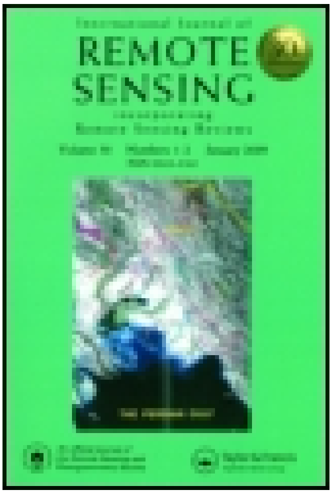

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MODIS-based vegetation growth of temperate grassland and its correlation with meteorological factors in northern China

Y.X. Jin[a], B. Xu[a]*, X.C. Yang[a], Z.H. Qin[a], Q. Wu[a], F. Zhao[a], S. Chen[a], J.Y. Li [a,b], and H.L. Ma[a]

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Vegetation dynamics, particularly vegetation growth, are often used as indicators of potential grassland degradation. Grassland vegetation growth can be monitored using remotely sensed data, which has rapid and broad coverage. Grassland ecosystems are an important component of the regional landscape. In this study, we developed an applicable method for monitoring grassland growth. The dynamic variation in the grassland was analysed using Moderate Resolution Imaging Spectroradiometer (MODIS) data. The normalized difference vegetation index (NDVI) was calculated from 2001 to 2010 during the grassland growing season. To evaluate the grassland growth, the use of the growth index (GI) was proposed. According to the GI values, five growth grades were identified: worse, slightly worse, balanced, slightly better, and better. We explored the spatial-temporal variation of grassland growth and the relationship between grassland growth and meteorological factors (i.e. precipitation and temperature factors). Our results indicated that, compared with the multi-year average, the spatial-temporal variation of grassland growth was significantly different between 2001 and 2010. The vegetation growth was worse in 2009 compared with the multi-year average. A GI of 'worse' accounted for 66.73% of the area. The vegetation growth in 2003 was the best of the years between 2001 and 2010, and a better GI accounted for 58.08% of the area in 2003. The GI from 2004 to 2008 exhibited significant fluctuations. The correlation coefficient between the GI and precipitation or temperature indicated that meteorological factors likely affected the inter-annual variations in the grassland growth. The peak of the grassland growth season was positively correlated with the spatial patterns of precipitation and negatively correlated with those of temperature. Precipitation during the growing season was the main influence in the arid and semi-arid regions. Monitoring grassland growth using remote sensing can accurately reveal the grassland growth status at the macro-scale in a timely manner. This research proposes an effective method for monitoring grassland growth and provides a reference for the sustainable development of grassland ecosystems.

1. Introduction

Grasslands are important natural resources that cover 41% of the Earth's land surface (Moore 1966). However, grasslands in arid and semi-arid regions are subjected to desertification or degradation caused by human activities and climate change. The Xilingol grassland is located in the centre of Inner Mongolia, which comprises some

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of the highest quality natural pastures in northern China. The climate of Xilingol is characterized by long, cold winters with strong winds and warm summers with low amounts of rain (Huang et al. 2004; Chen et al. 2008).

Grassland vegetation growth relates to the overall growth state and conditions of the grassland vegetation. Grassland vegetation growth is a relative concept (Yang et al. 2015) and is calculated by comparing the present grassland state with a past state, including the overall or actual state during a certain period, i.e. year, season, or month (Yang and Pei 1999). Grassland vegetation growth monitoring includes ground monitoring and remote sensing monitoring. Grassland vegetation growth monitoring using remote-sensing data, which are characterized by their rapid and broad coverage, has the potential for wide application (Jobbágy, Sala, and Paruelo 2002; Gao 2006; Zhang and Guo 2008; Yu, Luedeling, and Xu 2010; Xu et al. 2013). The remote-sensing-based monitoring of grassland ecosystem processes at large spatial scales is an effective way to obtain knowledge regarding vegetation growth where the most important components of global change take place (Li et al. 2009, 2013; Rossini et al. 2014). Furthermore, the normalized difference vegetation index (NDVI) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) is a key indicator for the monitoring of vegetation growth conditions and biomass (Tucker et al. 2001; Piao et al. 2006).

