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MODIS-based remote-sensing monitoring of the spatiotemporal patterns of China's grassland vegetation growth

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China has abundant grassland resources (approximately 400 million ha of natural grasslands), which account for 41.7% of China's total area. Grasslands are an important base for boosting the development of China's livestock husbandry economy and maintaining China's ecological security. Using Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed data, this study developed a grassland vegetation growth index that ranked the magnitude of grassland vegetation growth indices across a wide variety of field experiments. This study applied the grassland vegetation growth index to conduct remote-sensing monitoring of the spatiotemporal status of China's grassland vegetation growth in 2008. We found that the vegetation growth of China's grassland was classified as 'good' in 2008. The areas of grassland with desirable vegetation growth accounted for 38.47% of China's monitored grassland areas, and the areas with less desirable vegetation growth accounted for 22.85%. Additionally, the good vegetation growth was stable within each 10 day study period in 2008. The vegetation growth reached a balance in early June. After early September, the proportion of grasslands with desirable vegetation growth declined, and the proportion of grasslands with balanced and less desirable growth increased. The regions with less desirable vegetation growth mainly included the middle and eastern regions of Inner Mongolia, the northern region of Xinjiang, and most parts of Heilongjiang. The regions with desirable vegetation growth were mainly distributed in the north of Tibet, the southwest of Qinghai, the west of Inner Mongolia, Gansu, Ningxia, Shanxi, and the northwest of Liaoning. The remote-sensing monitoring of the spatiotemporal patterns of China's grassland vegetation growth in the present study revealed the overall vegetation growth status of China's grassland on a broad scale. These findings could provide a helpful scientific basis for understanding China's grassland vegetation conditions and the management and regulation of grassland livestock husbandry.

1. Introduction

China has approximately 400 million ha of various natural grasslands, which account for 41.7% of China's total land area (DAHV and GSAHV 1996). Grassland is an important

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base for boosting the development of China's livestock husbandry economy and maintaining China's ecological balance (Fang et al. 2010; Fan et al. 2008; Zha et al. 2003; Scurlock et al. 1998; Ni 2002). Understanding the status of grassland vegetation growth is important for managing and regulating grassland livestock husbandry in real time (Robert et al. 2006; Xu et al. 2005; Xie et al. 2001; Edwards et al. 1999). Comparisons are often made between the current and previous states of grassland vegetation. The previous state of vegetation may be the average of a certain period (e.g. a year, a quarter, a month, or a 10 day period) or the actual status in the past. Ground monitoring and remote-sensing monitoring are the two primary ways to monitor grassland vegetation growth (Wang et al. 2009; Xu et al. 2006a, 2006b). Ground monitoring is used to determine the vegetation growth indices for sample plots or areas, and these indices are compared with previous results to illustrate the current status of grassland vegetation growth. It is one of the important methods for directly reflecting grassland vegetation growth using the close relationship between Moderate Resolution Imaging Spectroradiometer (MODIS) data and the status of grassland vegetation (Huang et al. 2009; Chen et al. 2009; Reeves et al. 2006). Remote-sensing information from different periods can then be processed and compared (Ikeda, Okamoto, and Fukuhara 1999; Piao et al. 2006; Liu and Yang 2001). Grassland vegetation growth monitoring using remotely sensed data, which is characterized by its rapid and broad coverage, has the potential for wide application (Piao et al. 2007; Yu, Luedeling, and Xu 2010; Ma et al. 2010; Xu et al. 2008; Wang 1996; Yang and Pei 1999). Furthermore, Grassland vegetation growth monitoring using remotely sensed data can provide administrative authorities with a scientific basis for administration and decision-making.

2. Materials and methods

Downloading MOD02QKM and MOD03 data with spatial resolutions of 250 m and 1 km, respectively, we used MODIS data from May 2003 to September 2008. First of all, we used the MODIS Swath tool to conduct the precise geometric correction of 1B data of high-definition format provided in the NASA website. The MOD03 is an indispensable data source for the geometric correction of MOD02QKM. Then, after geometric correction, we used ENVI software to convert the digital number values of MODIS data to reflectivity values. Eventually, we conducted the normalized difference vegetation index (NDVI) calculation in ENVI software in accordance with Equation (1). This also allowed for the generation of the maximum value composite of each 10 day period and the establishment of a MODIS-based, 10 day period NDVI database for each year. Next, we developed a grassland vegetation growth index model and a remote-sensing grassland vegetation growth monitoring system. The NDVI values from each 10 day period from 2003 to 2008 were used to calculate and obtain the spatial distribution map of China's grassland vegetation growth. Based on the grassland vegetation growth index model, the statistics and analyses of growth grade were conducted to accomplish the remote-sensing monitoring of spatiotemporal patterns of China's grassland vegetation growth. The detailed calculation processes are described below.

