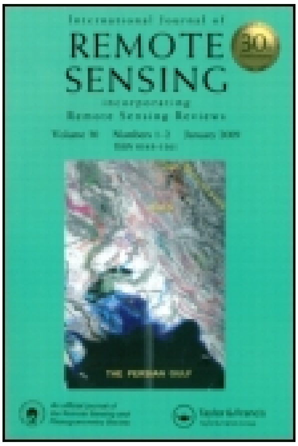

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Extracting grassland vegetation phenology in North China based on cumulative SPOT-VEGETATION NDVI data

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Plant phenology is one of the main indicators of climate or other environmental processes. This paper assesses the detection accuracy of start of season (SOS) and end of season (EOS) for grassland vegetation in north China from 2001 to 2010 using SPOT-VEGETATION normalized difference vegetation index (NDVI) data sets and *in situ* observations. The cumulative NDVI is calculated and fitted using a logistic model to identify phenological transition dates. The curvature of the fitted logistic models predicts phenological transition dates that correspond to the times at which the curvature in the yearly integrated NDVI exhibits local minimums or maximums. Validating with *in situ* observations, phenological dates are extracted from satellite time series data and are accurate to within 10 days. The spatial trends of SOS and EOS are very similar for 2001–2010. SOS mainly occurs from the day of year (DOY) 110 to DOY 170, and EOS occurs from DOY 240 to DOY 300. SOS displays a marked delay from south to north, while EOS gradually advances, indicating regional differences in climate and terrain. However, the effect of latitude and longitude on the average EOS of alpine grasslands is not significantly different, while SOS at low latitude and high longitude is 10 days earlier than at high-latitude and high-longitude regions. We detected an overall advance in SOS of 3.1 days over 10 years, and a 1.3-day delay in EOS. However, the amplitude is low (about 5 days) and the changes in most regions are not significant (close to zero). The results in this paper are concordant with many reported studies that explored the phenology of grasslands in North China, which is an important component of global grasslands science.

1. Introduction

Vegetation phenology dynamics reflect the response of the biosphere to global climate change and alterations in the terrestrial hydrological cycle. Vegetation phenology is related to primary productivity and the carbon cycle of the terrestrial ecosystem. As one of the best indicators of the influence of climate on vegetation, plant phenology has become a key component of global climate change research (Menzel 2002).

Many studies have employed various remote-sensing data to analyse plant phenology in the northern hemisphere. Earlier spring green-up and longer growing seasons in the northern hemisphere have been reported from *in situ* phenology observations (Badeck et al. 2004; Beaubien and Freeland 2000; Goetz et al. 2005; Linderholm 2006; Parmesan and Yohe 2003) and remote-sensing data (Myneni et al. 1997; Piao and Fang 2003; Chen and Yu 2007; Guo et al. 2010). Data consist primarily of annual time series of the normalized different vegetation index (NDVI) derived from the Advanced Very High

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Resolution Radiometer (AVHRR), SPOT-VEGETATION, and Moderate Resolution Imaging Spectroradiometer (MODIS). Different data could lead to different results. Analysis established for start of season (SOS) in the northern hemisphere based on AVHRR data showed an advancing trend in the 1980s and 1990s, but later demonstrated the converse (Zhang et al. 2012). MODIS data analysis indicated that SOS showed an advancing trend during the years 2000–2010. Fontana et al. (2008) analysed the phenology of alpine grasslands using AVHRR, SPOT, and MODIS and reported that the results of MODIS and SPOT data were superior to AVHRR data. SPOT-VEGETATION and MODIS data have become important supplements to phenological change studies in the last 10 years. However, contrary changes in spring phenology in the northern hemisphere in the 1990s were also reported (Piao et al. 2011; Delbart et al. 2006). Ground phenology observation data in China showed that the spring phenophase in North China has been arriving earlier since the 1980s (Zheng, Ge, and Hao 2002; Li and Zhou 2010). Yu, Luedeling, and Xu (2010) found that these events were closely related to increased temperature during the winter. In the temperate and frigid zones and high-altitude areas, the SOS of many plants is related to air temperature in winter and spring. Many uncertainties also exist in remote-sensing phenology because it is highly dependent on the quality of satellite data. In addition, no comprehensive understanding has been established of how remote-sensing phenology is related to ground-based phenology, because of the absence of *in situ* observations. Therefore, spatially and temporally explicit historical data sets from both satellite and *in situ* observations are required to validate and correct the results in future plant phenology studies.

In 1989, 400 million hectares, accounting for 41.7% of the total area of China, was classified as grassland, and more than half of this was in North China (Grasslands and Grassland Sciences in Northern China 1992). Some observers believe that human activities are responsible for conversion of grasslands, savannas, and other dry grazing lands into deserts (Cao et al. 2011; Su et al. 2011). This issue is nowhere more urgent than in North China, where population pressure and environmental sustainability have collided head-on. Likewise, the concern over global climate change has focused on the mid-continental regions of temperate Asia, where global warming may have great ecological and economic impacts. Meanwhile, in terms of its hydrothermal conditions at the biological limit level and the unique function of ensuring ecological security, grasslands in the study area play an essential role in China and even in the entire mid-northern latitudes. However, there are few studies on grassland vegetation phenology in North China.

