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Retrieval of Green-up Onset Date From MODIS Derived NDVI in Grasslands of Inner Mongolia

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ABSTRACT In this paper, moderate resolution imaging spectroradiometer (MODIS) derived normalized difference vegetation index (NDVI) was used to retrieve the onset date of spring phenology in grasslands of Inner Mongolia from 2002 to 2017. To validate the application of MODIS derived data, long-term retrieval and investigation on its reliability was performed. The correlation between MODIS derived green-up onset date and ground observations from 2002 to 2012 were given medium to high strength (R^2: 0.58–0.81). Besides, the relationship between seasonal climate variables, including winter and spring precipitation and temperature, and MODIS derived green-up onset date from 2002 to 2017 were established. Overall, linear regression analysis shows that there are 8–12 days RMSE for climate variables explaining green-up onset date shifting. This satellite method might have a poor performance in sparse and snow-cover grasslands but is fitted well in medium to dense vegetation and snow-free grasslands. These suggest that MODIS estimated spring phenology has the potential to be applied in grass resources utilization in Inner Mongolia.

INDEX TERMS Grassland, moderate resolution imaging spectroradiometer (MODIS), normalized difference vegetation index (NDVI), spring phenology.

I. INTRODUCTION

The onset date of spring phenology determines the regulation for livestock grazing and overstocking. The time of spring phenology has a directly effect on the optimal stock period. For majority stockman, the habit for grazing time is subjective and strongly relied on human experiences. Furthermore, the empirical value given by local government, is generally broad and arbitrary. However, the high risks of overgrazing and grassland degradation due to ignoring the location and interannual variance of spring phenology will have to be solved in demand.

Satellite methodology provides a way to estimate spatial distributed spring phenology at a large scale. For field measurements, since the sampling of individual plant species cannot indicate the complex phenological characteristics of whole collection of florae in the spatial coverage. Satellite application in green-up onset date determination has been intensively developed in previous decades [1]–[6], with merit of providing spatial heterogeneous and time-variable data. Among these studies, the well-developed normalized difference vegetation index (NDVI) has been proved the effective for investigating seasonal vegetation cycle [7]–[10], since it is related to green leaf area index (LAI) and photosynthetically active biomass [11]–[13]. There is solid foundation of using NDVI derived from remote sensors to detect vegetation phenology [9], [14]–[17]. Compared to other remote sensing data (AVHRR, Landsat, SPOT), moderate resolution imaging spectroradiometer (MODIS) sensor has a relatively finer spatial resolution, higher frequency of revisit period, and avoids error from discontinuous satellites.

Savitzky–Golay (SG) smoothing filter has been widely applied for the NDVI curve fitting. This is first raised by Savitzky and Golay as an asymmetric Gaussian function [16], and has been proved for reliable performance and spatially consistent on the estimation of start of the growing

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season compared to other filters (e.g. asymmetric Gaussian, spline smoothing, double logistic fitting) [17], [19]–[21]. Besides, smoothing series crossing from moving average can well capture the vegetation phenology, with flexibility of time lag for selecting the sensitive and significant trend changes [22], [23]. Comparing with other methods, largest NDVI increase have limitations in determining the onset of green-up when NDVI signal has abrupt change beyond the natural variability of the data [24], while fitting logistic functions require substantial parameters estimation without ecological or biological meanings [25], the moving average method has advantage that is stable and applicable for estimating substantial areas of vegetation phenology.

Grasslands of Inner Mongolia is one of the world's largest temperate grassland that support the biggest population of sheep and goats. Primary grassland types, including meadow steppe, typical steppe, and desert steppe, related to a climate gradient are spread in the Inner Mongolia from northeast to southwest [26]. There is variance of phenological patterns in temperature vegetation [27]. Regional phenology is often fluctuated and sensitive to climate and meteorology. The temperate grasslands in northern China are sensitive to climate change, and the effects have been varied with vegetation characteristics and water budget limitation [28]–[30]. Temperature and precipitation are the main factors controlling the vegetation seasonal variation and phenology dynamic in temperature grassland ecosystems [27], [31], [32].

In this paper, a long-term determination of onset date of green-up based on satellite remote sensing was performed in grasslands of Inner Mongolia. This is followed by a validation via using a ground measurement database of spring phenology in different sites. The study also includes building relationship between temperature and precipitation in prior winter and spring seasons and time-shift of green-up onset date.

