

# Differentiating climate- and human-induced drivers of grassland degradation in the Liao River Basin, China

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Received: 16 March 2014 / Accepted: 1 December 2014 / Published online: 16 December 2014  
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**Abstract** Quantitatively distinguishing grassland degradation due to climatic variations from that due to human activities is of great significance to effectively governing degraded grassland and realizing sustainable utilization. The objective of this study was to differentiate these two types of drivers in the Liao River Basin during 1999–2009 using the residual trend (RESTREND) method and to evaluate the applicability of the method in semiarid and semihumid regions. The relationship between the normalized difference vegetation index (NDVI) and each climatic factor was first determined. Then, the primary driver of grassland degradation was identified by calculating the change trend of the normalized residuals between the observed and the predicted NDVI assuming that climate change was the only driver. We found that the RESTREND method can be used to quantitatively and effectively differentiate climate and human drivers of grassland degradation. We

also found that the grassland degradation in the Liao River Basin was driven by both natural processes and human activities. The driving factors of grassland degradation varied greatly across the study area, which included regions having different precipitation and altitude. The degradation in the Horqin Sandy Land, with lower altitude, was driven mainly by human activities, whereas that in the Kungl Prairie, with higher altitude and lower precipitation, was caused primarily by climate change. Therefore, the drivers of degradation and local conditions should be considered in an appropriate strategy for grassland management to promote the sustainability of grasslands in the Liao River Basin.

**Keywords** Liao River Basin · Driving factors · Climate change · Human activities · Grassland degradation · Residuals trend analysis

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## Introduction

Grasslands comprise nearly 24 % of the planet’s terrestrial surface and are the most widely distributed vegetation type in the world (Glenn et al. 1993; Sims and Risser 2000). The Net Primary Production (NPP) of grasslands accounts for 20 % of the global total from all vegetation, and its capacity as a carbon sink is approximately 0.5 PgC/year (Scurlock et al. 2002; Ma et al. 2010). Grasslands therefore play a significant role in biogeochemical cycles and supply an ecosystem service for humans (Scurlock et al. 2002; Ma et al. 2010). Grassland degradation has become one of the most

serious environmental and socioeconomic problems in many arid and semiarid regions. Taking Inner Mongolia of China as an example, degraded grassland accounts for 59 % of the total grassland area, and average grassland production has decreased by 30–70 % compared with its value in the 1950s (Hou 2013). Such degradation will gradually pose a threat to sustainable utilization and regional sustainable development of grassland resources (Reynolds et al. 2007). The dynamics of grassland degradation are driven by both natural processes and human activities (e.g., livestock grazing, land-use/cover changes, etc.) (Wessels et al. 2006; Li et al. 2012). Distinguishing the two types of drivers of grassland degradation has received increasing attention because it is necessary for providing targeted measures for the protection of endangered grasslands (Li et al. 2012; Hou 2013).

Some research on distinguishing the driving factors of grassland degradation has been carried out in the past several decades. Prince et al. (1998) explored the responses of vegetation to precipitation using rain-use efficiency variability, and Zhang et al. (2004) assessed the impacts of grazing intensity on grassland degradation by conducting grazing trials. Tong et al. (2004) qualitatively analyzed steppe degradation caused by climatic fluctuation and anthropogenic factors in the Xilin River Basin, China. However, reliable approaches for quantitatively differentiating the driving factors of grassland degradation still require development (Li et al. 2012). Evans and Geerken (2004) first proposed the normalized difference vegetation index (NDVI)-based residual trend (RESTREND) method to distinguish between vegetation degradation due to climatic variations and that caused by human activities in Syria, and this method provided a new approach to differentiate the effects of these two factors associated with grassland degradation. The RESTREND method identifies the driving factors of grassland degradation by analyzing the trend of residuals between actual NDVI values and NDVI values predicted when assuming that climate change is the only driver. The method is simple and can be used to reveal the spatial heterogeneity of factors driving grassland degradation at cell resolution. Therefore, the RESTREND method has been used widely in arid regions (Herrmann et al. 2005; Wessels et al. 2007; Li et al. 2012). Herrmann et al. (2005) applied this method in the African Sahel to explore the relationship between climatic and anthropogenic causes of grassland degradation. Wessels et al. (2007) used the RESTREND method to distinguish land degradation

induced by human activities from that caused by rainfall variability in the Savanna of South Africa. Li et al. (2012) also used it to distinguish human-induced vegetation changes from those driven by climate change in the Xilingol grassland region of Inner Mongolia, China. The applicability and effectiveness of the method when adopted for arid and semiarid regions have been tested, but its applicability for semiarid and semihumid regions still needs to be evaluated.

The Liao River in Northeast China is a transitional zone for agriculture and livestock husbandry. The climate ranges from arid and semiarid to humid and semihumid monsoon; therefore, the ecological environment is vulnerable. Grassland, which is one of the main land-use types, is located in the middle and western parts of the river basin (Liu et al. 2014). In recent years, grassland degradation in the river basin has become very serious due to stresses from both intruding human activities and regional/global climate change (Zhao et al. 2012). The desertification area caused by grassland degradation in the Horqin Sandy Land in the middle part of the river basin increased from 1142 km<sup>2</sup> in the 1960s to 2460 km<sup>2</sup> in the 1990s (Wang et al. 2001; Li et al. 2005). The grasslands degraded gradually to fixed, semifixed, semishifting, and shifting sandy lands, resulting in multiple ecological problems including soil erosion and dust storms (Li et al. 2002; Li et al. 2003; Zuo et al. 2009). Adjacent regions, including the heartland of China (the Beijing–Tianjin area), are likely to be affected. Earlier research on grassland degradation in the Liao River Basin focused on detection of grassland degradation (Hu et al. 2002) and the effects of different grassland restoration approaches (Zhang et al. 2004; Yuan et al. 2012; Zhang et al. 2013). However, there remains a shortage of studies on differentiating climate- and human-induced drivers of grassland degradation, which greatly limits the ability to propose effective grassland management policies, making sustainable grassland utilization a real challenge.