Therefore, this study is primarily intended to evaluate the long-term trend of the seasonal timing of grassland growth in northern China, from 2001 to 2010, using pixel-level analysis of remote-sensing data. We consulted existing methods and developed an improved and simpler logistic method to extract the phenophase of grassland based on cumulative NDVI. We derived the seasonal timing of grassland growth through time series analysis and expressed the timing as two phenological measures, SOS and end of season (EOS).

2. Study area and data

2.1. Study area

The study was performed in grasslands in northern China (77°–135°E, 32°–53°N), which includes 13 provinces in the Northeast, including Heilongjiang, Jilin, and Liaoning; the Inner Mongolia Autonomous Region; the Ningxia Hui Autonomous Region; Gansu,

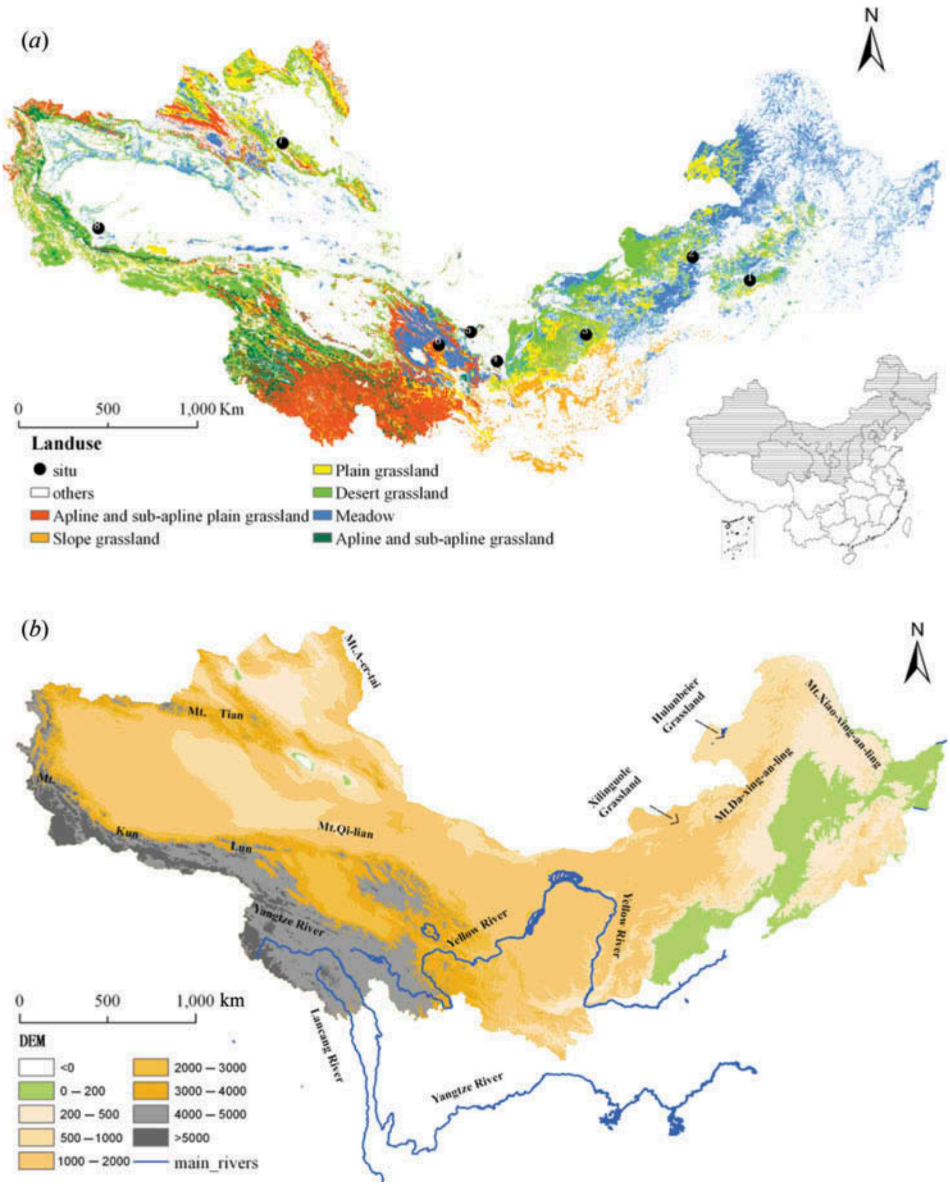

Figure 1. The study area (UTM-Zone 51N). (*a*) Location of the study area in China and grassland cover map of the study area, extracted from the GLC2000 database (http://www-gem.jrc.it/glc2000). There are six grassland types in the original cover classes. Bodies of water, cities, bare areas, and agricultural cover and other land-use types not considered in this study are shown in white. The numbers indicate the locations of the validation sites; (*b*) DEM and the main geography of the study area.

Shanxi, Shaanxi, and Qinghai provinces; and the Xinjiang Uighur Autonomous Region (Figure 1(*a*)). This is a region of open spaces, much of which is covered with grass. The region extends from the tall grasslands of the Songnen Plain in the east to the deserts and steppes on the Russian border in the west, with many variations in topography and climate

(Figure 1(*b*)). Most precipitation comes in summer, which may be hot, mild, or cool depending on elevation. Compared with the grassland areas of North America, North China is colder, generally drier in winter, more rainy during the summer growing season, and has greater variability in climate (Grasslands and Grassland Sciences in Northern China 1992). It is a key area for the study vegetation dynamics in response to climate change.

