

Keywords Land use and land cover change · Arid landscape dynamics · NDVI residuals trend (RESTREND) analysis · Land use policy · Grassland vegetation · Inner Mongolia

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Introduction

Understanding the spatial pattern and ecological effects of land use and land cover change is a key research topic in landscape ecology (Wu and Hobbs 2002, 2007). The dynamics of most landscapes are driven by both natural processes and human activities. Discerning the different impacts of these two general types of drivers is often formidable, but crucial for both understanding and managing landscapes (Burgi et al. 2010; Sohl et al. 2010; Wulf et al. 2010; Levick and Rogers 2011). This is particularly true for the world's drylands which account for about 41 % of the earth's land area and are home to more than 35 % of the global population (Safriel and Adeel 2005). In these arid landscapes, ecosystems and human livelihood are both influenced greatly by land use practices and extreme climate variations.

Vegetation degradation (i.e., reduced vegetation cover and production by natural and anthropogenic factors) has been one of the most pressing environmental and socioeconomic problems in arid and semiarid regions (Reynolds et al. 2007), and will become even more so in decades ahead as climate change is predicted to affect drylands more substantially than most other types of ecosystems (IPCC 2007). Assessing the effects of different kinds of drivers on vegetation degradation in arid lands, however, has been a central, but contentious, topic in dryland research (Archer 2004; Wessels et al. 2007; Wessels 2009). A major challenge hinges on how to distinguish between vegetation changes due to climatic variations and those caused by human land use activities on broad spatial scales. In particular, the impacts of human activities on vegetation dynamics can be extremely difficult to be separated out because both precipitation and vegetation in dryland areas typically have large inter-annual variations (Buyantuyev et al. 2007; Wessels et al. 2007; Buyantuyev and Wu 2009). While well-established procedures for analysis are still lacking, RESTREND—a relatively new method based on the residuals of the regression between NDVI and precipitation—has been advocated by several recent studies (Evans and Geerken 2004; Wessels et al. 2007). Although this method has been applied to detect land degradation in Syria (Evans and Geerken 2004), South Africa (Wessels et al. 2007), and the entire globe (Bai et al. 2008b), its applicability and effectiveness, especially when used in different dryland areas, still need to be evaluated.

The Eurasian Steppe is the largest contiguous grassland region in the world, extending from northeastern China, through Mongolia and the former Soviet Union, to Hungary in the west (Li 1979). The Inner Mongolia grassland is a key component of the Eurasian Steppe, and has a higher diversity of species and ecosystem types than most other grassland regions around the world (Wu and Loucks 1992; Bai et al. 2004, 2007, 2008a). Within Inner Mongolia, the Xilingol Grassland is well known for its extensive distribution, representativeness of the Eurasian steppe vegetation, and long traditions of nomadic life style (Fig. 1). The major land use in the Xilingol region historically has been grazing, but cultivation began to occur several decades ago, particularly in the southern part of the area (Fig. 1). Since the early 1980s, the Chinese government has implemented several major land use policies or institutional arrangements in this region. Assessing the relative impacts of climate change and human activities (as influenced by land use policies) in this region has important scientific and practical implications for the Inner Mongolia region as well as other arid landscapes elsewhere.

The main goal of this study, therefore, was to assess the impacts of land use practices—dictated by the government policies—on vegetation changes across the Inner Mongolia grassland landscape in recent decades. Achieving this goal would require distinguishing vegetation changes due to climate variations from those induced by human activities. Thus, our study was designed to address the following research questions: (1) Did vegetation cover and production in the Xilingol grassland region improve or deteriorate in the recent decades? (2) What were the main drivers for the observed vegetation changes—climate variations or human activities—and what was the role of land use policies? (3) Was the RESTREND method effective in addressing the above two questions?

Study area

The Xilingol grassland, delineated by the administrative boundary of Xilingol League (prefecture), is located in the central part of Inner Mongolia, China, covering a total area of 203,000 km^2 and spanning