Therefore, the aim of this study was to differentiate human-induced drivers from climatic drivers of grassland degradation in the Liao River Basin using the RESTREND method. The objectives were as follows: (1) to evaluate the effectiveness of the RESTREND method in the Liao River Basin, which is located in a semiarid to semihumid region with complex geomorphology; (2) to detect grassland degradation and distinguish grassland degradation due to climatic variations from that caused by human activities; and (3) to propose

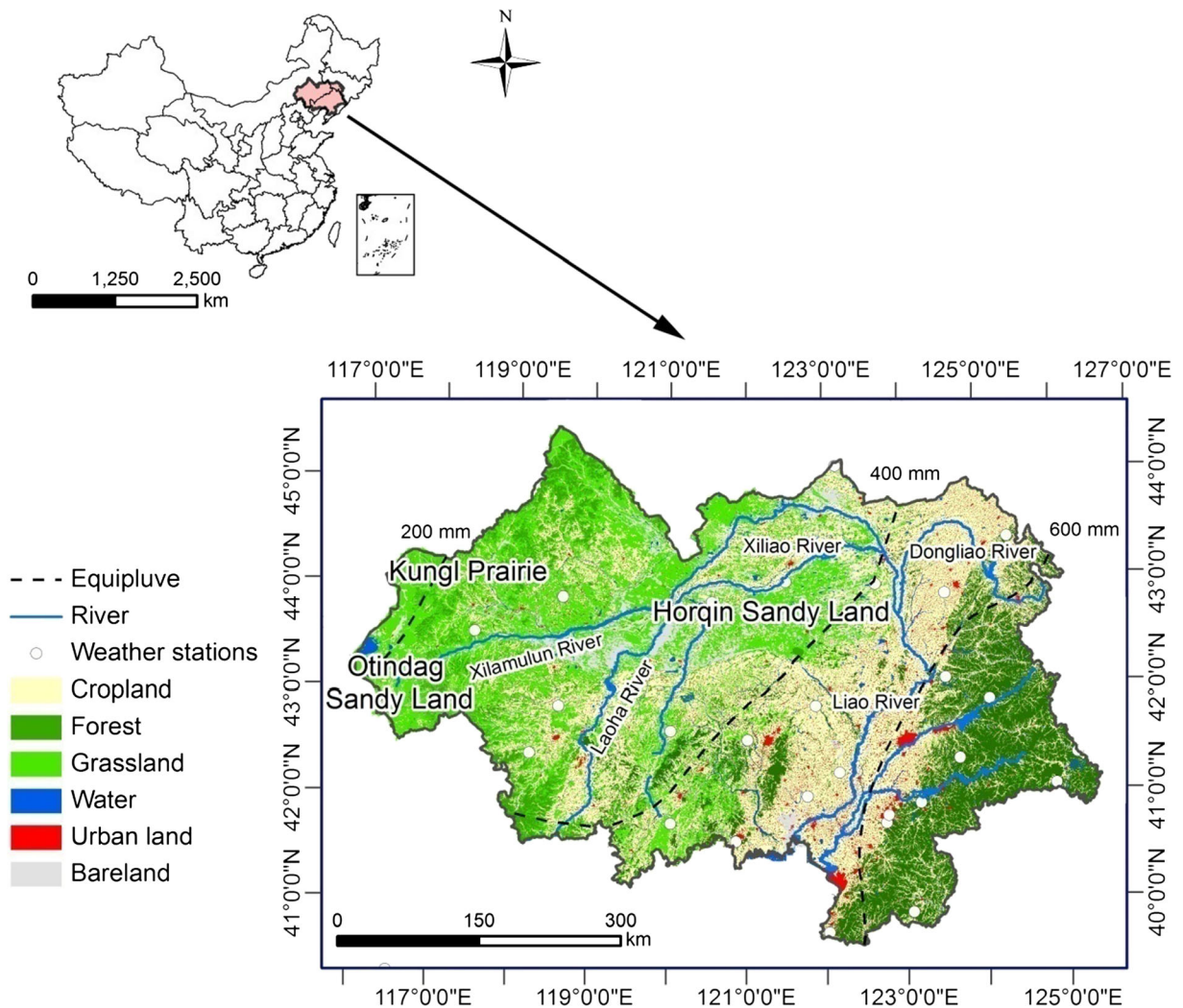
prevention and control measures in accordance with the main drivers of the degradation.

### Study area and data

#### Study area

The Liao River Basin is located in the southwestern part of Northeast China (116.30–125.47°E, 38.43–45.00°N) and borders the Songhua River Basin to the north, the Inner Mongolia Plateau to the west, and the Bohai Gulf to the south (Fig. 1). There is a floodplain in the central and lower reaches of the river. The basin also includes the Dongliao River, Xiliao River, Laoha River,

Xilamulun River, and others. The basin area has a temperate monsoon climate that is semiarid or semihumid depending on the season. A large proportion of the annual precipitation usually occurs during July to September. The average annual precipitation in the study area ranges from 200 mm in the west to 600 mm in the east. The type of soil is highly variable across the basin, with brown forest soil in the Liaodong Peninsula, moister soil in the lower stream floodplain of the Liao River, eolian sandy soil and meadow soil in the Horqin Sandy Land, and Chernozem and calcic soil in the Kungl prairie. The main land-use/cover types from east to west are forest, cropland, and grassland. Most of the grasslands are situated in the central area (the Horqin Sandy Land) and in the western portion (the Kungl



**Fig. 1** The study area and land-use/cover in 2005

Prairie and Otindag Sandy Land) of the basin. More specifically, *Setaria viridis* and *Pennisetum flaccidum* communities are widely distributed in and dominate the central area, where land is used for both agriculture and livestock husbandry, whereas the Kungl Prairie is covered primarily by zones of *Stipa grandis* and *Stipa klemenzii* (Li et al. 2011).

## Data

SPOT-VGT 10-day synthesis product (S10) images for the period January 1999–December 2009 were used for this study. In total, 396 S10 images were obtained from the VITO Research website (<http://free.vgt.vito.be/origin>). These images were all produced at a spatial resolution of 1 km. To further reduce atmospheric noise, the original images were filtered using the Savitzky–Golay method (Chen et al. 2004). An annual maximum value composite (MVC) of the NDVI was then produced for each year based on the processed monthly MVCs and used to represent the most vigorous condition during a single year (Hope et al. 2003).