2.2. Satellite data

The SPOT-VEGETATION NDVI data used in this study are 10-day composite data (S10) at a resolution of 1 km in Plate-Carree for the years 2001–2010, available from the free VEGETATION Products Gateway (http://free.vgt.vito.be/). The product has already been systematically corrected for the effects of atmosphere and terrain (Maisongrande, Duchemin, and Dedieu 2004). In addition, values of NDVI less than –0.1 were changed to –0.1.

We obtained a land-cover database of the study area from Global Land Cover 2000 (GLC2000), with a spatial resolution of 1 km, which was downloaded from the Environmental and Ecological Science Data centre for West China website (http://westdc.westgis.ac.cn). According to the Land Cover Classification System (LCCS) developed by the Food and Agriculture Organization (FAO) of the United Nations, GLC2000 was developed with the 10-day composite SPOT-VEGETATION NDVI data set over the period 1 January to 31 December 2000, and ancillary metrics were derived from temperature, precipitation, and DEM using the Analytic Hierarchy Process (AHP) algorithm (Saaty and Vargas 1979). As shown in Figure 1(*a*), water bodies, built-up areas, bare areas, agriculture cover, and other land-use types not considered in this paper are shown in white.

2.3. In situ *phenological records*

Phenological records used for validating the retrieval algorithm in this paper are from the eight sites detailed in Table 1 and indicated in Figure 1(*a*). Records of grassland growth dates are provided by the Chinese National Ecosystem Observation and Research Network (CNERN) (Fu et al. 2010). The method of phenological observations on grasslands is described in Wan and Liu (Wan and Liu 1979). The observed grassland species were selected according to spatial comparability and local representativeness, and the observations were carried out by research institutes, universities, and botanical gardens according to uniform observation criteria (Chinese Yearbook of Animal and Plant

Table 1. *In situ* phenological records: site names, coordinates, and temporal coverage.

Location	Coordinates	Temporal coverage of the records
1 Naiman	120°42′E, 42°55′N	2005–2007, 2009
2 Xilinguole	116°40′E, 43°57′N	2006
3 E’erduosi	110°11′29.4″E, 39°29′37.2″N	2006–2007
4 Shapotou	104°57′E, 37°27′N	2006–2009
5 Minqin	102°59′05″E, 38°34′28″N	2006–2007
6 Haibei	101°17′E, 37°37′N	2006–2009
7 Fukang	87°57′E, 44°05′N	2005–2006
8 Celei	80°42′E, 37°00′N	2005–2007

Phenological Observation No. 1 1965).The phenophases of grassland vegetation included leaf unfolding, flowing, seeding, seed dispersal, and leaf colouring. According to GLC2000, the predominant land cover types are desert grasslands in validation sites, except for Haibei and Xilinguole stations. The main grassland type at Haibei station is alpine and sub-alpine plain grassland, and at Xilinguole station the main type is temperate grassland.

3. Methodologies

3.1. Phenological records

SOS and EOS derived from SPOT-VEGETATION NDVI are compared with leaf unfolding and leaf colouring *in situ* records, respectively. Ground observation data are an effective way to validate the accuracy of the remote-sensing model. However, the two kinds of data exhibit numerous problems (White et al. 2009), including potential misregistration of *in situ* sites and remote-sensing pixels. There are also some uncertainties in regard to *in situ* observations due to the observers present. We deal with the observed dates in two steps. First, we calculated the dates of leaf unfolding and colouring of all recorded species at each observed site, and second, the dates on which 30% of the species at one station start to unfold or discolour stages are considered as the SOS and EOS of ground phenology records.

3.2. NDVI preprocessing

Before the phenological retrieval algorithms were performed, SPOT-VEGETATION NDVI data and land-cover data were projected into UTM-WGS84. The SPOT-VEGETATION data we obtained are in digital number (DN) form, apart from NDVI values. Thus, during the data preparation stage, NDVI values in DN form should be recalculated to fall within the range –0.1 to +1 according to the following formula (VEGETATION Programme 1998): $\text{NDVI} = 0.004 \times \text{DN} - 0.1$, as it is known that NDVI values for vegetation are greater than 0. However, negative NDVI values in winter and early spring in some pixels are caused by snow (Delbart et al. 2005) or other noise, and so negative NDVI pixel values must initially be replaced with 0 to reduce potential inaccuracy.

Although aerosols and thick cloud have been corrected during production of the SPOT-VEGETATION NDVI data set using a maximum value compositing (MVC) algorithm, some noise representing variability in the sensor viewing angle, solar altitude, aerosols, and water vapour still exists. Therefore, it was necessary to reduce the impact of spurious values in the NDVI data. Savitzky–Golay is a simplified least-square-fit convolution for smoothing and computing derivatives of consecutive values (Savitzky and Golay 1964). In order to further remove atmospheric and cloud effects in late spring and summer, we applied the Savitzky–Golay filter method twice.

For matching the specific dates of field records with phenological data, we resampled NDVI data at 1 day resolution from 10 day using the linear interpolation method.