Meteorological factors have a major influence on vegetation growth. The relationships between vegetation growth and meteorological factors are important in ecology (Piao et al. 2011; Guo et al. 2012; Gao, Xu, et al. 2013). Precipitation and temperature are the key factors that control spatial gradients and variability of vegetation. In arid and semi-arid environments, precipitation is positively correlated with vegetation growth and temperature is negatively correlated with vegetation growth (Okin, Murray, and Schlesinger 2001; Fang et al. 2001; Weiss et al. 2004; Piao et al. 2007). Spatial interpolation methods are tools for studying spatial meteorological data. Currently, several models and algorithms can be used for spatial interpolation, such as the nearest neighbour, Kriging, co-Kriging, and spline methods (Goovaerts 2000). In particular, independent variables are incorporated into the interpolation process when using the thin-plate spline function method. One such variable is elevation, which influences meteorological factors (Niekerk and Joubert 2011). This method has high interpolation accuracy (Price et al. 2000; Liu et al. 2008; Hutchinson and Xu 2013).

Vegetation growth dynamics should be monitored for grassland management. The availability of remote sensing has proved very useful for observing vegetative activity at various scales. The relationships between grassland vegetation and meteorological factors have been studied and applied (Piao et al. 2006; Fan et al. 2009; Hou et al. 2014); however, only a few studies have investigated the spatial-temporal correlation between grassland vegetation growth and meteorological factors. In this study, the vegetation GI is presented. Based on the GI, growth grade statistics and analyses were conducted to monitor grassland vegetation growth. In addition, we explored trends of grassland growth and correlations with meteorological factors.

2. Materials and methods

2.1. Study area

Xilingol is located in central Inner Mongolia, which is one of China's five major pastoral areas, between 41° 35′–46° 46′ N and 111° 09′–119° 58′ E (Jin et al. 2014). Xilingol is

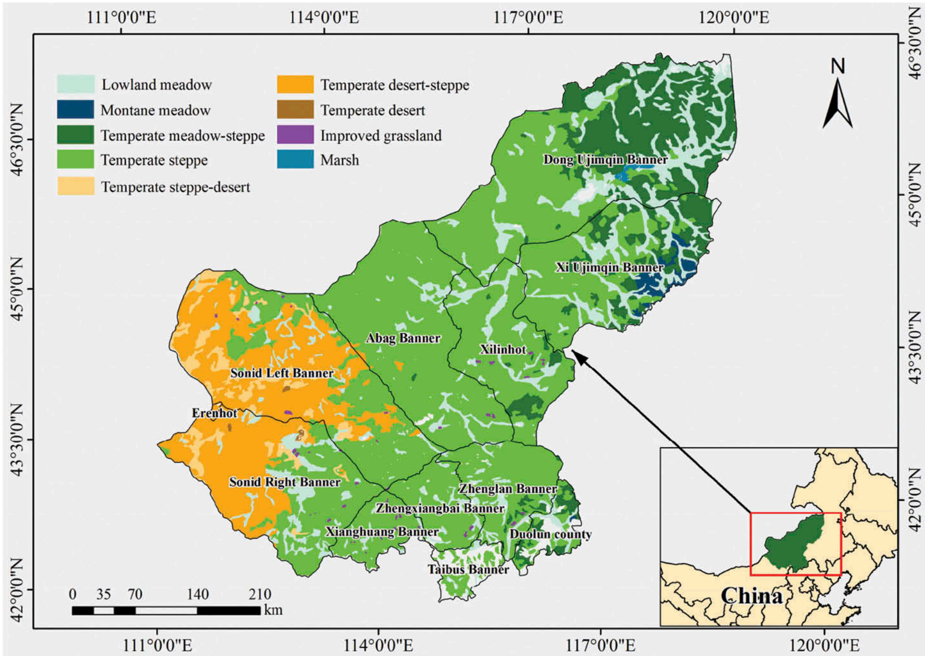

Figure 1. The study region and spatial distribution of grassland types.