2.1. Calculation of vegetation indices

A vegetation index is often calculated by using the reflectance spectrum characteristics of green vegetation in different wavebands. In the present study, we used the NDVI, which is given by the following equation:

$$\mathrm{NDVI} = (B_2 - B_1)/(B_2 + B_1), \tag{1}$$

where B_1 refers to the MODIS reflectance in the first waveband (red waveband), and B_2 refers to the MODIS reflectance in the second waveband (near infrared waveband).

Generally, bigger NDVI values represent more dense vegetation growth, and smaller NDVI values suggest more sparse vegetation growth. When the NDVI value is less than 0.1, the area is usually bare land. When the NDVI value exceeds 0.8, the area has very dense vegetation.

The 10 day maximum value composite method can mitigate the impact of damping factors such as sun angle, water vapour, aerosol, observation angle and clouds on the vegetation index. The maximum value composite method is defined by the following equation:

$$\mathrm{VI}(X, Y) = \mathrm{Max}[\mathrm{NDVI}(X,Y)], \tag{2}$$

where X and Y represent coordinates and $\mathrm{VI}(X,Y)$ is the maximum of NDVI value of the (X,Y) position for different time periods during the composite period. In this study, the time series of the values of 10 day maximum value composites of the NDVI were used to build the database.

The maximum of NDVI values of each 10 day period from May to September of each year from 2003 to 2007 were averaged to obtain the multiyear average value for each 10 day period:

$$\overline{\mathrm{VI}}(X,Y) = \mathrm{Average}[\mathrm{NDVI}(X_i, Y_i)]\ i = 2003, 2004, \ldots, 2007, \tag{3}$$

where $\overline{\mathrm{VI}}(X,Y)$ is the average maximum NDVI value at the $(X_\mathrm{i},Y_\mathrm{i})$ position for different time periods during the composite period. The same 10 day period across five years was considered to be the composite period (e.g. 'early May' includes the NDVI values from early May of each year from 2003 to 2007). This process allowed for the establishment of the standard 10 day average of NDVI value time-series database for 2003–2007.

2.2. *Classification of grassland vegetation growth*

After calculating the NDVI values, a comparison was made between the NDVI vegetation index charts of two periods to reflect the grassland vegetation growth. The following vegetation growth index model was built, and classifications were established based on the magnitude of corresponding index values from the equation:

$$\mathrm{GI} = (\mathrm{NDVI}_m - \mathrm{NDVI}_n)/(\mathrm{NDVI}_m + \mathrm{NDVI}_n), \tag{4}$$

where GI is the grassland growth index and NDVI_m and NDVI_n represent the vegetation index values at times 'm' and 'n', respectively. The NDVI value of each 10 day period, month or growing season from May to September of 2008 was considered to be NDVI_m. The average NDVI value from May to September 2003–2007 was considered to be NDVI_n.

To make a scientific and reasonable evaluation of nationwide grassland vegetation growth, the grassland vegetation growth of effectively monitored areas was classified into five grades (excellent, good, balanced, poor, and very poor) based on the magnitude of the GI values. Values lower than −0.15 are considered to be 'very poor', poor is between –0.15 and –0.05, balanced is greater than –0.05 and less than 0.05, good is between 0.05 and 0.15, and excellent is greater than 0.15. The areas with remotely sensed data quality problems or cloud interference, as well as the non-grassland areas, were considered to have no data, and this was the sixth grade. A thematic map was developed with different colours representing 1–6, and the six grades from 1 to 6 differently represented very poor, poor, balanced, good, excellent and no data. Spatial statistics were conducted across different grades using GIS software's spatial analysis function.

2.3. Statistics and analyses of image data

To obtain a spatial distribution map of grassland vegetation growth at different time scales, statistics were conducted using GIS software. The grassland vegetation growth statistics were conducted using provincial administration units for each 10 day period, month and growing season from May to September. This allowed for the generation of a dynamic change diagram of nationwide and provincial grassland vegetation growth status and an analysis of the dynamic spatiotemporal changes of China's grassland vegetation growth.