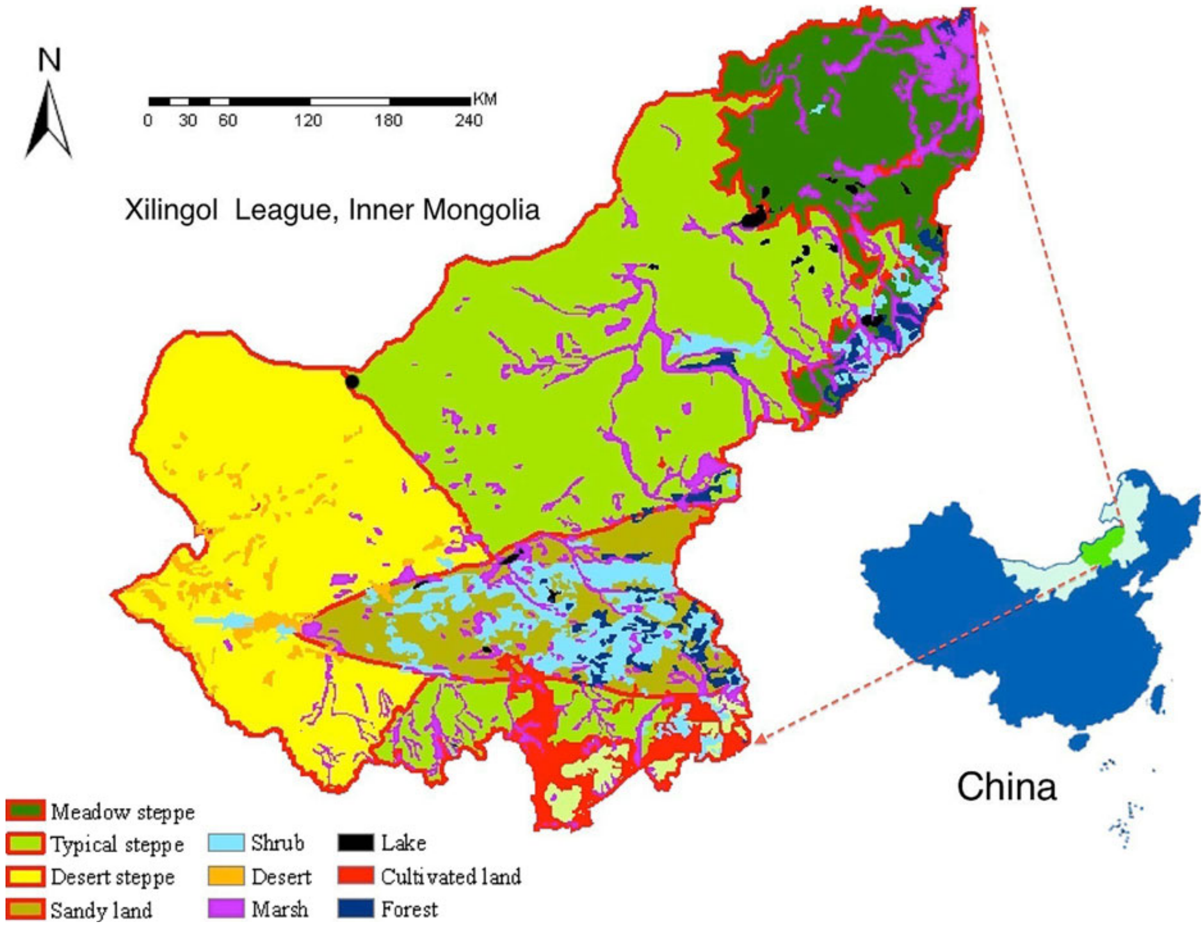

Fig. 1 Vegetation map of the Xilingol grassland region, Inner Mongolia, China, showing the spatial pattern of major ecosystem types present in the 1960s–1970s (redrawn from Hou 2001)

from 41.4°N to 46.6°N in latitude and from 111.1°E to 119.7°E in longitude (Fig. 1). Dominated by a semi-arid climate, the Xilingol region has a mean annual temperature of 2.2 °C (varying between −2.3 and 5.6 °C) and a mean annual precipitation of 278 mm (varying between 135 and 433 mm). The lowest mean monthly temperatures occur in January (−15.4 to −22.4 °C) and the highest in July (18.2–23.4 °C). About 60–80 % of the annual precipitation falls during the growing season (May–August), which coincides with the peak temperatures.

From east to west across the Xilingol grassland region, precipitation and soil fertility decrease gradually, resulting in three distinct vegetation types: meadow steppe, typical steppe, and desert steppe, which are commonly referred to as the zonal vegetation types in the Chinese literature (Liu 1960; Li 1962, 1979; Wu and Loucks 1992). Associated with the vegetation types are several zonal soil types: chernozem, chestnut, and calcic brown soils. The primary productivity of the steppe ecosystems peaks in August, and is determined primarily by annual precipitation (Wu and Loucks 1992; Bai et al. 2004; 2007). There are also "non-zonal" vegetation types in the Xilingol region, including forests at high elevations, saline meadows and marshes on lowlands, shrublands in localized areas, and large tracts of sandy lands (Fig. 1). These non-zonal vegetation types are often associated with local environmental conditions due to topography, water bodies, and salinization. The Xilingol grassland vegetation is composed primarily of C_3 perennial bunchgrasses and perennial rhizome grasses—two dominant functional groups in most plant communities. In addition, perennial forbs are common in meadow steppe and typical steppe, and shrubs and semi-shrubs are dominant in desert, sandy land, and degraded typical steppe (Wu and Loucks 1992; Bai et al. 2007).

Methods

Conceptual framework

The methods in our study were based on a conceptual framework that links vegetation conditions, ecosystem resilience, and land use policy (Fig. 2). The vegetation cover and plant biomass production of the grassland are influenced mainly by rainfall (positively) and livestock grazing (negatively). The ecosystem resilience of the grassland—the amount of disturbances that it can tolerate while maintaining its basic community composition and ecosystem functioning—is positively correlated with vegetation cover and production. Changes in land use policy may lead to increasing or decreasing stocking rates which in turn affect vegetation conditions. The relationship between ecosystem resilience and vegetation cover, as well as the relationship between vegetation cover and disturbances, is nonlinear and characterized by a pressure-response threshold. That is, excessive stocking rates (overgrazing) and prolonged droughts may severely weaken or deprive the grassland's ability to recover or to respond to rain events.

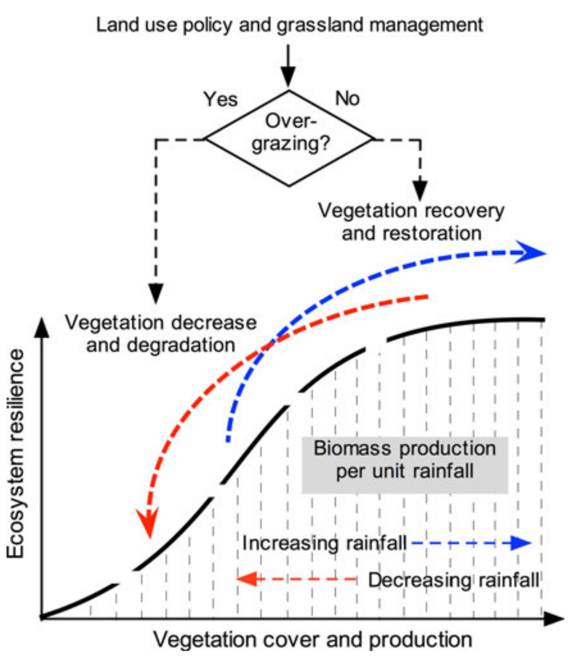

Fig. 2 Conceptual framework for analyzing rainfall- and human-induced vegetation changes and evaluating the impacts of changing land use policies in the Xilingol grassland region (see the main text for further explanations)

Overgrazing reduces vegetation cover and ecosystem resilience, resulting in a decrease in biomass production per unit rainfall, or rain use efficiency (RUE). A number of studies have used RUE as an indicator for land degradation (Hein and De Ridder 2006; Prince et al. 2007; Wessels et al. 2007), but recent research suggests that the residuals of the production-rainfall regression provide a more reliable way of detecting vegetation changes because RUE itself is correlated with rainfall (Wessels et al. 2007). By detecting directional changes in vegetation using the RESTREND method (described below), we expect to be able to evaluate the consequences of different land use policies.