dominated by natural grasslands of 192,512 km^2, accounting for 95.03% of the total area of the region. The Xilingol grassland is the material base of the livestock production and an important ecological barrier in northern China. This region has a typical temperate continental semi-arid climate. The mean annual temperature ranges from 1.3 to 4.8°C, and the mean annual precipitation is approximately 150–400 mm. The precipitation is concentrated from June to August, although the inter-annual variation in precipitation can be larger. The Xilingol grassland is dominated by temperate meadow-steppe, temperate steppe, and temperate desert-steppe (Figure 1).

2.2. *Remote-sensing data and climate data*

MODIS data have spatial and temporal advantages for grassland growth research. The MODIS data product used in this work is NDVI (MOD13Q1) with a 250 m spatial resolution and a 16 day composite from 2001 to 2010. The peak season included three periods from 28 July to 14 September. The NDVI value was calculated by selecting an Albers Equal Area Projection, converting the format and mosaicking using MODIS Reprojection Tools (MRT) software (Tang, Li, and Tang 2010). The NDVI data were developed using the maximum value composition (MVC), which can eliminate the interference caused by clouds, atmospheric aerosols, and the solar zenith angle (Holben 1986). We excluded no-grassland vegetation types by using 1:1,000,000 grassland-type vector figures (Department of Animal Husbandry and Veterinary 1996; Gao, Xu, et al. 2013). Considering that NDVI data in sparsely vegetated areas are influenced by the spectral characteristics of soil, we analysed areas with the peak season NDVI more than 0.1 (Shen et al. 2011; Gao, Yang, et al. 2013). We produced the spatial distribution of the

NDVI for the Xilingol grassland from 2001 to 2010. The maximum value composite method was defined as follows:

$$\mathrm{VI}(X, Y) = \mathrm{Max}\,[\mathrm{NDVI}(X_i, Y_i)], \tag{1}$$

where X_i and Y_i represent coordinates, i is an index that identifies the time period, and VI (X, Y) is the maximum NDVI value of the NDVI(X_i, Y_i) position in different periods.

Then, the maximum NDVI values from 2001 to 2010 were averaged to obtain the multi-year average as follows:

$$\overline{\mathrm{VI}}(X, Y) = \mathrm{Average}\left[\mathrm{VI}\left(X_j, Y_j\right)\right], \tag{2}$$

where X_j and Y_j represent coordinates, j is a year, and $\overline{\mathrm{VI}}(X, Y)$ is the average annual maximum NDVI of the VI(X_j, Y_j) position over the period studied.

The meteorological data included daily temperature and precipitation data from the National Meteorological Information Center (NMIC) from 2001 to 2010. The meteorological data were obtained from 36 climate stations distributed around the area. We calculated the average temperature and cumulative precipitation for the growing season (from May to September), the month of August, and the period of July–August. To analyse the relationships between grassland growth and meteorological factors, the ANUSPLIN spatial interpolation method, which was developed in Australia by Hutchinson (Hutchinson and Xu 2013), was used. A continuous spatial distribution of precipitation and temperature was generated. Meteorological data were calculated by spline interpolation for the three time periods with the longitude and latitude as the independent variables and digital elevation model (DEM) as covariates. From these calculations, we obtained the spatial distribution of temperature and precipitation over the period 2001–2010. The mean relative error (MRE) was used to evaluate the interpolation accuracy according to Equation (3). The MRE of the precipitation interpolation was 0.043, and the MRE of the temperature interpolation was 0.023.

$$\mathrm{MRE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{S_{\mathrm{a},i} - S_{\mathrm{c},i}}{S_{\mathrm{a},i}}\right|, \tag{3}$$

where $S_{\mathrm{a},i}$ and $S_{\mathrm{c},i}$ are the actual and calculated meteorological data at point i, respectively. N is the number of meteorological station points.