Meteorological data for the study area covering the same period (January 1999–December 2009) were collected from the official database of the China Meteorological Administration. The meteorological variables used in the study included monthly averages of temperature and precipitation, which were measured by the 75 meteorological stations distributed throughout the region. The point-based temperature and precipitation data were spatially interpolated to produce continuous raster images that had the same spatial resolution as the NDVI images (1 km). More specifically, monthly temperature was interpolated by considering latitude and elevation (Willmott et al. 1985), while monthly precipitation was interpolated using the Kriging method. Cross-validation suggested that the interpolated results were fairly accurate with a root mean square error (RMSE) of 0.54 °C for the interpolated monthly temperature and 4.5 mm for the interpolated monthly precipitation.

Land-use/cover data (2005) collected from China's land-use/cover datasets were used to map the grassland distribution in the study area (Liu et al. 2014). The digital elevation model (DEM) data were downloaded from the US Geological Survey Earth Resource Observation System data center. Statistical data of livestock carriage were collected from the statistical yearbook.

## Methods

Extracting the areas of degraded grassland by linear trend analysis

A linear trend analysis (LTA) was used to detect and map the grassland areas in the Liao River Basin where considerable degradation had occurred from 1999 to 2009. LTA has commonly been used to easily and visually monitor variations in vegetation vigor by constructing a linear regression between time (year) and the corresponding vegetation index (Myneni et al. 1997; Fensholt et al. 2009; Zhao et al. 2012).

First, the annual NDVI<sub>max</sub> during the period of 1999–2009 was correlated with time (year) for each pixel. The pixels with an absolute value of Pearson's correlation coefficient ( $R$ ) (Eq. 1) greater than 0.49 (at  $p=0.05$ ) were extracted and considered to be undergoing considerable vegetation variation (Zhao et al. 2012). Then, the slope  $a$ , estimated by an ordinary least-squares method (Eq. 2), represents the vegetation (NDVI<sub>max</sub>) change trend with time  $x$ . Pixels with a statistically significant  $R$  value and a negative  $a$  value were extracted as the grasslands significantly degraded from 1999 to 2009 (Zhao et al. 2012).

$$R = \frac{\sum_{i=1}^{11} (x_i - \bar{x}) (NDVI_{maxi} - \overline{NDVI_{max}})}{\sqrt{\sum_{i=1}^{11} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{11} (NDVI_{maxi} - \overline{NDVI_{max}})^2}}, \quad (1)$$

$$a = \frac{11 \times \sum_{i=1}^{11} x_i NDVI_{maxi} - \sum_{i=1}^{11} x_i \sum_{i=1}^{11} NDVI_{maxi}}{11 \times \sum_{i=1}^{11} x_i^2 - \left( \sum_{i=1}^{11} x_i \right)^2}. \quad (2)$$

In Eqs. 1 and 2,  $x_i$  is the time (1 for the year 1999, 2 for the year 2000, and so on) and NDVI<sub>maxi</sub> is the NDVI<sub>max</sub> for year  $i$ .

Differentiating the drivers of grassland degradation by the RESTREND method

The RESTREND method is based on the general observation that the net primary productivity (NPP) of ecosystems is correlated with the climatic factor (Wessels

et al. 2007). RESTREND takes a spatially explicit pixel-based approach to detect the dominant driver of grassland degradation by analyzing the residuals between observed NDVI (as a proxy of NPP) and predicted NDVI values when assuming that climate change is the only driver (Li et al. 2012). First, we constructed a climate–vegetation response relationship model based on the multiple linear regression. With the model, we were able to calculate the expected  $NDVI_{max}$  that would result exclusively from climate change, with no direct human influence. Then, the change trend of the normalized residuals between the observed  $NDVI_{max}$  and the predicted  $NDVI_{max}$  was calculated to differentiate the primary drivers of grassland degradation (Evans and Geerken 2004; Wessels et al. 2007; Li et al. 2012).

*Constructing the climate–vegetation response relationship model and modeling the expected  $NDVI_{max}$  in response to climate change*

First, a grassland reference site was defined as an area where the grasses are not adversely affected by human activities. According to Zhuo et al. (2007) and our knowledge of the study area, which was developed from both a literature review and field work, grassland reference sites were selected by identifying the pixel with the maximum  $NDVI_{max}$  value in its 5×5-km immediate neighborhood. In each 5×5-km neighborhood, the type of vegetation community, the geomorphology, the soil type, and the climate characteristics are spatially homogeneous to a large degree. Therefore, the grasses within such a relatively small area should display similar responses to climate change. Therefore, the pixel with the maximum  $NDVI_{max}$  value identified in each 5×5-km window was believed to be the pixel least disturbed (possibly undisturbed) by human activity, and it was thus selected as the reference site (or pixel) (Fig. 2) (Zhuo et al. 2007). Then, the multivariate regression was constructed between the reference  $NDVI_{max}$  and the climatic factors. Such a regression can be used to effectively model the quantitative relationship of grassland  $NDVI_{max}$  with climatic factors in arid and semiarid regions (Cao et al. 2006; Wessels et al. 2007). It is also known that the  $NDVI_{max}$  is strongly correlated with the accumulated precipitation and the accumulated positive monthly temperatures observed in the month prior to the annual NDVI peak (Wang et al. 2001; Zhuo et al. 2007). Therefore, assuming that climate change is the sole reason for the change in annual NDVI characteristics, the expected  $NDVI_{max}$  at each pixel can be

predicted by building a regression model of the accumulated precipitation ( $P$ , over the most effective length of time) and the accumulated positive temperature ( $T$ ) for the pixel as follows:

$$NDVI_{max,i}^{exp} = AP_i + BT_i + C, \tag{3}$$

where  $NDVI_{max,i}^{exp}$  is the expected  $NDVI_{max}$  at each pixel  $i$  without any effects from human activities, and  $A$ ,  $B$ , and  $C$  are regression coefficients that can be determined based on the time series data of  $P$ ,  $T$ , and  $NDVI_{max}$  at the reference pixel for a pixel of interest. Calculation of the most effective accumulated precipitation is a two-stage process: (1) The month with the  $NDVI_{max}$  within a year was searched for each pixel, and the retrospective precipitation accumulated over increasingly longer periods (e.g., 1, 2 months, etc.) from the month with the  $NDVI_{max}$  was calculated for each pixel. (2) A correlation coefficient was then calculated between the accumulated precipitation over the length of each period and the  $NDVI_{max}$  value based on the data for all of the degraded pixels. The size of the time window that resulted in the highest coefficient value was selected for the calculation of the accumulated precipitation that was likely to be most effective for predicting the  $NDVI_{max}$ .