Data acquisition and processing

We analyzed the vegetation changes in the Xilingol region using the time series data of normalized difference vegetation index (NDVI) between 1981 and 2006. The NDVI time series was composed of monthly maximum values at a spatial resolution of 8×8 km^2, processed by the Global Inventory Modeling and Mapping Studies (GIMMS) Group at NASA's Goddard Space Flight Center (Tucker et al. 2004; Pinzon et al. 2005; Tucker et al. 2005). The dataset was corrected for sensor degradation, intersensor differences, effects of cloud cover, solar zenith angle, and viewing angle (Tucker et al. 2004). These NDVI data are well-suited for studying long-term vegetation changes in the arid and semi-arid areas where the annual rainfall was <1,000 mm (Fensholt et al. 2009). We extracted the NDVI data from the GIMMS dataset for the period of 1981–2006, delineated with the administrative boundary of the Xilingol League, and then computed the maximum annual NDVI ($NDVI_{max}$) for the study region.

Long-term precipitation data were acquired from China Meteorological Data Sharing Service System, and time-series data of precipitation were compiled from 80 weather stations within or in the vicinity of the Xilingol League. Based on these data, we used the ordinary Kriging method to generate a precipitation map with the same resolution and geographic coordinate system as those of the GIMMS NDVI dataset. Land use data, including stocking rates and cultivated area, were obtained from the annual census archives of the local governments of Inner Mongolia. A land use and land cover map of the Xilingol region (Fig. 1), showing the spatial pattern of major vegetation types in the 1960s–1970s, was recreated from Hou (2001).

The RESTREND method and its implementation

The method of residual trend (RESTREND) analysis (Wessels et al. 2007) is based on the general observation that the net primary productivity (NPP) of arid and semiarid ecosystems is positively correlated with rainfall. RESTREND takes a spatially explicit, pixel-based approach to detecting the trends of residuals based on NDVI (as a proxy of NPP) and observed rainfall data (Evans and Geerken 2004; Wessels et al. 2007; Wessels 2009). The observed cumulative NDVI values are regressed against rainfall to generate a statistical model, which is then used to compute the predicted values of the cumulative NDVI at each pixel. The residuals (i.e. the differences between observed and predicted NDVI values) for each pixel are then analyzed for detecting trends with respect to time. If the residuals show no trend over time, the observed changes in vegetation are thought to be attributable to climatic factors; a decreasing trend in the residuals indicates vegetation degradation presumably induced by human activities (e.g., grazing, agriculture, and urbanization); and an increasing trend in the residuals suggests improved vegetation conditions which may be attributed to conservation and restoration efforts (Evans and Geerken 2004; Geerken and Ilaiwi 2004; Wessels et al. 2007; Wessels 2009).

To detect vegetation changes in the Xilingol region using RESTREND, first we conducted linear regressions between $NDVI_{max}$ and rainfall (original and log-transformed) during the study period (1981–2006) at the pixel level for each vegetation type (Fig. 3). To better reflect the spatial variations in rainfall and vegetation dynamics across the region, we used site-specific data—rather than the entire regional dataset—to conduct the regression between $NDVI_{max}$ and rainfall and generate residuals. To explore the best fitted statistical relationship, annual $NDVI_{max}$ was regressed against eight precipitation variables on the pixel basis. The precipitation variables included cumulative precipitation with different time lags (the time lengths before NDVI reached the maximum): cumulative precipitation from January to July (PJJ), cumulative precipitation from April to July (PAJ), cumulative precipitation from April to August (PAA), cumulative precipitation from June to August (PJA), and the logarithmic forms of the above precipitation variables. At each pixel, the regression equation with the highest R^2 was selected for generating residuals. The statistic significance of the selected regression equations was tested, and only those pixels with significant regression models ($p < 0.05$) were kept in the subsequent RESTREND analysis. Most of those pixels with statistically non-significant regression models were found in areas that were cultivated or covered by non-zonal vegetation.

After the pixel-level regression residuals were obtained, their temporal trends were examined with the least square method. In order to examine the possible effects of land use policies, we divided the entire time period of 26 years into three sub-periods based on major institutional changes in the Xilingol grassland region: 1981–1990, 1991–2000, and 2000–2006. The first sub-period is characterized by the transition from a collective economy (before 1984) to a market economy; the second by a full-fledged market economy driven by the household production responsibility system; and the third by the implementation of several grassland protection policies in the period of 2000–2006. For each time period, we determined the changing trend by the slope of the regression line of residuals, and the statistical significance of the slope was tested with the t-statistic.

Then we defined eight categories based on two-tail t-distribution, in combination with three confidence intervals (0.05, 0.10 and 0.25). Specifically, we categorized the decreasing trends (negative slopes) into four classes: D1 ($|t \text{ statistic}| > t_{0.05\ (n-2)}$), D2 ($|t \text{ statistic}| > t_{0.10\ (n-2)}$,), D3 ($|t \text{ statistic}| > t_{0.25\ (n-2)}$), and DNC ($|t \text{ statistic}| < t_{0.25\ (n-2)}$). Accordingly, the increasing trends (positive slopes) also had four classes: I1 ($t \text{ statistic} > t_{0.05\ (n-2)}$), I2 ($t \text{ statistic} > t_{0.10\ (n-2)}$), I3 ($t \text{ statistic} > t_{0.25\ (n-2)}$), and INC ($t \text{ statistic} < t_{0.25\ (n-2)}$). That is, the trends indicated by D1, D2 and D3, as well as by I1, I2 and I3, were statistically significant at p values of 0.05, 0.10, and 0.25, respectively. DNC and INC denote visually discernable decreasing and increasing trends that were not statistically significant at p values of smaller than 0.25.