2.3. Methods

Grassland vegetation growth compares the current vegetation growth with the status of previous growth, such as the average for multiple years. We used the vegetation GI to reflect the grassland growth. The GI was calculated between the NDVI of two periods using Equation (4):

$$\mathrm{GI} = \frac{(\mathrm{NDVI_m} - \mathrm{NDVI_n})}{(\mathrm{NDVI_m} + \mathrm{NDVI_n})}, \tag{4}$$

where GI is the grassland GI for the year from 2001 to 2010, $NDVI_m$ is the NDVI for the year from 2001 to 2010, and $NDVI_n$ is the average annual NDVI between 2001 and 2010.

The GI reflected the inter-annual variations in the peak grassland growth. Vegetation growth grades were established based on the GI values. For a scientific and reasonable evaluation of vegetation growth, the GI was classified into five grades: better, slightly better, balanced, slightly worse, and worse. The values of the GI grades were confirmed after research and surveys in the field over several years (Xu et al. 2013). The 'better' class has values greater than 0.15, 'slightly better' is between 0.05 and 0.15, 'balanced' is between −0.05 and 0.05, 'slightly worse' is between −0.15 and −0.05, and 'worse' is lower than −0.15. The non-grassland areas were considered non-monitoring areas. Spatial statistics were conducted using ArcGIS software.

We selected the Pearson correlation method to analyse the correlations between the GI and precipitation and temperature using Equation (5). A greater absolute value of the correlation coefficient has a stronger correlation; thus, when the correlation coefficient is closer to 1 or −1, there is a strong correlation. When the correlation coefficient is closer to 0, there is a weak correlation. The correlation coefficient, r, is given by

$$r = \frac{N\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{N\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{N\sum y_i^2 - \left(\sum y_i\right)^2}}, \tag{5}$$

where x_i is the GI for year i, y_i is the temperature or precipitation for year i, i is the year from 2001 to 2010, and N is the total number of attributes.

3. Results

3.1. Grassland vegetation growth compared with the multi-year average

To compare the vegetation growth from 2001 to 2010 with the multi-year average, GIs in different periods were obtained during the peak seasons (Table 1). The vegetation growth

Table 1. Percentages of the grassland area that had different growth index categories, including worse, slightly worse, balanced, slightly better, and better, between each year and the multi-year average.

	Percentage of grassland area (%)				
Period	Worse	Slightly worse	Balanced	Slightly better	Better
2001	33.24	29.62	29.81	7.06	0.27
2002	5.51	17.22	41.56	30.51	5.2
2003	0.53	4.39	37.00	46.64	11.44
2004	4.66	14.41	41.25	37.17	2.51
2005	16.01	22.64	38.23	21.25	1.87
2006	3.03	9.97	37.66	39.32	10.02
2007	16.89	23.54	30.46	21.62	7.49
2008	0.52	5.16	37.42	46.73	10.17
2009	27.16	39.57	28.99	3.78	0.5
2010	14.86	39.28	36.84	8.59	0.43
Average	12.24	20.58	35.92	26.27	4.99

in 2001 was slightly worse to worse compared with the multi-year average. GI grades of better, slightly better, balanced, slightly worse, and worse accounted for 0.27%, 7.06%, 29.81%, 29.62%, and 33.24%, respectively, of the area. The vegetation growth in 2002 was balanced with the multi-year average. The balanced grade accounted for 41.56% of the total area. The vegetation growth in 2003 was the best of all years compared with the multi-year average. GI grades of better, slightly better, balanced, slightly worse, and worse accounted for 11.44%, 46.64%, 37.00%, 4.39%, and 0.53%, respectively, of the area. The GI from 2004 to 2008 exhibited significant fluctuations. The vegetation growth during 2004, 2006, and 2008 was slightly better to better. In particular, the GI in 2008 was similar to that in 2003. GI grades from slightly better to better in 2008 accounted for 56.90% of the area. However, the vegetation growth in 2009 and 2010 was worse. GI grades from slightly worse to worse in 2009 and 2010 accounted for 66.73% and 54.14%, respectively, of the area.