3. Results

3.1. China's grassland vegetation growth in 2008

Compared with the average status of the same period across multiple years, the nationwide grassland vegetation growth of China was good from May to September of 2008. The areas where the vegetation growth was excellent, good, balanced, poor, and very poor from early May to mid-September accounted for 9.97%, 28.50%, 38.68%, 14.69%, and 8.16% of China's total grassland area, respectively. Indeed, the grassland areas with good vegetation growth accounted for approximately 38.47% of the monitored grassland area throughout China, whereas the areas with poor vegetation growth accounted for 22.85%. Thus, 2008 was a satisfactory year (Figure 1).

3.2. China's steady grassland vegetation growth in 10 day periods of 2008

The grassland vegetation growth status of each 10 day period between May 2008 and September 2008 is shown in Figure 2 and Table 1. Compared with the multiyear average,

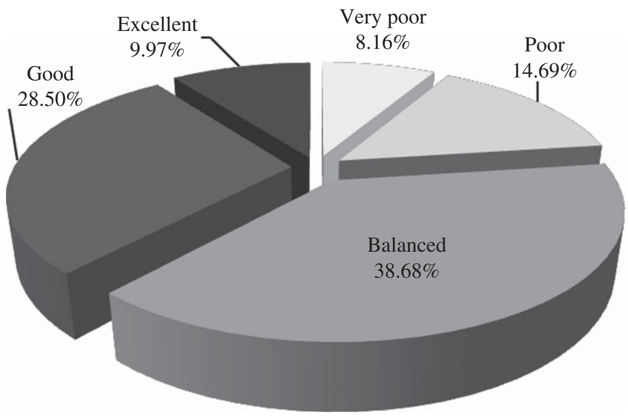

Figure 1. Grassland vegetation growth in 2008. The categorization is based on the calculated values of the growth index.

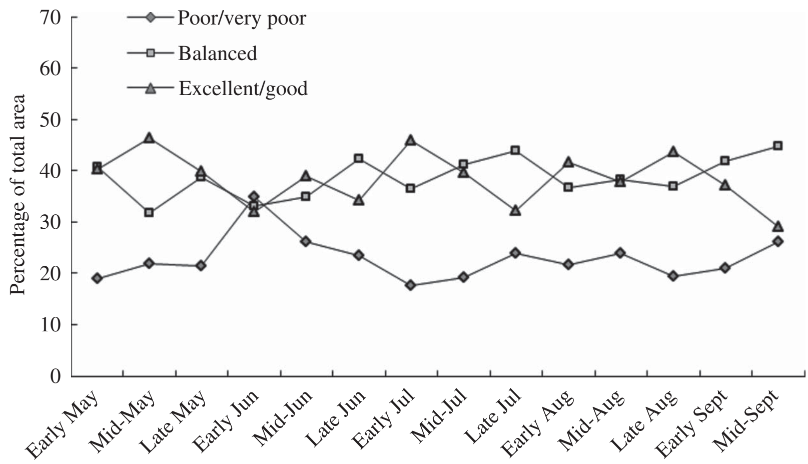

Figure 2. China's grassland vegetation growth in 2008, categorized according to the growth index value for each 10 day time period.

China had good grassland vegetation growth in each 10 day period of the growing season throughout 2008. Furthermore, each 10 day period experienced steady growth. Although the vegetation growth was near homeostasis in early June, around early September the proportion of areas with good growth declined, and the proportion of areas with balanced and poor growth increased.

On average, 38.68% of China's grassland had balanced grassland vegetation growth over all of the 10 day periods in 2008. The values for individual 10 day periods varied between 32% and 45%. The area of grassland with good growth averaged 28.5%, and this area ranged from 24% to 33% over the different 10 day periods. The grassland area

Table 1. Percentage of China's total grassland area that fell into different growth categories for each 10 day period from May 2008 to September 2008.

	Percentage of total grassland area (%)				
Time period	Very poor	Poor	Balanced	Good	Excellent
Early May	6.56	12.35	40.84	32.32	7.93
Mid-May	9.63	12.34	31.75	33.07	13.21
Late May	7.88	13.67	38.62	31.25	8.57
Early June	14.32	20.63	33.03	20.10	11.93
Mid-June	10.17	16.08	34.81	26.78	12.15
Late June	7.38	15.98	42.39	26.44	7.80
Early July	5.31	12.40	36.41	30.95	14.93
Mid-July	6.57	12.74	41.09	29.62	9.98
Late July	7.54	16.27	43.93	24.16	8.10
Early August	8.49	13.27	36.69	32.55	9.01
Mid-August	9.97	13.92	38.31	29.37	8.43
Late August	6.41	13.09	36.85	29.20	14.45
Early September	6.65	14.26	41.92	29.06	8.10
Mid-September	7.36	18.73	44.78	24.17	4.96
Average	8.16	14.69	38.67	28.50	9.97