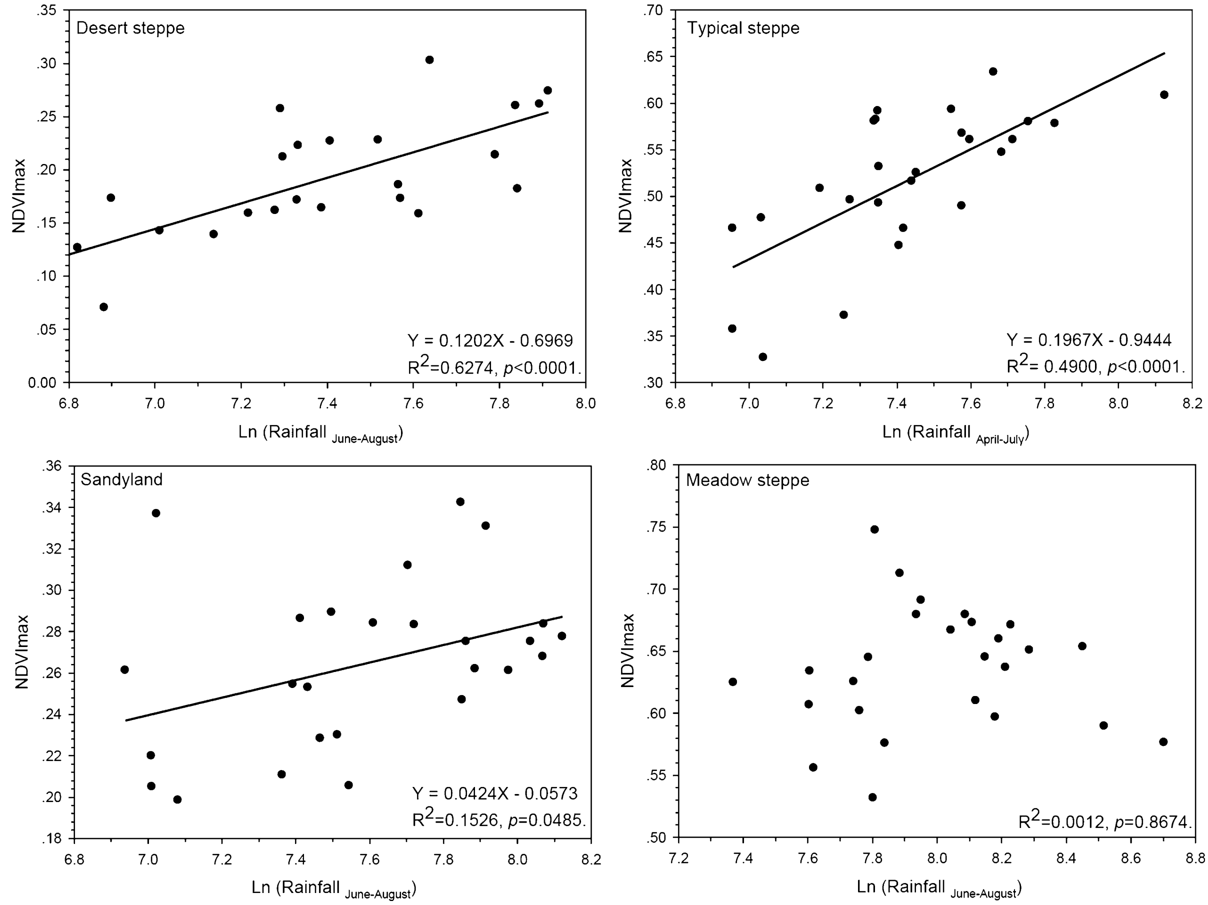

Fig. 3 Pixel-level regressions between $NDVI_{max}$ and rainfall between 1981 and 2006 for the four major vegetation types: desert steppe, typical steppe, meadow steppe, and sandy land. For the purpose of illustration, the values of $NDVI_{max}$ and rainfall for each vegetation type were the means of 30 randomly selected pixels. The time period of rainfall for each vegetation type (April–July for typical steppe and June–August for the other three) was chosen so as to develop a statistically significant regression equation with the highest R^2 (this was not possible in the case of meadow steppe)

Results

Correlations between $NDVI_{max}$ and rainfall

Our analysis showed that, for the time period of 1981–2006, $NDVI_{max}$ and rainfall were significantly correlated for 100 % of the pixels in desert steppe, 84.48 % of pixels in typical steppe, and 54.27 % of the pixels in sandy land. However, the majority of pixels in meadow steppe did not show a statistically significant correlation between $NDVI_{max}$ and rainfall, with only 26.41 % of the pixels that did. Overall, 73.6 % of the pixels for the four major vegetation types had a statistically significant regression model at the level of $p < 0.05$. Examples of the regressions for the four vegetation types are given in Fig. 3. The best pixel-specific regression model explained, on the average, 42.3 % of the variance in annual $NDVI_{max}$ in desert steppe, 30.3 % in typical steppe, 20.4 % in meadow steppe, and 24.4 % in sandy land. The spatial pattern of the R^2 and p-value of the pixel-level regressions is presented in Fig. 4.

Trends in the regression residuals

When examined over the entire study period of 1981–2006, the residuals from the $NDVI_{max}$–rainfall regressions for most pixels of each vegetation type did not show a statistically significant trend. Different trends emerged when the residuals were analyzed for the three land use policy periods: 1981–1990, 1991–2000, and 2000–2006 (Table 1; Fig. 5). Considering the four