According to the grassland GI grades from 2001 to 2010, the spatial distribution presented significant differences (Figure 2). Grassland vegetation growth was overall worse in 2001, with worse growth in the central and western regions and better growth in the northeastern region. In 2002, the vegetation growth was worse in the central region and better in the north. The vegetation growth in 2003 was overall better, with worse growth in the central region. The vegetation growth in 2004 was worse in the northwestern region and better in the southern and eastern regions. The vegetation growth in 2005 was worse in the western region and better in the central region. The vegetation growth in 2006 was better in the western region and worse in the northeastern region. In 2007, the vegetation growth significantly differed by region, with worse growth in the northeastern region and better growth in the western region. In 2008, the overall vegetation growth was better, particularly in the central region. The grassland vegetation growth in 2009 and 2010 was worse overall; it was relatively better in the central region in 2010, whereas the growth for most of the other regions was worse.

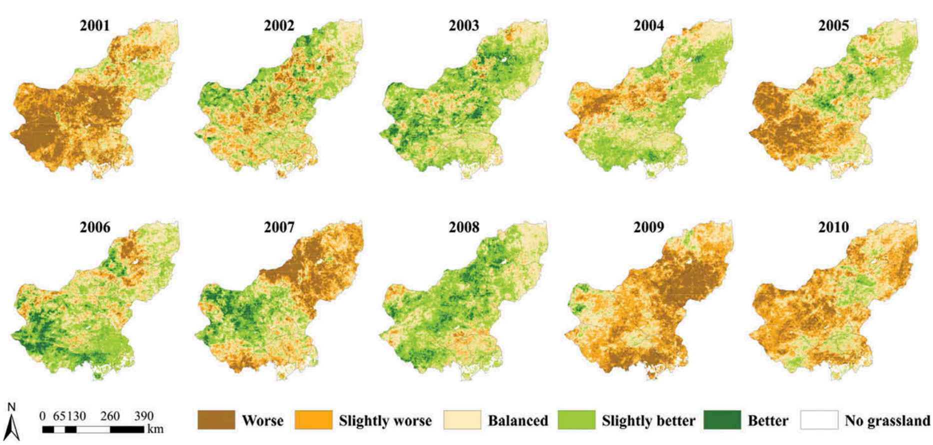

Figure 2. Spatial distribution of Xilingol grassland growth from 2001 to 2010 compared with the multi-year average.

3.2. The relationship between grassland vegetation growth and precipitation

According to the Pearson correlation analysis (Figure 3a–c, Table 2), there was mainly a positive correlation between vegetation growth and precipitation. Vegetation growth and growing-season precipitation were significantly positively correlated, in which the positive correlation area accounted for approximately 96.39% of the area. A negative correlation occurred in the central area (only 3.37%). A positive correlation occurred between vegetation growth and precipitation in August in the central and western regions, and a negative correlation occurred in some parts of the northeast. A high correlation occurred in the southwestern desert grassland. The area with a positive correlation (74.08%) was larger than the area with