3.3. Phenology metrics extraction

Field records suggest that the green-up of plants tends to follow a rapid increase in NDVI values and is then followed by a periodic and steady increase until reaching maximum NDVI (Zhang et al. 2003). The transition to senescence follows a similar but reverse

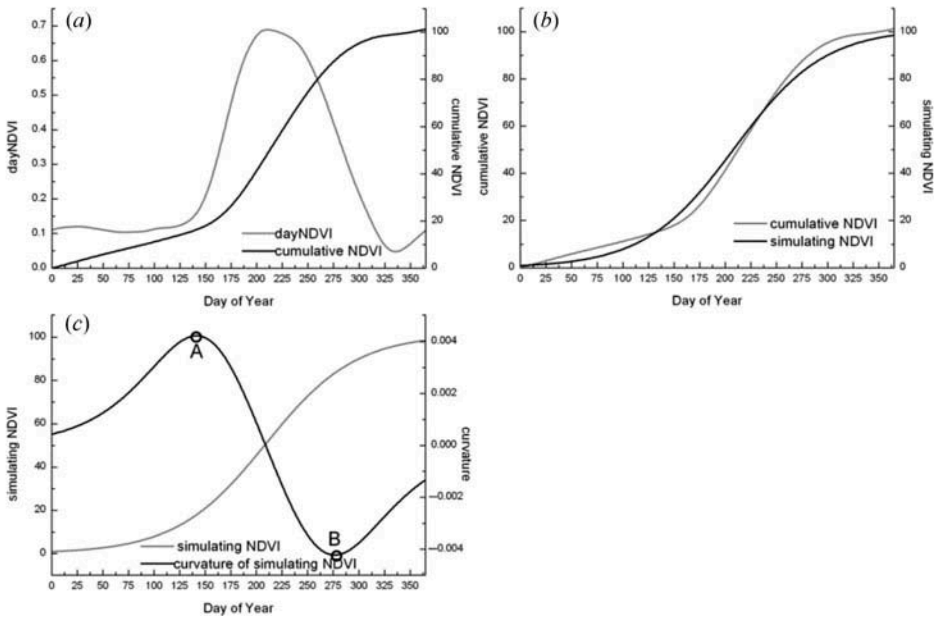

Figure 2. A simple schematic diagram of our method of extracting transition dates using minimum and maximum values in the curvature of cumulative NDVI over a single season. The circles in Figure 2(*c*) indicate transition dates. In Figure 2(*c*), 'A' indicates the date of SOS, 'B' indicates the date of EOS.

pattern in the autumn. The integrated NDVI curve of grassland vegetation in an entire growth season is a sigmoid curve that can easily be fitted using a logistic model (Ratkowsky 1983). Based on this idea, this paper extracted the phenology of grasslands in North China.

Figure 2 shows the main processes that allow the phenology of grassland to be identified using SPOT-VEGETATION NDVI.

Cumulative integrated NDVI was calculated based on filtered one-day NDVI (Figure 2(*a*)). The integrated NDVI profile was fitted using a logistic model as follows (Figure 2(*b*)):

$$y(t) = \frac{c}{1 + e^{a+bt}} + d, \tag{1}$$

where $y(t)$ is the fitted VI value at time t, a, and b are the fitting parameters, $c + d$ is the maximum cumulative NDVI value, and d is the initial background VI value, recognized as the minimum NDVI value of the original one-day NDVI curve. Both a and b are calculated using the Levenberg–Marquardt method (Levenberg 1944; Marquardt 1963). This approach is very similar to the method employed by Zhang et al. (2003), who fitted the temporal variation in MODIS EVI using a piecewise logistic function of time for a single growth or senescence cycle. The methodology used in this paper made it fairly easy to identify the phenological phase of a single growth cycle. However, it is not necessary to identify the growth or senescence phase before modelling the NDVI profile using a logistic function.

Similar to Zhang et al. (2003) and Jeong et al. (2011), we calculated the first and second curvature of the fitted cumulative NDVI, respectively, and we found that the extreme values of the first have a better correlation with ground observation records of phenology. Thus, in this paper, we simply computed the first curvature (K) of Equation (1) at any time t using Equation (2) (Figure 2(c)):

$$K = \frac{d\alpha}{ds} = -\frac{b^2 cz(1-z)(1+z)^3}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}}, \tag{2}$$

where $z = e^{a+bt}$, α is the angle (in radians) of the unit tangent vector at time t along a differentiable curve, and s is the unit length of the simulated NDVI curve.

We defined the extreme values of curvature of the fitted cumulative NDVI as the key phenological phases of grassland vegetation (Figure 2(c)).

In this paper, all processes were performed using the software ENVI/IDL and ArcGIS 9.3. The images were processed pixel by pixel.

4. Results

4.1. Spatial maps of phenological dates and validation

Figure 3 shows the spatial variation of the onset of greenness and end of senescence over the grassland vegetation in northern China for 2001–2010. For all years, SOS displayed a marked delay from south to north while EOS gradually advanced, thus manifesting regional differences in climate and terrain.

SOS showed that the date of greenness mainly occurred on DOY 110–170, but arrived before DOY 110 in some lower river valley areas, such as the source area of the Yangtze, Yellow, and Lancang Rivers. SOS occurred after DOY 170 in some high-altitude or high-latitude areas, such as the southern Altai Mountains in Xinjiang Province.