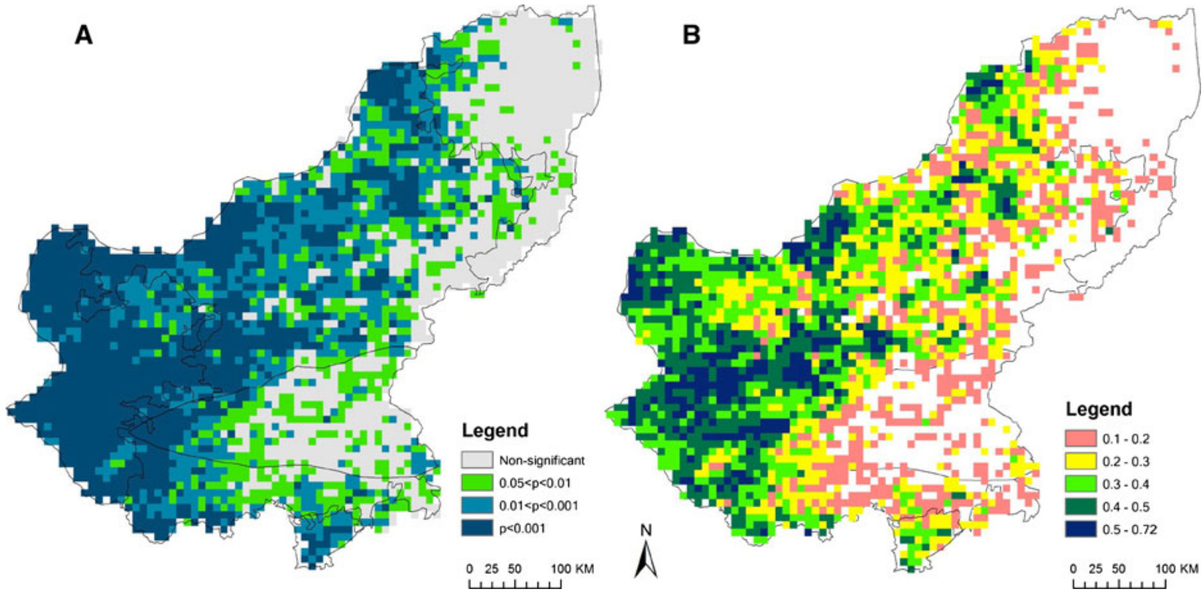

Fig. 4 The spatial pattern of the *p* values (**A**) and R^2 values (**B**) of pixel-specific regressions between $NDVI_{max}$ and rainfall over the time period of 1981–2006

vegetation types altogether, the percentage of pixels (approximately the same as the proportion of the total study area) showing a decreasing trend (D1, D2, and D3) was highest for the period of 1991–2000 (19.7 %) and lowest for the period of 2000–2006 (11.2 %). The percentage of pixels exhibiting an increasing trend (I1, I2, and I3) was highest for the period of 2000–2006 (50.4 %), and the other two periods had similar values (about 20 %). The percentage of pixels that showed an apparent, but statistically insignificant, decreasing trend (DNC) was similar for the two earlier periods, but dropped by almost two thirds in the last period (Table 1). The percentage of pixels showing an apparent, but statistically insignificant, increasing trend (INC) was more evenly distributed among the three periods (Table 1).

Table 1 Percentage of pixels with different residual trends for the three land use policy periods (the eight classes of residual trends and the criteria of determination are detailed in the Methods section)

Residual trend	1981–1990 (%)	1991–2000 (%)	2000–2006 (%)
D1, D2, D3	16.99	19.65	11.15
DNC	30.19	29.34	16.29
INC	34.22	30.76	22.13
I1, I2, I3	18.59	20.23	50.42
Total	99.99	99.98	99.99

Within each vegetation type, the residuals exhibited different trends among the three time periods (as an example, the trends of a particular pixel from each vegetation type is shown in Fig. 5). During 1981–1990, the majority of pixels of each of the four vegetation types (about 64 % in total) exhibited either a DNC or an INC pattern, indicating no consistent trend, and 35 % of pixels showed either an increasing or a decreasing trend with a similar probability (Table 1; Fig. 6). However, increasing numbers of pixels showed a decreasing residual trend during 1991–2000 and an increasing trend during 2000–2006 (Table 1; Fig. 6).

Relationship between residual trends and stocking rates

To verify the essential assumption of the RESTREND method, also the key part of our conceptual framework (Fig. 2), we examined if the changes in the $NDVI_{max}$–rainfall regression residuals and stocking rates were correlated using field observation data from nine townships (Sumu) in East Ujimqin Banner (county), located in the typical steppe of the Xilingol region. The trend of change in the residuals was significantly