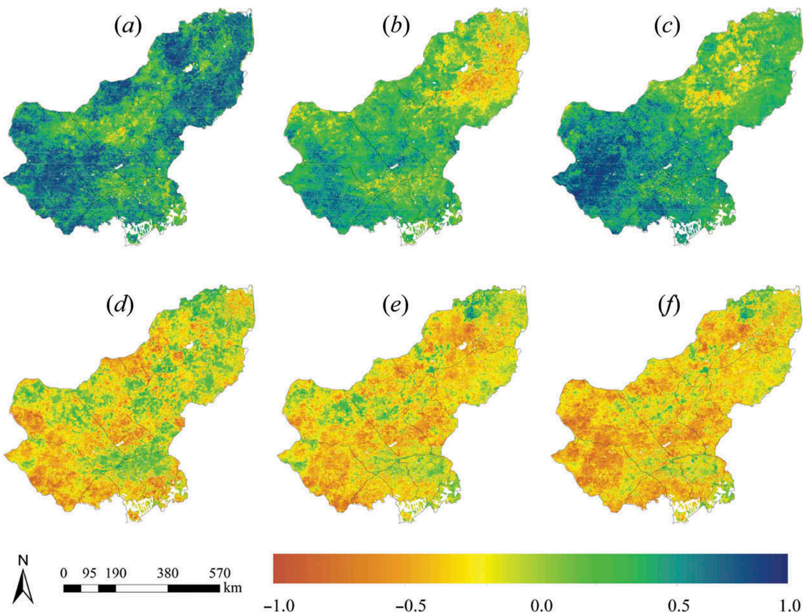

Figure 3. Values of the correlation coefficient (r) between the GI and precipitation (*a*–*c*) and between the GI and temperature (*d*–*f*) from 2001 to 2010. (*a*): Precipitation in the growing season; (*b*): precipitation in August; (*c*): precipitation during July–August; (*d*): temperature in the growing season; (*e*): temperature in August; and (*f*): temperature during July–August.

Table 2. Percentages of the grassland area that had different values of the correlation coefficient between GI and meteorological factors.

	Precipitation			Temperature		
	Growing season	August	July–August	Growing season	August	July–August
$r > 0$	96.39	74.08	90.25	17.96	10.81	6.01
$r = 0$	0.24	0.35	0.28	0.38	0.32	0.26
$r < 0$	3.37	25.57	9.47	81.66	88.87	93.73

a negative correlation (25.57%). Vegetation growth was more closely correlated with precipitation during the July–August period than in July, and there was a greater positive correlation between vegetation growth and precipitation during the July–August period in the western region. Some areas in the northeastern region showed a negative correlation, but the correlation was not significant. Overall, the correlation was the highest between vegetation growth and growing-season precipitation, followed by the correlation between vegetation growth and precipitation during July–August. Vegetation growth and precipitation during July–August showed a significant positive correlation in the western desert grassland. A significant positive correlation occurred between vegetation growth and growing-season precipitation or July–August precipitation in the central temperate grassland; a significant positive correlation occurred between vegetation growth and growing-season precipitation in the eastern meadow grassland.

3.3. The relationship between grassland vegetation growth and temperature

According to the Pearson correlation analysis (Figure 3e–f, Table 2), there was mainly a negative correlation between vegetation growth and temperature. The vegetation growth and growing-season temperature had some correlation. A negative correlation occurred in the western region, whereas some positive correlation occurred in the eastern region. The negative correlation accounted for 81.66% of the area, whereas the positive correlation accounted for 17.96% of the area. The vegetation growth and temperature in August and temperature during July–August showed a significant negative correlation. The correlation between vegetation growth and temperature in the western desert grassland was higher than that of other regions. In some areas of the northeast, the correlation between vegetation growth and temperature was positive. Negative correlations between vegetation growth and temperature in August or the July–August temperature accounted for 88.87% and 93.73%, respectively, of the area. Overall, the correlation between vegetation growth and temperature during July–August was the highest, whereas the correlation between vegetation growth and growing-season temperature was weak.