Note: The categorization is based on calculations of the growth index value for each period.

with good growth in early June only showed a change of 20.10%, which was the lowest in good growth from May to September of 2008. The proportion of areas with excellent growth averaged 10% and ranged from 5% to 15%. The area of Chinese grassland with poor growth accounted for about 14.69% of the total on average, and this ranged from 12% to 18% over the different 10 day periods. The grassland area with poor growth in early June showed a 20.63% change, which was the highest in poor growth from May to September of the year 2008. The grassland with very poor growth accounted for about 8.16% of the total grassland, and the values for the 10 day periods ranged from 5% to 10%. The grassland area with very poor growth in early June showed a 14.32% change, which was the highest in very poor growth from May to September of 2008. In general, China had good grassland vegetation growth during the 2008 growing season, and the growth was near balance in early June.

3.3. *Spatial patterns of China's grassland vegetation growth*

In 2008, the areas with poor and very poor grassland vegetation growth in China mainly included middle and east Inner Mongolia, north Xinjiang, and most parts of Heilongjiang (Figure 3). The areas with good vegetation growth were mainly distributed in north Tibet, southwest Qinghai, west Inner Mongolia, Gansu, Ningxia, Shanxi, and northwest Liaoning (Figure 3).

3.4. *Dynamic changes in the spatial patterns of China's grassland vegetation growth*

The remote-sensing monitoring results of all 10 day periods from early May to mid-May 2008 show that the areas with good vegetation growth extended further south and the areas

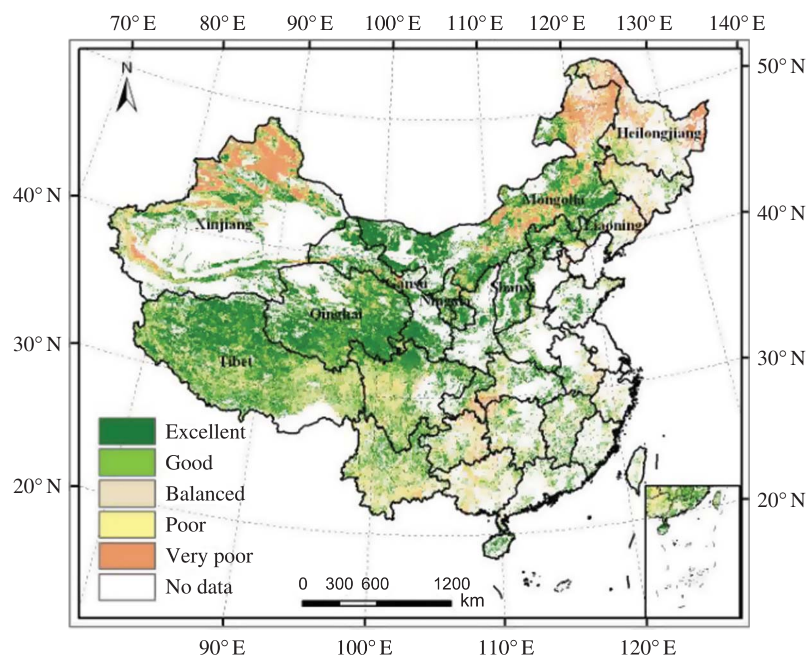

Figure 3. Spatial distribution map of the different categories of China's grassland vegetation growth in 2008.

with balanced growth decreased. In late May, the areas with balanced growth increased, and the grassland area with good vegetation growth decreased. From early June to mid-June, the grassland area with good vegetation growth continuously expanded, but the areas with balanced growth increased in late June. The areas with good vegetation growth became concentrated in middle and east Inner Mongolia, north Shanxi, east Guizhou and east Yunnan. The areas with poor vegetation growth were distributed in middle and west Heilongjiang, east Qinghai, and north Xinjiang.

In early July 2008, the nationwide grassland growth was better than the multiyear average. In middle and late July, the areas with good vegetation growth decreased, and the areas with poor growth increased. In late July, the grassland vegetation growth in west Hulunbeier in Inner Mongolia, north Xilinguole in Inner Mongolia, Tibet, west Sichuan, and most parts of Guangxi was better than the multiyear average, whereas the grassland growth in southeast Inner Mongolia, Xinjiang, Qinghai, and Middle China was worse than the multiyear average.