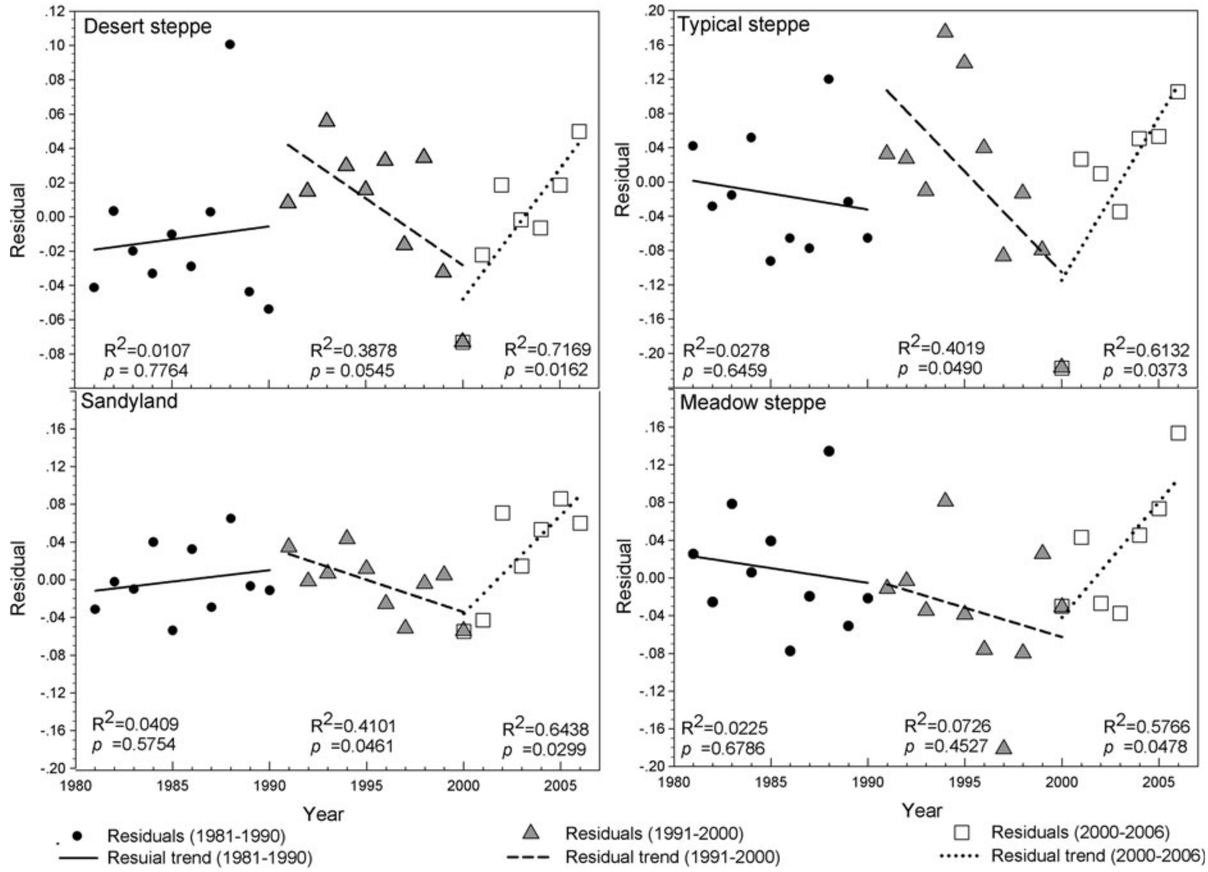

Fig. 5 Trends of the residuals from the pixel-level $NDVI_{max}$–rainfall regressions for the four major vegetation types, where three time periods (1981–1990, 1991–2000, and 2000–2006) corresponded to the major changes in land use policy). For illustration purposes, each vegetation type was represented by a pixel selected from the interior or central part of the distribution area of that vegetation type

negatively correlated with the trend of change in the stocking rate (Fig. 7), where the trend of change was defined as the slope of the linear regression in the form of $Y = bX + a$. The trends of change were computed for the three land use time periods based on actual stocking rates between 1981 and 2005. This result indicates that the decreases in the $NDVI_{max}$–rainfall regression residuals corresponded to the increases in the stocking rate over time, and vice versa.

Discussion

Changes in the vegetation of the Xilingol grassland landscape

To address our first research question, it is important to estimate the changes in biomass production per unit rainfall that are related to ecosystem resilience in the face of fluctuating vegetation cover and production in response to large precipitation variations from year to year (Fig. 2). Several previous studies based on vegetation trend analysis using remote sensing data reported that the net primary production of the Xilingol grassland increased from the 1980s to the early 2000s (Fang et al. 2004; Brogaard et al. 2005; Piao et al. 2006). These results may be interpreted as suggesting that the land use policies and practices during this period of time had positive impacts on the grassland. However, the results from a number of field observations were quite different (Tong et al. 2004; Jiang et al. 2006; Huang et al. 2009). This discrepancy indicates that focusing solely on vegetation change without teasing out the effects of climate factors (especially rainfall) may lead to misleading implications for landscape management and land use policy.

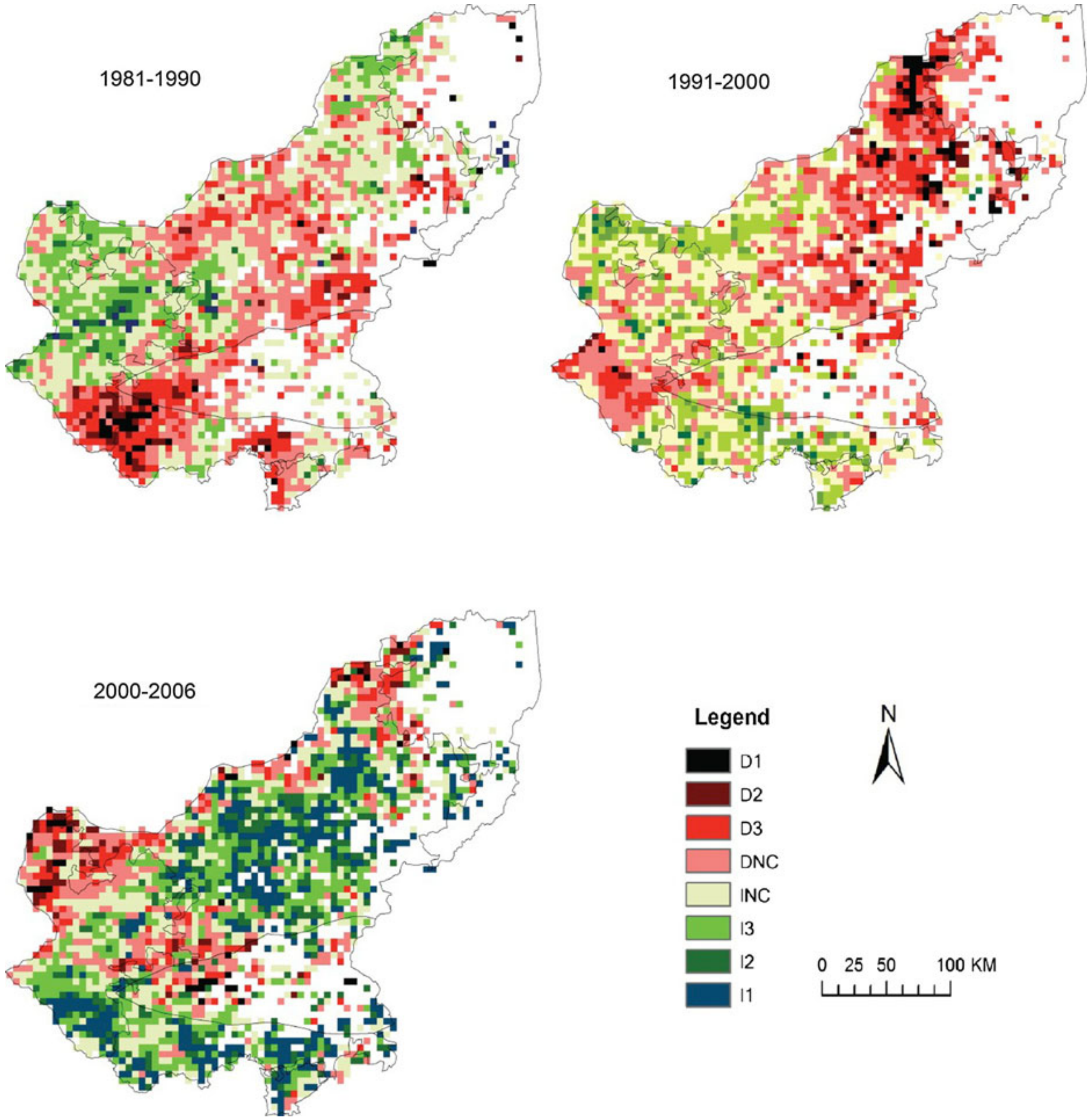

Fig. 6 The spatial pattern of vegetation changes as indicated by residual trends for the three land-use policy periods. D1, D2, and D3 denote decreasing trends, and I1, I2, and I3 stand for increasing trends, with subscripts 1–3 indicating the different degrees of statistical significance (see text for more detail)