3.4. Grassland vegetation growth with precipitation and temperature in different grassland types

According to the correlation analysis between vegetation growth in different grassland types and precipitation (Table 3), the highest correlation occurred between the growing-season precipitation in the meadow steppe and temperate desert-steppe. The average value of *r* was above 0.5. The correlation between vegetation growth and growing-season precipitation in the temperate desert-steppe was the highest, with the average value of *r* of 0.63 and a standard deviation (STD) of 0.17. Vegetation growth with precipitation in August had a weak positive correlation in the improved grassland, temperate desert-steppe, and temperate desert. Vegetation growth and precipitation during July–August in the desert steppe regions, including temperate steppe-desert, temperate desert-steppe, and temperate desert, showed a significant positive correlation, with the average value of *r* of 0.73 and an STD of 0.18 in the temperate desert.

According to the correlation analysis, a negative correlation occurred between vegetation growth and temperature in different grassland types (Table 4). The correlation with temperature during July–August was higher, and the correlation was the highest in the

Table 3. Statistics for the correlation between the GI and precipitation in different grassland types.

	Growing season		August		July-August	
Grassland type	Mean	STD	Mean	STD	Mean	STD
Lowland meadow	0.48	0.23	0.10	0.36	0.35	0.29
Improved grassland	0.52	0.18	0.45	0.18	0.59	0.20
Montane meadow	0.61	0.15	0.00	0.22	0.42	0.14
Temperate meadow-steppe	0.52	0.22	−0.10	0.30	0.24	0.24
Temperate steppe-desert	0.55	0.18	0.35	0.25	0.62	0.23
Temperate steppe	0.44	0.24	0.24	0.28	0.41	0.28
Temperate desert-steppe	0.55	0.19	0.42	0.24	0.71	0.18
Temperate desert	0.63	0.17	0.43	0.19	0.73	0.18
Marsh	0.35	0.23	−0.10	0.29	0.15	0.30

Table 4. Statistics for the correlation between the GI and temperature in different grassland types.

	Growing season		August		July-August	
Grassland type	Mean	STD	Mean	STD	Mean	STD
Lowland meadow	−0.21	0.27	−0.28	0.24	−0.33	0.23
Improved grassland	−0.35	0.24	−0.38	0.18	−0.47	0.19
Montane meadow	−0.23	0.23	−0.15	0.16	−0.22	0.17
Temperate meadow-steppe	−0.17	0.27	−0.22	0.27	−0.28	0.26
Temperate steppe-desert	−0.37	0.22	−0.32	0.20	−0.51	0.18
Temperate steppe	−0.25	0.26	−0.31	0.23	−0.37	0.22
Temperate desert-steppe	−0.32	0.24	−0.29	0.23	−0.47	0.19
Temperate desert	−0.34	0.19	−0.35	0.17	−0.50	0.17
Marsh	−0.16	0.24	−0.31	0.29	−0.31	0.28

temperate steppe-desert, with the value of r of −0.51 and an STD of 0.18. A strong negative correlation occurred between the growing-season temperature in the temperate steppe-desert and temperate desert, with the values of r of −0.37 and −0.34, respectively. Vegetation growth in the temperate steppe-desert and temperate desert also showed a strong negative correlation with temperature in August, for which the values of r were −0.32 and −0.35, respectively. Furthermore, a significant negative correlation occurred in the improved grassland. However, the vegetation growth in the improved grassland had large inter-annual variations due to human activities.