EOS primarily occurred between DOY 240 and 300, and also displayed regional variations with altitude and latitude. The earliest EOS generally appeared in the Altai-Tianshan Mountains. EOS in the Hulunbeier grassland in the north of Inner Mongolia Province was also earlier than in other regions because of the high latitude. After DOY 280 (late September), the grasslands in the Yellow River entered the end of senescence due to water resource insufficiency.

Validation is a key issue in phenology studies based on remote-sensing data over large areas (Schwartz and Reed 1999). Results of the comparative analysis between metrics based on cumulative NDVI temporal profiles and *in situ* observations are illustrated in Figure 4. The results are for all sites and all available years. For comparison, the remote-sensing SOS and EOS dates are calculated as the average date of eight pixels of grassland that are closest to the site coordinates. It is clear that most errors in estimated phenology dates fall within ±10 days compared with statistical dates, especially EOS. This illustrates that the method is feasible with respect to time resolution of the remote-sensing data used in this paper.

To illustrate the metrics, summary statistics are also given in Figure 4. In terms of uncertainties, RMSE values are 11.82 and 9.41 days by comparison with SOS and EOS, respectively. The bias values are 3.48 days extracting SOS and 1.08 days when we compared EOS with *in situ* observation. The correlation value is also higher between EOS and phenological statistical data, at 0.75 ($p < 0.001$), and is 0.45 ($p < 0.05$) for SOS.

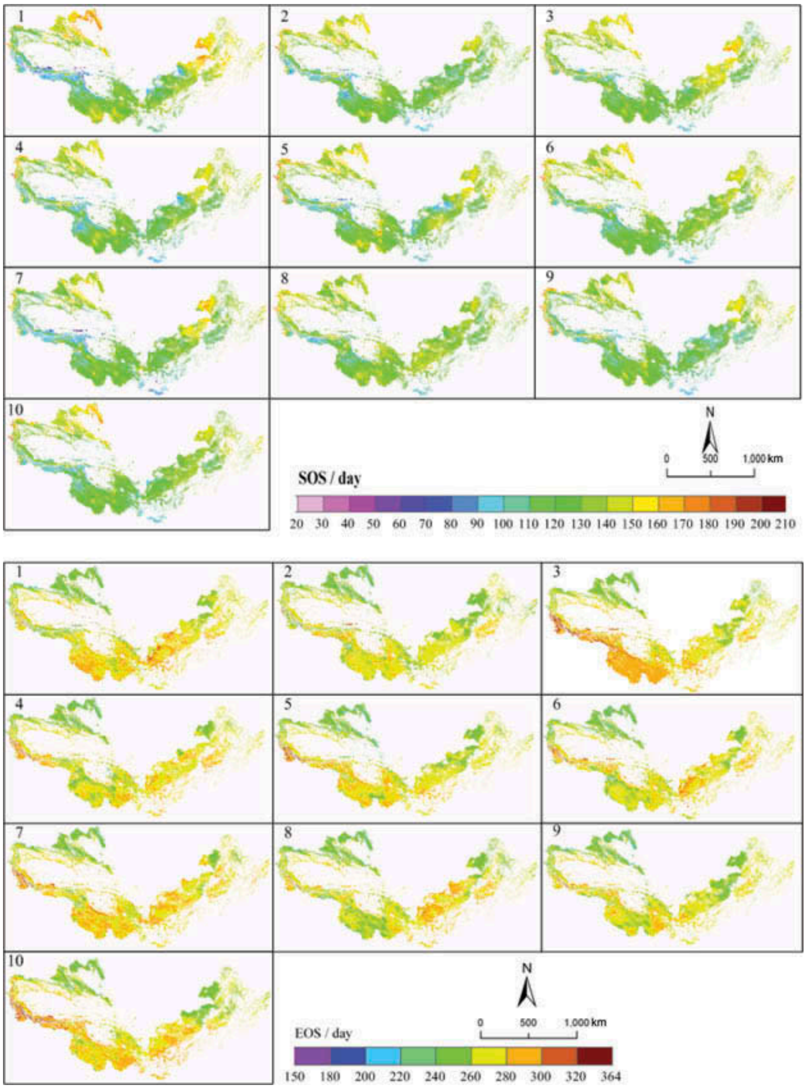

Figure 3. Maps of SOS and EOS dates of grassland vegetation in northern China estimated using the method described in Section 3.2 and Figure 2.

The best agreement between predictions and *in situ* observations is obtained between EOS and *in situ* phenology. This may be because temperatures fluctuate in spring, and starting dates for spring vary considerably between years, affecting the results of remote sensing. However, the climate is relatively stable in autumn, affecting grassland phenology to a lesser extent, and the phenology is more accurate (Wei et al. 2007).