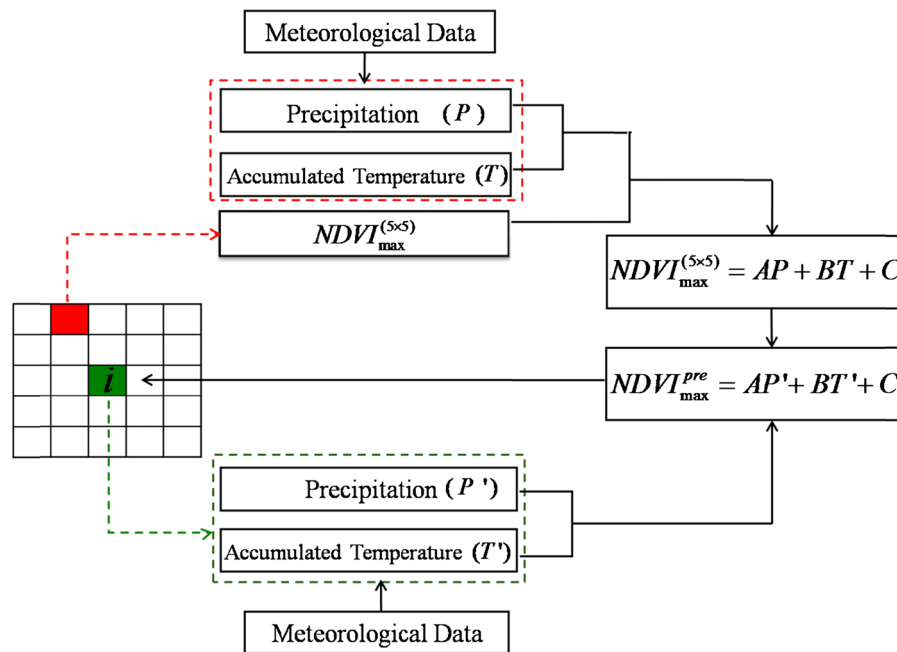
*Differentiating climate- and human-induced drivers of grassland degradation*

According to Zhuo et al. (2007), the linear trend of the normalized residuals (Eqs. 4 and 5) of the  $NDVI_{max}$  in each pixel during 1999–2009 can be used to distinguish between the degradation due to climate change and human activities:

$$\text{norm}NDVI_{max}^{res}(i, t) = \frac{NDVI_{max}^{act}(i, t) - NDVI_{max}^{exp}(i, t)}{NDVI_{max}^{ref}(i, t)} \tag{4}$$

$$\text{norm}NDVI_{max}^{res} = ax + b, \tag{5}$$

where  $\text{norm}NDVI_{max}^{res}(i, t)$  denotes the spatially normalized  $NDVI_{max}^{res}$  for pixel  $i$  in year  $t$ ,  $NDVI_{max}^{ref}(i, t)$  is the  $NDVI_{max}$  value at the reference pixel in each local neighborhood,  $x$  is the year,  $a$  is the slope, and  $b$  is the intercept. If the normalized residuals show no trend over time, the observed changes in vegetation are thought to be attributable to climatic factors; however, a significant decreasing trend in the normalized residuals ( $a < 0$ ,  $P < 0.05$ ) indicates vegetation degradation presumably induced by human activities (Evans and Geerken 2004; Wessels et al. 2007; Wessels et al. 2008).