4. Discussion

We monitored and analysed grassland vegetation growth during the peak of the growing season between 2001 and 2010 in the Xilingol grassland. There were significant differences in the annual vegetation growth. The grades of vegetation growth from 2002 to 2008 were principally balanced or better than previous growth. ‘Better’ grades in 2003 and 2008 accounted for more than 55% of the area. The grassland vegetation growth during 2001, 2009, and 2010 was worse (66.73% of the area in 2009). Previous studies have indicated that grassland vegetation has a positive correlation with precipitation (Sala et al. 1988; Bai et al. 2000; Ni 2004). Our study also showed that vegetation growth increased as precipitation increased from 2001 to 2010 in most areas. We also found that vegetation growth mainly had a negative correlation with temperature. To analyse the period during which meteorological factors had the greatest impact on vegetation growth, we selected the vegetation growing season and August of the peak season to calculate the Pearson correlation. Because northern China is strongly influenced by the East Asian summer monsoon, most of the annual precipitation is concentrated in the summer, particularly in July (Zhang et al. 2014). July–August is the critical period for vegetation growth. We also selected meteorological data from July to August for the calculation. When the value of r was greater than 0.5, a significant positive correlation between vegetation growth and growing-season precipitation accounted for 52.47% of the total area. A significant positive correlation between vegetation growth and precipitation during July–August accounted for 46.24% of the area. A significant positive correlation between vegetation growth and precipitation in August accounted for 20.12% of the area. These results indicated that growing-season precipitation had the greatest impact on the variation in the vegetation growth. When the value of r was less than −0.5, the percentages of area of the significant negative correlation between vegetation growth and growing-season temperature, the temperature in August, and the temperature during July–August accounted for 18.69%, 18.76%, and 29.54%, respectively. Temperature during July–August had the greatest impact on vegetation growth. However, precipitation played a much more important role than temperature in vegetation growth. This research clearly shows that precipitation in the growing season is generally the main factor that influences the peak of grassland vegetation growth in arid and semi-arid regions.

The relationships between vegetation growth and meteorological factors also show differences in a variety of grassland types. The correlation between vegetation growth and precipitation or temperature was low in the meadow steppe, whereas the correlation was high in the desert steppe. Vegetation in the desert steppe is more sensitive to climate change. The dominant plant species of the desert steppe region were *Stipa klemenzii* Roshev. and *Caragana korshinskii* Lam. (Jin et al. 2014). Plant photosynthesis is further controlled by temperature under desert steppe conditions. High temperatures result in a reduced photosynthetic rate (Xu and Zhou 2005). Furthermore, higher temperatures enhance evaporation and reduce vegetation growth. Our findings reflect the trend of greater inter-annual variation in desert steppe communities. The trends of a positive correlation with precipitation and negative correlation with temperature were reflected in the values for grassland types in relation to their aridity. These trends conformed to the classic xeromorphic adaptations of plants with abundant mechanical tissue.

5. Conclusions

The measurements of grassland vegetation growth provide an essential baseline for the long-term grassland management of a region. This study applied the grassland vegetation GI to monitor grassland vegetation growth between 2001 and 2010 using remote sensing. The results revealed the relationships between vegetation growth and meteorological factors on inter-annual variations in temperate grassland. The following conclusions were derived from the results:

(1) Overall, grassland growth was slightly worse to worse in 2001, 2009, and 2010 compared with the multi-year average. A GI grade of 'worse' during these years accounted for 33.24%, 27.16%, and 14.86%, respectively, of the total area. The vegetation growth was the best in 2003 compared with multi-year average between 2001 and 2010. A GI grade of slightly better to better accounted for 58.08% of the area. The GI from 2004 to 2008 exhibited significant fluctuations. The GI in 2008 was similar to that in 2003. In summary, the spatial-temporal trends of grassland growth showed significant variations between 2001 and 2010.

(2) According to the correlation analysis of meteorological factors between 2001 and 2010, the inter-annual variations in grassland vegetation growth were mainly explained by changes in precipitation and temperature. Grassland growth had a positive correlation with precipitation and a negative correlation with temperature on the spatial patterns. Precipitation was one of the main influences in the arid and semi-arid regions. The correlation coefficients of the GI, from high to low, with precipitation in the growing season were greater than those with precipitation during July–August, followed by precipitation in August. The correlation between the GI and meteorological factors in different grassland types presented obvious differences. The correlation in the desert steppe was the highest, and the correlation in the meadow steppe was the lowest.

The application of remote sensing to monitor grassland vegetation growth revealed the large-scale vegetation growth status of an arid and semi-arid grassland. The results also suggest that vegetation growth is influenced by climate change. This study demonstrates that remote sensing is an effective approach for monitoring grassland growth, and it provides a framework for research in other regions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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