To explain the improvement found in our method, we also extracted the grassland phenology of eight *in situ* sites using two similar methods, mentioned in Fisher, Mustard, and Vadeboncoeur (2006) and Elmore et al. (2012). The results are shown in Figure 5. The correlations (r = 0.48, p < 0.05) between estimated SOS extracted using Fisher, Mustard, and Vadeboncoeur (2006) and records from *in situ* sites are similar to the results

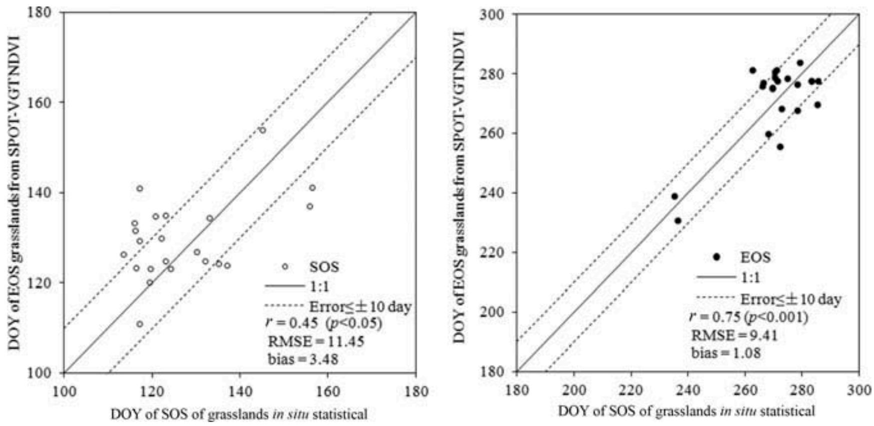

Figure 4. One-to-one comparison between estimated phenological dates extracted using extreme change of curvature of cumulative NDVI and statistical data.

of this paper (Figures 4 and 5(*a*)), although with a higher RMSE, having a value of 37.58 days. The accuracy of estimated EOS is very low (Figure 5(*b*)), with $r = 0.07 (p > 0.1)$. Figures 5(*c*) and (*d*) show estimated SOS and EOS of grasslands using the method of Elmore et al. (2012). Similar to our results shown in Figure 4, correlation is also higher between EOS and phenological statistical data at 0.60 ($p < 0.001$) (Figure 5(*d*)), and is 0.48 ($p < 0.05$) (Figure 5(*c*)) for SOS. However, there are fewer errors in estimated phenology dates, falling within ±10 days compared with statistical dates. The RMSE of the results in Figures 5(*c*) and (*d*) is higher than that of the results obtained using our method.

4.2. Variations in phenological dates from 2001 to 2010

To study the trends of inter-annual variations in SOS and EOS over the study area, linear regressions were fitted to the start of greening and end of season dates for each pixel of the study area from 2001 to 2010. Figure 6 shows the number of days of advance (negative) or delay (positive) of SOS and EOS, taken as the slope of the regressions multiplied by the number of years. Over the study area and for the entire period, the average trend corresponds to an advance in SOS of 3.1 days in 10 years, and a delay of 1.3 days in EOS. However, the trends are spatially heterogeneous (Figure 7).

Three regions display a strong advancement in spring phenology, shown as light blue in Figure 6(*a*). The first of these is in the southern Altai Mountains in northern Xinjiang Province, the second is the alpine and sub-alpine plain grassland in southern Qinghai Province. The third region extends from the southwestern Hulunbeier grassland toward the northeast of the Xilinguole grassland, where most of the temperate meadow steppe is distributed. However, an obvious delay of 5 days over the 10-year study period is seen in the spring phenophases in the northwestern Xilinguole grasslands, the Loess plateau in Ningxia Province, and the piedmont area of the Himalayas-Kunlun Mountains. Other regions display no trends (close to zero).

For 2001–2010, the change trend of EOS in grasslands in North China displays a large spatial difference, as shown in Figure 6(*b*). Most areas exhibit a later EOS, but the variation in amplitude is low (0–5 days). Early EOS is seen in a few areas, such as the

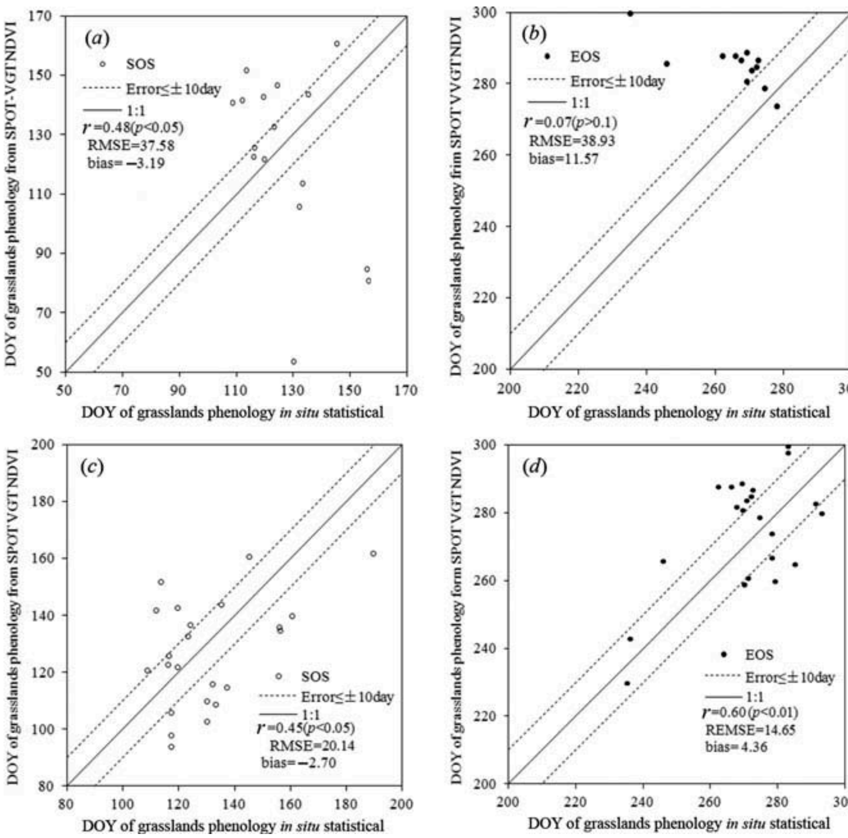

Figure 5. One-to-one comparison between estimated phenological dates extracted using two similar methods and statistical data. (*a*) and (*b*) are estimated SOS and EOS, respectively, using the method of Fisher, Mustard, and Vadeboncoeur (2006); (*c*) and (*d*) are the results of SOS and EOS, respectively, using the method of Elmore et al. (2012).