**Fig. 2** Working procedure for calculating the expected  $NDVI_{max}$  for each 1-km pixel

## Results

### Distribution of grassland degradation

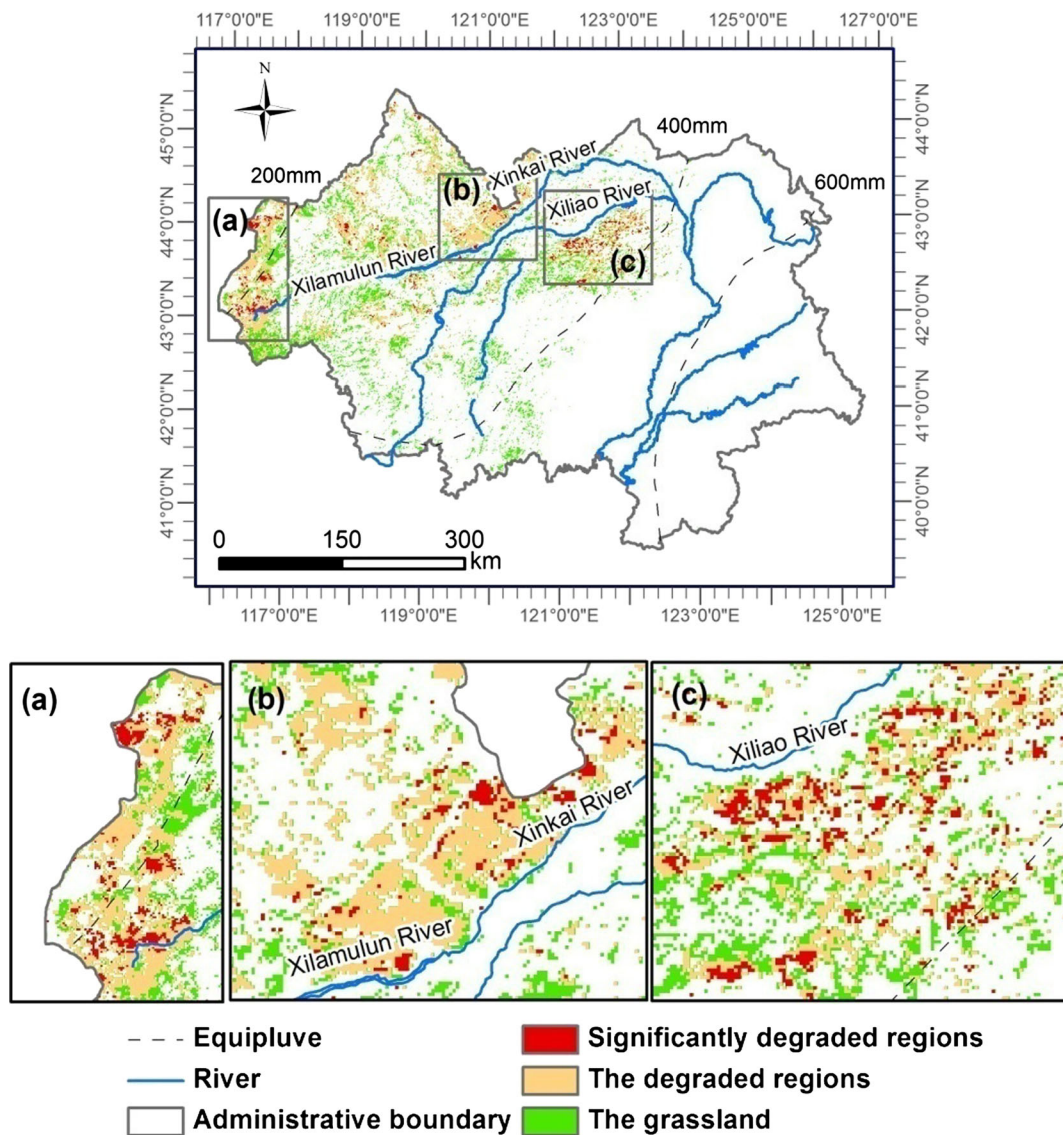
Grassland is one of the largest land-use/cover types in Liao River Basin. The grasslands, which are located in the central area (the Horqin Sandy Land) and in the western portion (the Kungl Prairie and Otindag Sandy Land) of the basin, cover an area of 33,700 km<sup>2</sup> and account for 15 % of the region's total.

In general, the grasslands showed a degraded trend in the past two decades. The area of grasslands with a degraded condition from 1990 to 2009 was 18,100 km<sup>2</sup> (53.71 % of the total grassland area). The area of grassland that experienced significant degradation over the time period of the study was 2449 km<sup>2</sup>, about 13.53 % of that with a degraded condition. Close examination revealed that the significant degradation occurred mainly in the areas of the Kungl Prairie and the Otindag Sandy Land (Fig. 3(a)), the upstream reaches of the Xilamulun River, and the downstream reaches of the Xinkai River (Fig. 3(b)) and midstream region of the Xiliao River (the Horqin Sandy Land) (Fig. 3(c)). The areas of significant degradation in the three regions were 679, 287, and 733 km<sup>2</sup>, accounting for 27.73, 11.72, and 29.93 % of the total significant degradation in the entire study area, respectively.

### Spatial variation in the climatic and human drivers of the grassland degradation

The grassland degradation in the Liao River Basin was driven by both natural processes and human activities. The majority of the degradation identified in the basin was driven primarily by climate change from 1999 to 2009. This area was 1387 km<sup>2</sup>, and it accounted for 56.64 % of the total significant degradation. Human activities drove the significant degradation of approximately 1062 km<sup>2</sup> of grassland (43.36 % of the total significant degradation).

The factors driving grassland degradation varied greatly across the study area. With respect to different land-use types, climate change was the dominant factor driving the degradation in the Kungl Prairie (Fig. 4(a)), human activities drove the significant degradation in the Horqin Sandy Land (Fig. 4(c)), and both climate change and human activities contributed equally to the degradation in the Otindag Sandy Land (Fig. 4(b)). For regions with different precipitation, degradation of grasslands in arid regions (precipitation of less than 200 mm) and semiarid regions (precipitation 200–400 mm) was driven mainly by climate change. The percentage of grassland degradation driven by climate change in the two regions was 97.41 and 51.48 %, respectively. The degradation in semihumid regions (precipitation of 400–