In early August 2008, China's grassland vegetation growth was better than the multiyear average. In mid-August, the areas with good vegetation growth decreased, and the areas with poor growth increased. In late August, the areas with good growth significantly increased, and the areas with poor growth decreased. Although the vegetation growth in middle and west Inner Mongolia, north Yunnan, and northwest and south Tibet was better than the multiyear average, the grassland growth in areas such as north Xinjiang and northeast Inner Mongolia was lower than the multiyear average.

In early September 2008, China's grassland vegetation growth was slightly better than the multiyear average. In mid-September, the grassland area with balanced growth increased, and the area with good growth decreased.

3.5. Monitoring the results of grassland vegetation growth in key provinces and municipalities

Inner Mongolia, Tibet, Xinjiang, Gansu, Qinghai, and Sichuan are the important pastoral areas of China. The change in grassland vegetation growth in these key provinces and municipalities reflected the dynamic change of nationwide grassland vegetation growth.

3.5.1. Inner Mongolia

In Inner Mongolia, the general vegetation growth was better than the multiyear average. Compared with the average status of the same period from 2003 to 2007, the areas with excellent, good, balanced, poor, and very poor vegetation growth in Inner Mongolia accounted for 10.22%, 32.36%, 37.68%, 14.08%, and 5.66% of the region's total grassland area, respectively, in 2008. Therefore, from May to September of the year 2008, the general grassland vegetation growth in Inner Mongolia was better than the multiyear average. The monthly dynamic data (Table 2) show that the grassland vegetation growth of Inner Mongolia in May was higher than the multiyear average, the status in June was almost the same as the multiyear average, and the proportion of grassland with poor growth was larger than the area with good growth. During July to September, the vegetation growth was also better than the multiyear average. The dynamic data of the 10 day periods (Table 3) show that the grassland vegetation growth of Inner Mongolia during early May to late May 2008 was better than the multiyear average. Although early June had poor vegetation growth, middle and late June had balanced growth. The growth status from early July to mid-September was better than the multiyear average.

Table 2. Monthly dynamic data of Inner Mongolia's grassland vegetation growth in 2008.

	Percentage of grassland area (%)					
Time	Very poor	Poor	Balanced	Good	Excellent	Monitored area
Average for May	7.78	9.41	31.59	40.29	10.93	85.78
Average for June	9.57	24.06	40.74	19.91	5.73	96.17
Average for July	4.96	14.99	38.87	27.09	14.07	97.19
Average for August	2.96	10.81	38.25	37.79	10.20	98.94
Average for September	1.71	9.67	39.57	38.90	10.14	99.24

Note: The categorization is based on the value of the growth index for each month.

Table 3. Data for each 10 day period categorizing Inner Mongolia's grassland vegetation growth in 2008.

	Percentage of total grassland area (%)					
Time	Very poor	Poor	Balanced	Good	Excellent	Monitored area
Early May	1.31	3.67	31.96	49.87	13.19	64.90
Mid-May	14.65	11.27	24.99	35.35	13.74	94.44
Late May	7.39	13.28	37.82	35.64	5.87	97.99
Early June	11.19	29.88	40.56	14.63	3.74	96.90
Mid-June	9.71	21.20	38.82	24.67	5.61	98.94
Late June	7.80	21.09	42.83	20.43	7.85	92.67
Early July	5.72	17.44	37.96	23.31	15.56	95.01
Mid-July	3.15	9.97	36.16	35.66	15.05	97.86
Late July	6.01	17.57	42.50	22.31	11.60	98.69
Early August	4.80	11.00	37.04	38.18	8.97	99.73
Mid-August	1.12	8.86	42.39	38.20	9.42	99.92
Late August	2.96	12.55	35.30	36.97	12.21	97.16
Early September	1.97	10.70	41.06	36.60	9.68	98.72
Mid-September	1.45	8.65	38.09	41.21	10.61	99.76
Average	5.66	14.08	37.68	32.36	10.22	95.19

3.5.2. Tibet

The general grassland vegetation growth in Tibet was better than the multiyear average. Compared with the average status of the same period in previous years, the areas with excellent, good, balanced, poor, and very poor vegetation growth in Tibet accounted for 13.38%, 30.06%, 35.86%, 11.41%, and 9.29% of the region's total grassland area, respectively, in 2008. The areas with good growth accounted for 43.44% of the region's total grassland area, and the areas with poor growth accounted for 20.70%. The general grassland vegetation growth of Tibet in 2008 was better than the multiyear average. The monthly dynamic data show that the grassland growth status remained balanced in May. From June to September, the grassland vegetation growth throughout the region was better than the multiyear average. The dynamic data of the 10 day periods showed that the grassland vegetation growth of Tibet during May remained the same as the multiyear average. Although the growth status in early June was lower than the multiyear average, the growth status from mid-June to mid-September was higher than the multiyear average.