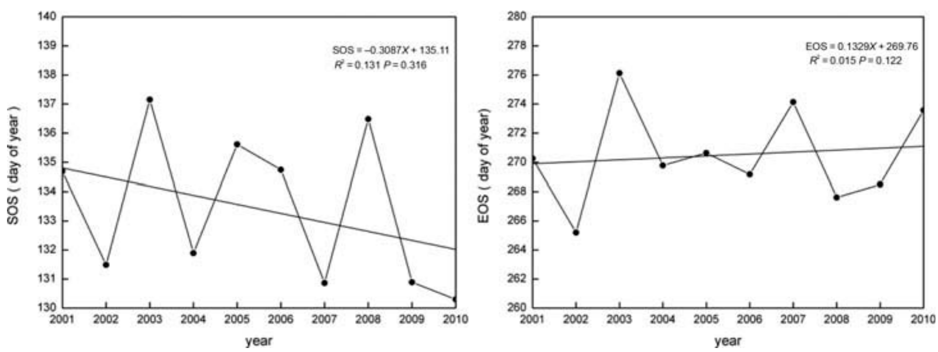

Figure 6. Inter-annual variation in grassland SOS and EOS from 2001 to 2010 in northern China.

northeastern Hulunbeier grassland. Concordant with Ding et al. (2012), who studied the phenology of alpine grassland in the Tibetan plateau, the EOS of grasslands in southwest Qinghai advanced by 0–5 days.

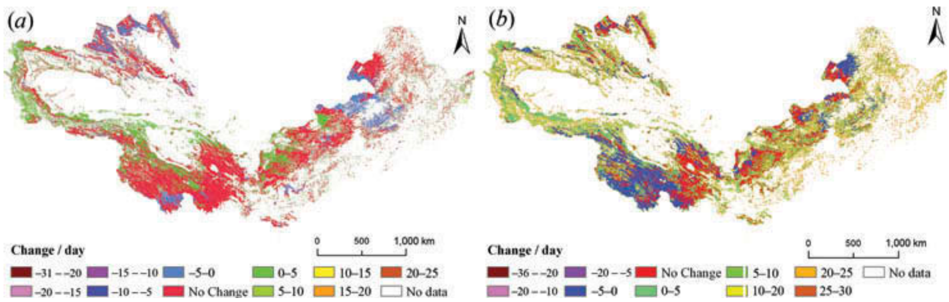

Figure 7. Spatial distribution of inter-annual change trend of grassland SOS (*a*) and EOS (*b*) from 2001 to 2010 in northern China.

4.3. Relationships with latitude and longitude

The average multiyear phenophase can reflect the general growth stage. Therefore, the average SOS and EOS of alpine grassland over 10 years was extracted to quantify the effect of latitude and longitude on the phenological variables. Figure 8 shows the results of phenological variables for alpine grasslands within a 30 min increment of latitude and longitude in a partial sub-region (104°–126°E, 36°–48°N). At low latitude and high longitude (the eastern part of this region), the SOS of alpine grasslands is earlier (at about DOY 120) than in high-latitude and high-longitude regions, where SOS occurs at about DOY 130. Considering the differences between regions, the delay in onset of greenness for alpine grasslands is mainly controlled by arrival of the monsoon from the Pacific Ocean. The date of arrival in the eastern part of this region is earlier compared

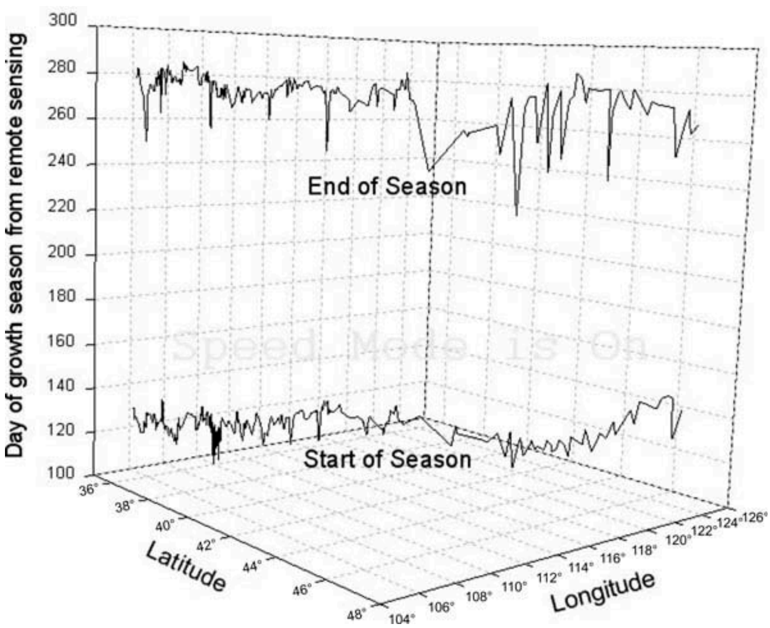

Figure 8. Latitudinal and longitudinal variation in the onset of greenness and the end of senescence for alpine grasslands in North China.

with the western part. As a result, the SOS in the western area is delayed compared with the eastern.