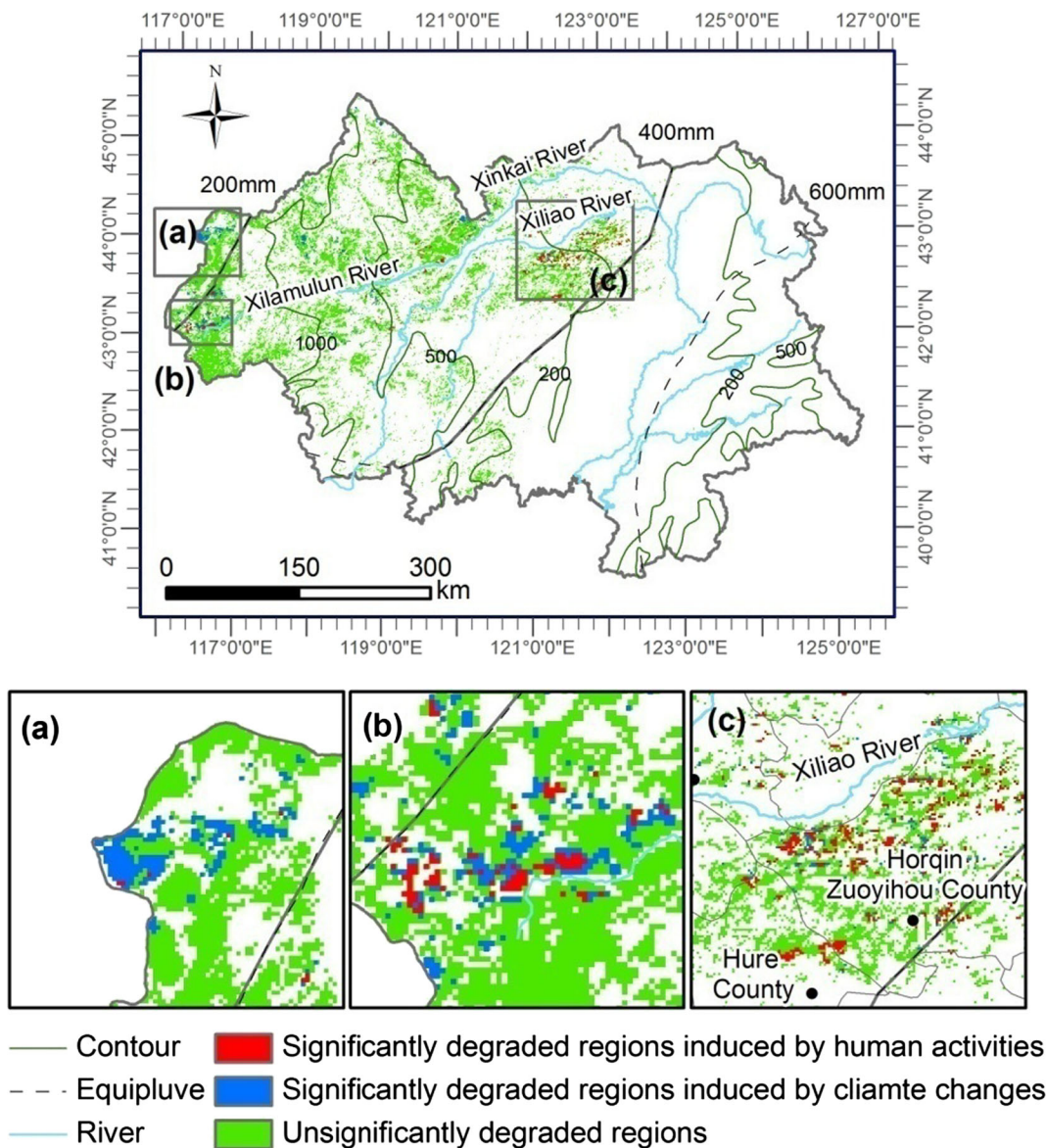
**Fig. 3** Spatial distribution of the degraded grassland areas in the Liao River Basin

600 mm) that was attributed to human activities was approximately 81.08 % of the total degradation. As for regions with different altitudes, the degradation in the plains (altitude lower than 200 m) and the hilly regions (altitude of 200–500 m) was dominantly caused by human activities. The areas of degradation driven by human activities in the two regions accounted for 76.51 and 64.87 % of the totals, respectively. The degradation in the mountains (altitude of 500–1000 m) and plateaus (altitude higher than 1000 m) was related to climate change. The degraded areas driven by climate change in these two regions accounted for 75.96 and 83.40 %, respectively (Table 1).

**Discussion**

High applicability of the RESTREND method for differentiating drivers of grassland degradation in semiarid and semihumid regions

Research on quantitatively distinguishing the driving factors of grassland degradation using the RESTREND method has been carried out mainly in dry land. To evaluate the effectiveness of the RESTREND method in the Liao River Basin, which is located in a semiarid and semihumid region, three aspects were analyzed.



**Fig. 4** Spatial distribution of the degraded grassland areas due to human activity and climate change ((a) Kungl Prairie; (b) Otindag Sandy Land; (c) Horqin Sandy Land)

First, according to Zhuo et al. (2007), the change trend of the grazing pressure index (GPI) was calculated to verify the results obtained in the Horqin Sandy Land. This index is derived from the number of livestock supported by one primary productivity unit and can be effectively used to assess the grazing stress on a grassland. Grasslands degrade when they are overgrazed, and the grazing index increases accordingly (Zhuo et al. 2007). The statistical data showed that the livestock carriage and GPI values in Horqin Zuoyihou County and Hure County in the Horqin Sandy Land increased

significantly from 1999 to 2009 (Fig. 4(c), Table 2). The livestock carriage in Horqin Zuoyihou County was  $18.78 \times 10^4$  in 1999, but it reached  $57.63 \times 10^4$  in 2009. Accordingly, the GPI increased from 0.018 in 1999 to 0.052 in 2009. Similarly, the livestock carriage increased from  $9.67 \times 10^4$  (in 1999) to  $44.25 \times 10^4$  (in 2009) in the adjacent Hure County. This resulted in a significant increase in the GPI value, from 0.036 to 0.151, during the same period. These results are consistent with our findings that the grassland degradation in the Horqin Sandy Land was strongly driven by excessive human activity.



**Table 1** Distribution of the degraded grassland areas due to human activity and climate change with different ranges of precipitation and altitude

	Regions significantly degraded by human activities		Regions significantly degraded by climate changes		
	Area (km <sup>2</sup> )	Percentage (%)	Area (km <sup>2</sup> )	Percentage (%)	
Precipitation (mm)	<200	18	5.59	304	94.41
	200–400	1014	48.52	1076	51.48
	400–600	30	81.08	7	18.92
Altitude (m)	<200	215	76.51	66	23.49
	200–500	613	64.87	332	35.13
	500–1000	100	24.04	316	75.96
	>1000	134	16.60	673	83.40

Second, we further analyzed the regional climate characteristics of the Horqin Sandy Land. The average temperature for the moist season (April–September) decreased, while precipitation showed a fluctuating increase (Fig. 5). Because the Horqin Sandy Land is semiarid with an annual precipitation of less than 400 mm, moisture is crucial to grass growth in the area. Theoretically, slightly lower temperatures and larger amounts of precipitation should have improved the growth of grasses in the region due to lower ground water evaporation and enhanced soil water retention (Fang et al. 2005; Bai et al. 2007; Zhao et al. 2011). However, the occurrence of severe grassland degradation, as opposed to growth, implies that human activities were the primary driving force in the process. These results revealed by historical climate data are consistent with those obtained by the RESTREND method.