Our results, based on the residual trend analysis that removed the effects of rainfall effects, show that the changes in the vegetation of the Xilingol grassland exhibited different trends between 1981 and 2006. Specifically, vegetation cover and biomass production, as indicated by NDVI, declined from the early 1980s to the late 1990s, but improved from 2000 onward. These results are consistent with field observations (Tong et al. 2004; Jiang et al. 2006; Huang et al. 2009). The worsening trend in vegetation in the Xilingol region between 1983 and 1999 was also reported in Cao et al. (2006). Our study suggests that distinguishing vegetation changes induced by human activities from those by climatic variations is crucial to

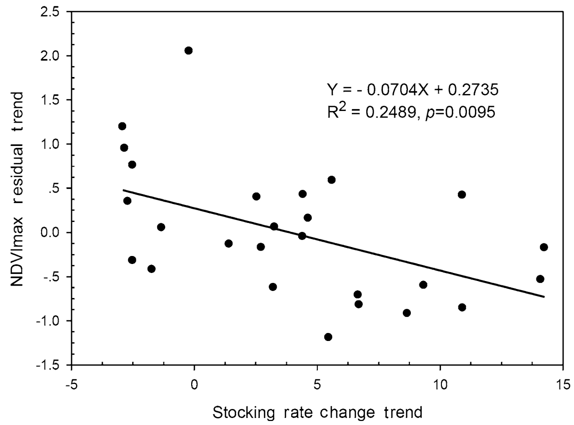

Fig. 7 The correlation between the trend of change in the $NDVI_{max}$–rainfall regression residuals and the trend of change in the stocking rate in 9 townships (Sumu) in the Xilingol grassland region. The trend of change in the residuals was defined as b in the regression equation, Residuals = $b \times$ Time + a, and the trend of change in the stocking rate was defined as b' in the regression equation, Stocking rate = $b' \times$ Time + a'

correctly identifying the underlying causes and designing appropriate land use policies.

Impacts of land use practice and policy on vegetation changes

In principle, RESTREND can identify the pixels that has experienced a reduction or an increase in biomass production per unit rainfall over a period of time, but cannot explain the causes without additional information (Wessels et al. 2007). Our second research question was addressed by the results of the identified trends of the $NDVI_{max}$-rainfall regression residuals, in combination with field observations on stocking rates (Figs. 5, 6, 7). The residuals may result from a number of factors, including climatic variations (mainly precipitation and temperature), natural disturbances (e.g., wild fires, flooding), and human activities (livestock grazing, population outbreaks of rodents and grasshoppers, desertification, agriculture, and urbanization). Short-term climatic variations and natural disturbances usually do not lead to a directional change in the residuals, but vegetation degradation induced by increasing human activities does.

The dominance of a decreasing trend in the residuals at the pixel level for the major vegetation types from 1981 to 2000 indicates vegetation degradation, whereas a strong upward trend in the residuals was evident from 2000 to 2006, indicative of vegetation improvements. The increasing residual trend corresponded closely to soaring stocking rates, and the decreasing residual trend was associated with sharply declining stocking rates (Fig. 8). A number of field-based observational and experimental studies in this region have shown that overgrazing decreases vegetation cover and biomass production substantially (Zhao et al. 2005; Bai et al. 2007; Li et al. 2008; Schönbach et al. 2009; Lin et al. 2010). Our results suggest that livestock grazing was the main driver for the observed vegetation changes in the Xilingol region between 1981 and 2006. Other land use practices, such as cultivation and urbanization, must have played a role in shaping the spatiotemporal pattern of the Xilingol grassland vegetation. The effects of these land uses were not evaluated in our study because of their rather limited distribution in area (Fig. 1) and the inapplicability of the RESTREND method to these areas (more discussion in the next section).

The changes in stocking rates in the Xilingol region were influenced by land use policies enacted by the Chinese government. The HPRS—assigning livestock and grazing lands to herder households—was introduced after 1984 to shift from the centrally-planned economy to a market-based economy (Li et al. 2007; Zhang and Li 2008). Consequently, the stocking rate and cultivated area in Xilingol both increased substantially from 1981 to 2000 (Fig. 8). Therefore, the HPRS policy, although intended to avoid the "tragedy of commons" (Hardin 1968) and to improve both human and ecosystem well-being, actually led to large-scale severe ecosystem degradation, mainly

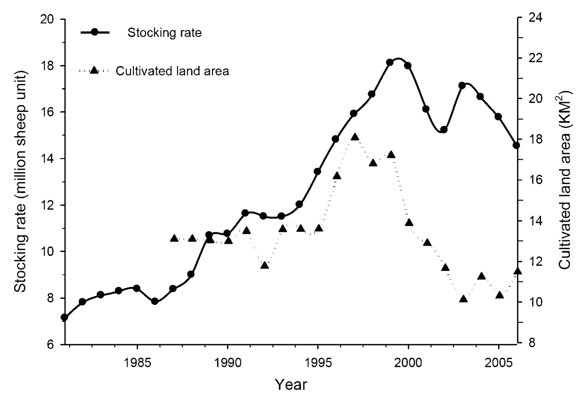

Fig. 8 Changes in the stocking rate and cultivated land in the Xilingol grassland region between 1981 and 2006

because of the rapid increase in stocking rates. After 2000, several government-supported programs for grassland protection and nature conservation, such as "Beijing–Tianjin Sandstorm Source Control Project" and "Grain-to-Green Plan" (Zhao et al. 2008; Cao et al. 2009), were implemented in northern China, including the Xilingol region. Some herders were relocated from their rangeland as part of the ecological emigration program, resulting in a decline in the number of domestic animals. A number of peasants also converted some of their cultivated land to grassland—literally "giving up grain for green." Since the implementation of these new land use policies, a considerable decline in the stocking rate and cultivated area from 2000 to 2006 (Fig. 8).