3.5.3. Xinjiang

The general vegetation growth in Xinjiang was lower than the multiyear average. Compared with the average status of the same period in previous years, the areas with excellent, good, balanced, poor, and very poor vegetation growth in Xinjiang accounted for 7.31%, 19.26%, 37.20%, 25.36%, and 10.87% of the region's total grassland area, respectively, in 2008. From May to September, the general grassland vegetation growth of Xinjiang was lower than the multiyear average. Although the general grassland vegetation growth of Xinjiang from May to September was slightly lower than the multiyear average, the area with growth remaining balanced occupied a large proportion of grassland. The dynamic data of the 10 day periods show that the grassland vegetation growth of Xinjiang from early May to late September was relatively stable, and the percentage of areas with balanced growth remained between 32% and 43%. With time, fluctuations occurred within the grassland vegetation growth status, but the general growth was lower than the multiyear average.

3.5.4. Gansu

The general vegetation growth in Gansu was good, and there were significant changes between different 10 day periods in the east area. From May 2008 to September 2008, the areas with excellent, good, balanced, poor, and very poor vegetation growth in Gansu accounted for 10.52%, 32.97%, 44.04%, 10.12%, and 2.35% of the region's total grassland area, respectively. The monthly dynamic data show that the grassland vegetation growth in May was better than the multiyear average. Although the status remained balanced in June, July, and September, in August, the growth was better than the multiyear average. The dynamic data of the 10 day periods indicated that the grassland vegetation growth of Gansu during early May to mid-June was better than the previous multiyear average. From late June to mid-July, the grassland growth was generally good and alternated with a balanced status. In late July, however, the grassland growth was mostly poor. From early August to mid-September, the grassland growth was mostly good, and the proportion of area with balanced growth was large.

3.5.5. Qinghai

Generally, vegetation growth was good in Qinghai. From May 2008 to September 2008, the areas with excellent, good, balanced, poor, and very poor vegetation growth in Qinghai accounted for 8.58%, 29.39%, 45.66%, 11.91%, and 4.46% of the region's total grassland area, respectively. The general grassland vegetation growth was better than the multiyear average, and the area with balanced growth accounted for a large proportion of the grassland. The monthly dynamic data indicate that the proportion of area with balanced growth from May to September was high, and the general vegetation growth was better than the multiyear average. The dynamic data from the 10 day periods showed that the grassland vegetation growth from early May to mid-July was better than the multiyear average, and the proportion of area with balanced growth was large. In late July, the grassland growth was mostly poor. In August, however, grassland growth was mostly good. During early September to mid-September, growth remained balanced, and the proportion of area with poor and very poor growth was high.

3.5.6. Sichuan

The general vegetation growth in Sichuan was slightly better than the multiyear average. From May 2008 to September 2008, the areas with excellent, good, balanced, poor, and very poor vegetation growth in Sichuan accounted for 10.65%, 26.58%, 39.65%, 10.87%, and 12.25% of the region's total grassland area, respectively. The general grassland vegetation growth of Sichuan was slightly better than the multiyear average. The monthly dynamic data show that the grassland vegetation growth from May to July was better than the multiyear average. In August, however, the growth was slightly lower than the multiyear average (but mostly remained balanced). In September, the status remained balanced for most of the month and was slightly better than the multiyear average. The dynamic data of the 10 day periods showed that the grassland vegetation growth from early May to early July was better than the multiyear average. Although growth primarily remained balanced from mid-July to early August, it was slightly lower than the multiyear average. From mid-August to early September, the growth status was better than the multiyear average. In mid-September, however, the growth primarily remained balanced, and the proportion of area with poor growth was larger than the area with good growth.

4. Conclusions and discussion

This study applied the grassland vegetation growth index to conduct remote-sensing monitoring of the spatiotemporal status of China's grassland vegetation growth in 2008. The following conclusions were derived from the results of the present study.