We also analyzed the regional climate features of the Kungl Prairie. A coupled decrease in the average temperature and total precipitation in the moist season (April–September) was found during the period of the study (Fig. 6). This climate change characteristic is extremely unfavorable to grass revival or growth (Bai et al. 2007; Song and Ma 2011; Zhao et al. 2011), and it is consistent with our result based on the RESTREND method. It should also be noted that the Dalinor National Nature Reserve (in the Otindag Sandy Land) and the Kungl Prairie Nature Reserve were established in 1997<sup>1</sup> and 2000<sup>2</sup>, respectively. The grasslands in these reserves have been well protected from agriculture, overgrazing,

and other kinds of natural resource extraction. It is therefore logical to conclude that climate change was the predominant factor driving grassland degradation in the area.

Thus, it is credible that human activities and climate change are the primary driving force of degradation in the Horqin Sandy Land and the Kungl Prairie, respectively. It is also clear that the RESTREND method is highly applicable in semiarid and semihumid regions.

#### Management considering the local conditions and driving factors as a foundation of sustainable utilization of degraded grasslands in the Liao River Basin

Human activities and dry climate are the main factors leading to grassland degradation (Li et al. 2012; Hou 2013). Improper human activities, e.g., overgrazing (Li et al. 2000), land-use changes (Li et al. 2009), and urbanization (Dingaan and du Preez 2013), may pluck, occupy, or trample grasslands, affecting the vigor of vegetation. Subsequently, grassland ecosystem functions change, and the grasslands degrade. Climate change influences grassland vegetation by affecting soil moisture, soil nitrogen content, soil organic carbon content, and soil microbes (Hou 2013). The management of grassland degraded by different drivers should therefore be performed according to the local conditions and driver categories. Specifically, for restoration of grassland degraded mainly by human activities, the human intervention measures of ecological migration, fencing and enclosures, and grazing beneath the carrying capacity of the grassland should be considered (Tong et al. 2004). Degradation due to climate

<sup>1</sup> <http://www.kqdlh.com>.

<sup>2</sup> <http://www.grassland.gov.cn>.

**Table 2** Temporal variation in the index of grazing pressure in the Horqin Sandy Land (central Liao River Basin)

Year	Horqin Zuoyihou County		Hure County	
	C ( $10^4$ )	GPI	C ( $\times 10^4$ )	GPI
1999	18.78	0.018	9.67	0.036
2000	19.84	0.021	9.72	0.04
2001	16.29	0.017	9.92	0.039
2002	20.14	0.02	9.35	0.036
2003	27.54	0.029	13.26	0.052
2004	36.82	0.036	16.42	0.063
2005	45.64	0.044	22.00	0.08
2006	55.99	0.054	32.92	0.121
2007	62.08	0.06	36.82	0.137
2008	62.49	0.056	40.5	0.137
2009	57.63	0.052	44.25	0.151

C livestock carriage, GPI grazing pressure index

change is difficult to change or control because the degradation is always a normal response of the grassland to environmental change. We can only try to adapt by introducing new species or industrial structural adjustments (Cao et al. 2006).

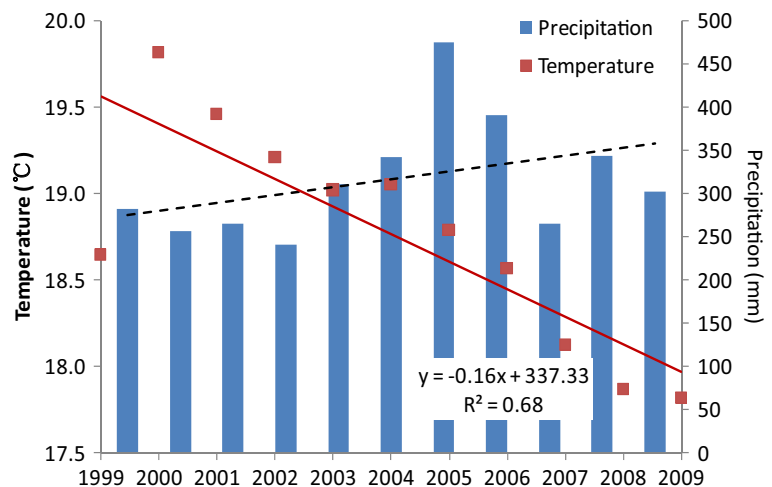
The grassland degradation in the Liao River Basin was driven simultaneously by natural and human factors, and these driving factors showed obvious spatial heterogeneity. Therefore, degraded grasslands should be managed according to the factors driving the degradation. The grassland degradation in the Horqin Sandy Land in the northern part of the Liao River Basin, for example, was caused mainly by human activities. Thus, an artificial sparsely

forested grassland restoration approach (e.g., *Pinus sylvestris* var. *mongolica*, *Ulmus pumila*) can be adopted to restore the grassland, alleviate wind erosion, enhance sand surface stabilization, and improve soil physicochemical and biological properties (Yuan et al. 2012). Meanwhile, the grazing capacity should be controlled (Zhao et al. 2009). A grazing intensity of two to three sheep equivalents per hectare has been adopted to keep the grassland sustainable (Zhang et al. 2004). Additionally, the vegetation productivity can be increased by fertilizing at an appropriate level, but it should be considered that fertilization may lead to a decline in biodiversity and simplicity of community structure (Zhang et al. 2013).

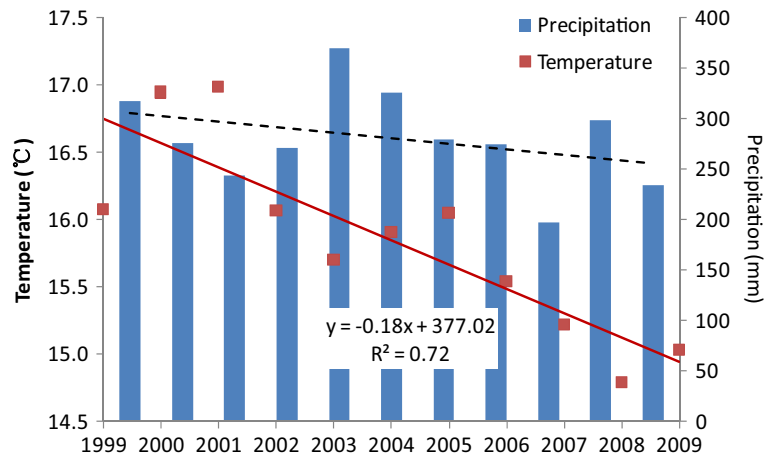
However, the measures taken in the regions driven by climate change should be different. Because grassland degradation in the Kungl Prairie was found to be driven primarily by local climate change, which has included cooling and drying, drought- and cold-resistant grasses should be introduced to the area in addition to adapting the native grasses to the changed climate through genetic engineering. These strategies can reduce the interference of unfavorable climate fluctuation on the grassland to a limited extent. Additionally, the grassland can be restored by irrigating to meet the water demand of the vegetation and guarantee grass production in regions of great significance for producing (Conant et al. 2001; Hou 2013).