Evaluation of the RESTREND method

Our results showed that the RESTREND analysis was highly applicable to the typical steppe and desert steppe, but less effective for the meadow steppe in the Xilingol region. The method became essentially unusable for non-zonal vegetation types as well as cultivated and urbanized areas. Our study provides new insights into two critical issues on the use of the RESTREND method, as discussed below.

Importance of spatial heterogeneity in the vegetation–rainfall relationship

The first step in the RESTREND analysis is to establish a statistically significant relationship between vegetation production (or its surrogate—NDVI) and rainfall. Severe human disturbances and localized redistributions of water (and heat energy) may decouple the relationship (Buyantuyev and Wu 2009). In this case, the effects of rainfall cannot be removed, and the basic premise of the RESTREND method is violated.

Although it is commonplace that vegetation and rainfall usually are highly correlated to each other in arid and semiarid ecosystems, the spatial heterogeneity in this relationship at the landscape level, as revealed in our study, was tremendous. Based on data from a long-term ecological research site in the typical steppe in the Xilingol region (established in 1979), Bai et al. (2004) reported that rainfall explained about 40 % of the variance in annual aboveground biomass production from 1980 to 2003. A 7-year field survey showed that rainfall explained 66 % of the variance in the net primary production of desert steppe in southern Mongolia (Wehrden and Wesche 2007). The production-rainfall relationship was weak in sandy land and, somewhat surprisingly, did not show up for most of the pixels in meadow steppe (Figs. 3, 4).

A high degree of spatial heterogeneity in the production-rainfall relationship also existed within each vegetation type. The regression models at some pixels, for example, were not statistically significant even for desert and typical steppes, probably due to local land use practices (e.g., cultivation and urbanization) and errors in approximating biomass production using NDVI. Also in the typical steppe, there were severely degraded areas dominated by slowly-growing subshrubs (e.g., *Artemisia frigida*) and shrubs (e.g., *Potentilla* spp.), as well as patches of saline meadows and wetlands along rivers. Such areas were less sensitive to rainfall variations. Not surprisingly, the number of such pixels was much higher in meadow steppe and sandy land. Several factors might be responsible for this. First, meadow steppe was commonly distributed along riverbanks in the Xilingol region (Fig. 1), and rainfall was less a limiting factor because of higher soil water contents (Li et al. 2000). Second, plants in sandy lands of this region were able to use groundwater which was located only 0.5–3 m below the soil surface. In the 1980s, there were about 110 freshwater lakes in the sandy lands of the Xilingol region (Yang et al. 2007). Third, in denuded areas of the sandy land (as well as the typical steppe)—likely a consequence of desertification—no plants grew and thus there was no vegetation response to rainfall variations.

The spatial heterogeneity in the vegetation–climate relationship and the regression residuals may significantly weaken the accuracy of the RESTREND method. Thus, spatially explicit approaches—e.g., based on individual pixels as done in this study or patches that are clusters of pixels with similar vegetation and environmental conditions—are necessary for the effective application of the method. A patch-based approach is ecologically more sensible and computationally more efficient, which can be facilitated by vegetation classification following the hierarchical patch dynamics paradigm (Wu and Loucks 1995; Wu 1999), as applied in the object-specific analysis by Hay et al. (2001). In addition, teasing out pixels without a significant relationship between vegetation and rainfall in the analysis is also important.

Scale effects in terms of pixel size and time duration

The spatial and temporal scales of analysis in terms of grain and extent often affect the results of spatial analysis (Jelinski and Wu 1996; Wu 2004, 2007). This is also the case with the RESTREND method. First, the spatial resolution of the remote sensing data used in our study was determined primarily by the availability of the GIMMS dataset. Although we do not expect that our major results on the spatiotemporal pattern of vegetation change will be qualitatively altered, using finer-resolution data may improve the accuracy of the analysis and provide more explanatory power. Because too coarse a resolution may omit important details while too fine a resolution may result in noises overwhelming signals, future studies are needed to explore the "optical" pixel or patch size in the application of the RESTREND analysis.

Second, the results of the RESTREND method vary with the time scale (duration) used for computing the NDVI-rainfall regression and the trends of its residuals. For example, the proportions of pixels with statistically significant regression models and residual trends both change with scale in time. While there were a number of ways to select time scales in this study, we chose the entire time series for the NDVI-rainfall regression to produce an ecologically sensible and statistically robust relationship. Also, we analyzed the residual trends for three time periods based on major changes in land use policy and institutional arrangements in the study region. In general, the selection of time scale should not be arbitrary; instead, it should be based on research objectives and patterns in the time series of data on vegetation, rainfall, land use, and land use policy.

Conclusions

Our study indicates that the grassland vegetation in the Xilingol region of Inner Mongolia deteriorated from the early 1980s to 2000 primarily because of increased livestock grazing which was associated with the implementation of the HPRS. This land use policy by the Chinese government has produced economically and environmentally positive results in agricultural regions, but not in the grazing lands of Inner Mongolia. The degrading trend in vegetation was reversed between 2000 and 2006 due to decreased stocking rates, which was attributable to several new land use policies geared toward grassland conservation and restoration. Our results suggest that the degraded grassland vegetation in the Xilingol region can recover if the stocking rate is kept at a moderate level, and this can be done effectively through appropriate land use policies and institutional arrangements. The RESTREND method provides an effective tool to distinguish between the effects of climatic factors and human activities on vegetation changes when used properly. In particular, the issues of spatial heterogeneity and scale should be explicitly considered in the application of the method.

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