(1) In general, 2008 was a year during the past five years in which China's grasslands experienced good vegetation growth. The areas of grassland with desirable vegetation growth accounted for 38.47% of China's monitored grassland area, whereas the areas with less desirable vegetation growth accounted for 22.85%. The vegetation growth almost became balanced in early June. After early September, the proportion of grasslands with desirable vegetation growth declined, and the proportion of balance and less desirable parts increased.

(2) The regions with less desirable vegetation growth mainly included the middle and east regions of Inner Mongolia, the north region of Xinjiang, and most parts of Heilongjiang. The regions with desirable vegetation growth were mainly distributed in the north region of Tibet, the southwest region of Qinghai, the west region of Inner Mongolia, Gansu, Ningxia, Shanxi, and the northwest region of Liaoning.

(3) The changes in major provinces varied. Inner Mongolia, Tibet, and Qinghai generally had better vegetation growth in 2008 than the multiyear average. In addition, the vegetation growth in Sichuan was slightly better than the multiyear average. Gansu generally had desirable vegetation growth, but there was significant variation between different 10 day periods in the eastern areas. Furthermore, the overall vegetation growth in Xinjiang was less desirable than the multiyear average.

Satellite remote-sensing information boasts quick speed, macroscopic view, and is labour saving, thus making up for the shortcomings of ground monitoring. The following improvements may be made in any future study on the growth tendency of grassland vegetation.

The monitoring of growth tendency mainly depends on NDVI, while other indices were seldom used in this study. The application of NDVI is influenced by many factors. When the NDVI value is more than 0.1, it begins to show the vegetation growth. When the NDVI value is less than 0.2, the change of value does not necessarily indicate vegetation growth due to the big influence of other factors. When the NDVI value is between 0.1 and 0.7, the growth can reflect green vegetation growth. As pasture growth is a complicated process, NDVI cannot completely and objectively mirror pasture growth conditions due to rainfall, atmospheric temperature, and topography. We, however, could integrate different vegetation indices, analyze the suitable time for monitoring of vegetation indices and vegetation patterns, and thus get precise monitoring results. The different characteristics of different grasslands were left out of consideration in the current study of growth tendency, and furthermore, the one way to conduct the monitoring of growth tendency could not provide an objective and fair appraisal for the growth tendency of grassland. Therefore, the selection of suitable vegetation indices and monitoring methods for different grasslands to conduct the monitoring of growth tendency of different grasslands and regions could, to a certain degree, improve the accuracy of appraisal for growth tendency.

The use of remotely sensed data in grassland growth monitoring conducted in this study on the spatiotemporal patterns of China's grassland vegetation growth revealed the overall vegetation growth status of China's grasslands on a broad scale. These results provide a helpful scientific basis for understanding China's grassland vegetation conditions and for managing and regulating grass and livestock.

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References

Chen, J., S. Gu, M. G. Shen, Y. H. Tang, and B. Matsushita. 2009. "Estimating Aboveground Biomass of Grassland having a High Canopy Cover. An Exploratory Analysis of in situ Hyperspectral Data." *International Journal of Remote Sensing* 30: 6497–6517.

DAHV (Department of Animal Husbandry and Veterinary, Institute of Grassland, Chinese Academy of Agricultural Sciences), and GSAHV (General Station of Animal Husbandry and Veterinary, China Ministry of Agriculture). 1996. *Rangeland Resources of China*, 1–32. Beijing: China Agricultural Science and Technology Press.

Edwards, M. C., J. Wellens, and D. Eisawi. 1999. "Monitoring the Grazing Resources of the Badia Region, Jordan, Using Remote Sensing." *Applied Geography* 19: 385–398.

Fan, J. W., H. P. Zhong, W. Harris, G. R. Yu, S. Q. Wang, Z. M. Hu, and Y. Z. Yue. 2008. "Carbon Storage in the Grasslands of China Based on Field Measurements of Above- and Below-Ground biomass." *Climatic Change* 86: 375–396.

Fang, J. Y., Y. H. Yang, W. H. Ma, A. Mohammat, and H. H. Shen. 2010. "Ecosystem Carbon Stocks and their Changes in China's Grasslands." *Science China Life Sciences* 53: 757–765.

Huang, C., E. L. Geiger, W. J. D. Van Leeuwen, and S. E. March. 2009. "Discrimination of Invaded and Native Species Sites in a Semi-Desert Grassland Using MODIS Multi-Temporal Data." *International Journal of Remote Sensing* 30: 897–917.

Ikeda, H., K. Okamoto, and M. Fukuhara. 1999. "Estimation of Aboveground Grassland Phytomass with a Growth Model Using Landsat TM and Climate Data." *International Journal of Remote Sensing* 20: 2283–2294.