#### Limitations and prospects

There are some limitations to our studies. First, the selection of reference sites, which largely determines the results of the RESTREND method, is still an

**Fig. 5** Temporal variation in the average temperature and total precipitation for the moist season (April–September) in the Horqin Sandy Land (1999–2009)

**Fig. 6** Temporal variation in the average temperature and total precipitation for the moist season (April–September) in the Kungl Prairie (1999–2009)



uncertainty. There is some argument over how reference sites should be selected (Hobbs and Norton 1996; Du et al. 2003), and two general approaches to selection have been presented in the literature. One approach is to select areas of primitive grassland, and the other is to select the grassland patches that are in the best condition. Following Zhuo et al. (2007), we adopted the latter approach, and the grassland reference sites were therefore selected by identifying the pixel with the maximum NDVI<sub>max</sub> value in its 5 × 5-km immediate neighborhood. This pixel was believed to be the pixel least disturbed (possibly undisturbed) by human activity. However, this method lacks an explanatory mechanism because the neighborhood size is based on knowledge from field work and data analysis.

Furthermore, the study was conducted at only one scale, which cannot comprehensively reflect the impacts of climate change and human activities on grassland degradation because the spatial and temporal scales of analysis often affect the results of a spatial analysis (Wu 2004). The spatial resolution of the remote sensing data used in our study was 1 km, which was determined primarily by the availability of SPOT-VGT NDVI images. The temporal resolution was 1 year, consistent with that of NDVI<sub>max</sub>. Such a relatively coarse temporal resolution may inevitably omit some details in the analysis, such as changes in biodiversity and community structure in the process of grassland degradation (Li et al. 2005; Zuo et al. 2009) or the intra-annual change in NDVI in degraded regions (White et al. 1997; Herrmann et al. 2005; Ding et al. 2013).

Future studies are needed to explore grassland degradation and its driving forces at multi-scales. Field experiments should be conducted to understand the

vegetation and soil characteristics of degradation intensity gradients (Zhou et al. 2008; Zuo et al. 2008, 2009; Jing et al. 2014; Zhao et al. 2014) and to evaluate the impacts of climate change and human activities (especially overgrazing) on grassland degradation (Zhang et al. 2004; Retzer 2006; Li et al. 2011). Relevant work may also provide theoretical support for scientifically selecting the reference site of degradation. Additionally, a system for monitoring grassland degradation dynamics should be constructed with the help of remote sensing, geographic information system (GIS), and global positioning system (GPS) technology. The spatial heterogeneity of driving factors of grassland degradation at different scales will be better understood by combining multi-resolution remotely sensed data (e.g., Landsat TM/ETM+, MODIS, SPOT-VGT, NOAA/AVHRR), GIS, and GPS (Hope et al. 2003; Tong et al. 2004; Zhao et al. 2012). Based on these approaches, an appropriate strategy for grassland management could be developed, making a contribution to sustainable utilization.

### Conclusions

This study investigated the spatial variation in climatic and human-induced factors driving grassland degradation in the Liao River Basin. The evaluation based on statistical and meteorological data demonstrated that the RESTREND method is an effective and reliable tool to help identify the driving factors of grassland degradation in semiarid and semihumid landscapes. Increasing grazing pressure, along with wetting and cooling climate, indicated that human activities were the major reason for grassland degradation in the Horqin Sandy

Land. Cooling and drying climate is unfavorable for the growth of grasses and has been driving grassland degradation in the Kungl prairie. Both of these results based on other data are consistent with those of the RESTREND method.

This study found that the area of the Liao River Basin with the most significant degradation trend from 1999 to 2009 was approximately 2449 km<sup>2</sup>. Most of the degraded grassland areas were located in the Kungl Prairie and Otindag Sandy Land, the upstream region of the Xilamulun River and the downstream region of the Xinkai River, and the midstream region of the Xiliao River in the Horqin Sandy Land. Climate change was found to be the sole driver of grassland degradation in an area of 1387 km<sup>2</sup>, whereas human activities were responsible for driving the degradation of 1062 km<sup>2</sup> of grassland. Furthermore, the two drivers and their strength varied greatly across space. Climate-driven degradation was found mainly in the western Kungl Prairie, while human-driven degradation was found primarily in the central basin area of the Horqin Sandy Land. Climate and human activities contributed equally to the degradation in the Otindag Sandy Land. The degraded grasslands in the arid and semiarid region were driven mainly by climate change, while those in the semihumid region were attributable to human activities. The degradation in the plains and the hilly regions was dominated by human activities, while that in the mountains and plateaus was related to climate change.

Therefore, different measures should be taken in areas with different driving factors to tackle the degradation problem effectively. Livestock fencing and determining the livestock carrying capacity based on the condition of the grass may be appropriate for restoring the grasslands in the regions with human-driven degradation, such as the Horqin area with lower altitude. For the regions of climate-driven degradation, such as the Kungl Prairie with higher altitude and drier climate, irrigation and the introduction of drought-resistant grasses that are more adaptive to the changed climate may be used to maintain the local prosperity of grasses and sustain regional socioeconomic development.

**Acknowledgments** We express our respect and gratitude to the anonymous reviewers and the handling editor for their valuable comments, which improved the quality of the paper. Our research was supported in part by the National Natural Science Foundation of China (Grant Nos. 41401095 and 41321001). It was also supported by the National Basic Research Programs of China (Grant No. 2014CB954302).

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