The EOS is early at high latitudes and longitudes (the southeastern part of the study region) (at DOY 275) compared with that at low latitudes and high longitudes (the northwestern part of study area) (at DOY 280). However, latitude and longitude variables are less pronounced than for SOS. There is a small, near-linear negative change from the western to the eastern part of the study area. This change is attributed to the fact that senescence is a much more complex phenomenon compared with onset of greenness (Schaber and Badeck 2003).

5. Discussion and conclusion

This paper presented an improved logistic method to determine the date of the SOS and the end of senescence of grasslands in North China, based on the SPOT-VEGETATION NDVI data set. The prerequisite to determining grassland phenology was to eliminate the noise affecting NDVI. Consequently, a simple filter method (Savitzky–Golay filter) was used twice to reduce contamination in the NDVI curve caused by atmospheric and other disturbances (Jonsson and Eklundh 2002; Chen et al. 2004). The cumulative NDVI of each year was calculated according to the daily NDVI value and the profile was fitted using a logistic model. SOS and EOS of grasslands in North China from 2001 to 2010 were extracted based on the extreme points of curvature of the integral NDVI curves.

The dates obtained from the remote-sensing method differed from *in situ* records at eight validation sites by less than 10 days. This means that remote sensing of onset of greening and end of senescence corresponds well to the observed phenology of grasslands.

Spatial variations in SOS and EOS over the study area were very similar in all years. SOS mainly occurred between DOY 110 and 170 and displayed a marked delay from south to north. EOS primarily occurred between DOY 240 and 300 and gradually advanced. These two phenology parameters significantly manifest the regional differentiation of climate and terrain. However, the effect of latitude and longitude on average EOS over 10 years in alpine grassland is not obvious, and EOS is near linear from west to east. SOS of alpine grasslands at low latitude and high longitude is 10 days earlier than in the high-latitude and high-longitude regions. Over the whole study area and the entire study period, SOS of grasslands appeared earlier, and the variation in amplitude for every 10 years was 3.1 days (R^2 = 0.131, p= 0.316). Compared with SOS in other areas, the result in this study is similar to 3d/10a for the whole world (Julien and Sobrino 2009), 3.3d/10a in the Eurasian continent (Zhou et al. 2001), 3.1d/10a in the northern hemisphere (Jeong et al. 2011), and lower than 7.9d/10a in China (Piao et al. 2006) or 6d/10a in the Qinghai–Tibet plateau (Ding et al. 2012). Jeong et al. (2011) also reported that the amplitude in the northern hemisphere during 2000–2008 increased by 0.2d over 10 years based on AVHRR data; the results of the present study are obviously higher than this value. However, the inter-annual change trend of EOS was weakly delayed, and the variation in amplitude every 10 years was just 1.3 days (R^2 = 0.015, p= 0.122), which was lower than 2d/10a in the Qinghai–Tibet plateau (Ding et al. 2012), 2.5d/10a in the northern hemisphere in 2000–2008 (Jeong et al. 2011), and 3.7d/10a in China (Piao et al. 2006). However, the result was greater than 0.5d/10a for the whole world in 1980–1990 (Julien and Sobrino 2009).

This method allows the study of variations in phenology in a simpler way than previous studies, and will allow continuation of this analysis in the future with SPOT-VEGETATION or MODIS. Also, the extension of the growth season resulting from the advancement of SOS, and the delay in EOS, especially the advancement of spring phenophase, is considered one of the main factors that enhances the carbon sink function in middle–high-altitude areas in the northern hemisphere, reduces CO_2 accumulation in the atmosphere, and decreases the rate of climate warming. However, the effects of change in growth season duration on carbon balance are not clear at present and require further studies.

The findings from this paper again show that remote sensing is useful in a phenological survey. However, we analysed only the effect of latitude and longitude on grassland phenology. Climate change, pests, and human activities also contribute to the fluctuation in phenology, especially climatic factors. Ge et al. (2003) used phenological observation and meteorological data to study the relationship between climate change (temperature and precipitation) and spring phenology in China over the past 40 years, and found that changes of temperature in plant growth period had a good corresponding relationship with changes of plant phenology, while precipitation and plant growth had no statistically significant relationship. The same conclusions could also be found in the research of Xiao and Moody (2004). In addition, many studies have suggested that there is a lag in time between vegetation growth and climate change. Piao et al. (2006) studied the relationship between plant phenology and climate factors before the growing season, and concluded that plant phenology had a very significant negative correlation with temperatures over 2–3 months before the start of vegetation growth, and also with precipitation over 5 months before the start of plant growth. Piao et al.'s research showed that rising temperatures before the growth season can lead to advance of phenology, and also increased precipitation in winter. The above studies suggest that temperature has a significant role in changes in phenology, while precipitation changes had fewer effects on this. How climate factors affect grassland vegetation in North China should be given more consideration in future studies.

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