Liu, Y. J., and Z. D. Yang. 2001. *Principle and Algrorithm of Remote Sensing Processing Based MODIS*, 232–240. Beijing: Science Press.

Ma, W. H., J. Y. Fang, Y. H. Yang, and A. Mohammat. 2010. "Biomass Carbon Stocks and their Changes in Northern China's Grasslands During 1982–2006." *Science China Life Sciences* 53: 841–850.

Ni, J. 2002. “Carbon Storage in Grasslands of China.” *Journal of Arid Environments* 50: 205–218.
Piao, S. L., J. Y. Fang, L. M. Zhou, K. Tan, and S. Tao. 2007. “Changes in Biomass Carbon Stocks in China’s Grasslands between 1982 and 1999.” *Global Biogeochemical Cycles* 21: 1–10.
Piao, S. L., A. Mohammat, J. Y. Fang, Q. Cai, and J. M. Feng. 2006. “NDVI-Based Increase in Growth of Temperate Grasslands and Its Responses to Climate Changes in China.” *Global Environmental Change* 16: 340–348.
Reeves, M. C., M. S. Zhao, and S. W. Running. 2006. “Applying Improved Estimates of MODIS Productivity to Characterize Grassland Vegetation Dynamics.” *Rangeland Ecology & Management* 59: 1–10.
Robert, A. W., E. W. Neil, R. D. Ramsey, and A. E. Rebecca. 2006. “A Protocol for Retrospective Remote Sensing-Based Ecological Monitoring of Rangelands.” *Rangeland Ecology & Management* 59: 19–29.
Scurlock, J. M. O., and D. O. Hall. 1998. “The Global Carbon Sink: A Grassland Perspective.” *Global Change Biology* 4: 229–233.
Wang, H., X. B. Li, H. L. Long, and W. Q. Zhu. 2009. “A Study of the Seasonal Dynamics of Grassland Growth Rates in Inner Mongolia Based on AVHRR Data and a Light-Use Efficiency Model.” *International Journal of Remote Sensing* 30: 3799–3815.
Wang, N. B. 1996. *Dynamic Monitoring and Estimate the Yield of Wheat by Remote Sensing in China*, 124–144. Beijing: China Science and Technology Press.
Xie, G. D., Y. L. Zhang, C. X. Lu, D. Zheng, and S. K. Cheng. 2001. “Study on Valuation of Rangeland Ecosystem Services of China .” *Joumal of Natural Resources* 16: 47–53.
Xu, B., Z. H. Qin, J. Liu, Z. C. Shi, X. C. Yang, and G. X. Yang. 2005. “Remote Sensing Monitoring of Grassland in North China’s Key Provinces.” In *IEEE 2005 International Geosciences and Remote Sensing Symposium*, July 25–29, Seoul, South Korea, 3266–3269.
Xu, B., W. G. Tao, X. C. Yang, Z. H. Qin, H. Q. Liu, and J. M. Miao. 2006a. “Based Remote Sensing Monitoring upon the Vegetation Growth of China’s Grassland.” *Acta Agrestia Sinica* 28: 68–74.
Xu, B., W. G. Tao, X. C. Yang, Z. H. Qin, H. Q. Liu, J. M. Miao, and Y. Y. Bi. 2006b.” Vegetation Growth Monitoring in the Grassland of China Using MODIS Remote Sensing Data. *2nd International Symposium Recent Advances in Quantitative Remote Sensing*, September 26–29, Valencia, Spain, 704–707.
Xu, B., X. C. Yang, W. G. Tao, Z. H. Qin, H. Q. Liu, J. M. Miao, and Y. Y. Bi. 2008. “MODIS-Based Remote Sensing Monitoring of Grass Production in China.” *International Journal of Remote Sensing* 29: 5313–5327.
Yang, B. J., and Z. Y. Pei. 1999. “Definition of Crop Condition and Crop Monitoring Using Remote Sensing.” *Transactions of the Chinese Society of Agricultural Engineering* 15: 214–218.
Yu, H. Y., E. Luedeling, and J. C. Xu. 2010. “Winter and Pring Warming Result in Delayed Spring Phenology on the Tibetan Plateau.” *Proceedings of the National Academy of Sciences of the United States of America* 107: 22151–22156.
Zha, Y., J. Gao, and S. X. Ni. 2003. “Most Recent Progress of International Research on Remote Sensing of Grassland Resources.” *Progress in Geography* 1122: 607–617.