II. MATERIAL AND METHODOLOGY

A. STUDY AREA

The grassland in the Inner Mongolian of China is situated in northern hemisphere mid-latitude temperate area. Temporal character of climate as one of the most notable features in this area, has cold, dry winter and spring, warm, wet summer and autumn, with seasonal drought in spring and early summer, frosts at early autumn, and frequently windy in long winter [26]. The area has a pronounced east-west precipitation gradient, with annual precipitation varying from 500 mm in the east to less than 100 mm in the west. Precipitation is time asymmetry at east of Inner Mongolia, where 70-80% rain falls between June and August. Due to higher elevation and farther distance from the Pacific Ocean, the west region is colder in winter and drier throughout the year [33], [34].

Types of the temperate grasslands express similar gradient with the climate in this area, especially precipitation gradient. From east to west, the grassland types are meadow steppe, typical steppe and desert steppe [26]. Grassland distribution in the Inner Mongolia was masked by MODIS land cover type data product (MCD12Q1) [33]. Based on this, grassland classifications derived from 1:1,000,000 grassland-type vector figure [34] was used to divide three grassland types. In the main part of Inner Mongolia, grasslands vary gradually from meadow steppe in the northeast and typical steppe in the middle to desert steppe in the southwest (Fig. 1). Plants become sparse in the western desert steppe, due to the sharp decrease of precipitation. Dominated species in most of the grasslands are perennial grass of Chinese leymus (Leymus chinensis [Trin.] Tzvel.) [35].

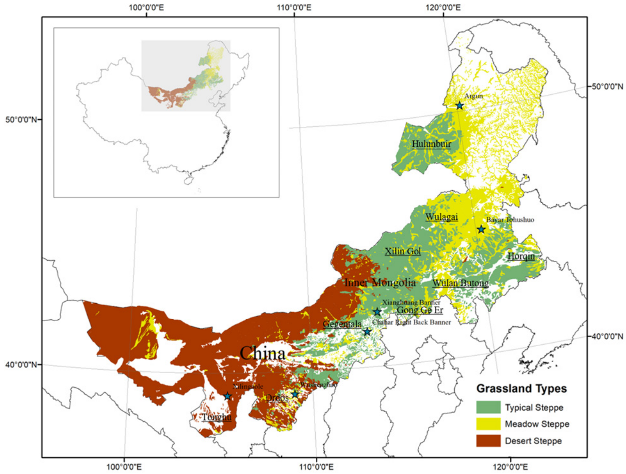

FIGURE 1. Study area of the Inner Mongolia, China with three grassland types (typical steppe, meadow steppe, desert steppe), location of major grasslands (text with underline) and six ground observation sites (blue stars).

B. REMOTE SENSING DATE

1) MOD13_Q1 PRODUCT

The product MOD13_Q1 of Terra MODIS from year 2001 to 2017 is used in this study, providing consistent and spatio-temporal NDVI values as result of dividing differences in infrared and red reflectance measurements, with a 250-m spatial resolution in a 16-d interval [38].

$$NDVI = (NIR - R)\Big/(NIR + R) \tag{1}$$

where NIR is the band of near-infrared, and R is red.

Spectral data have been improved by applying atmospheric correction for water, clouds, heavy aerosols and cloud shadow calibration [39]. The daily basis data have been integrated into 16-day composite products via a series of algorithms for selecting nadir pixels [40]. A set of locations and time periods via ground-reference data have been verified to ensure data quality [41]. In this study, snow mask included in MOD13_Q1 product is used to exclude the NDVIs, by only reserving pixels with no possible snow/ice before smoothing [42].

2) SPRING PHENOLOGY ESTIMATION

The SG filter is used for reconstruction to remove the random noise and smooth the NDVI time series (Fig. 2).

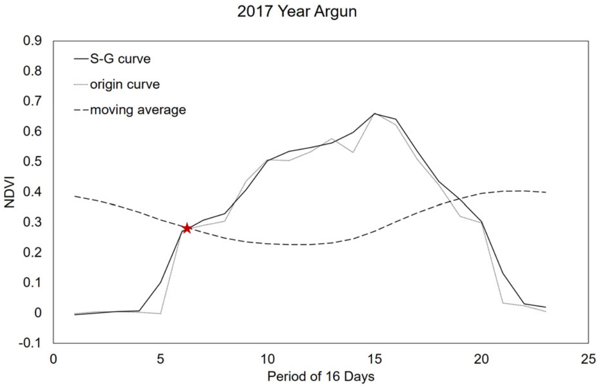

FIGURE 2. **Illustration of green-up onset date derived from MODIS-NDVI at the site of Argun in year 2017 using the SG filter and moving average method (short dash line is the origin NDVI curve, solid line is smoothed NDVI curve after SG filter, long dash line is the moving average curve, and the first crossing between SG curve and moving average is spot of green-up onset date and NDVI).**

Polynomial fit (N) was 3 and window length (F) was 4. After that, autoregressive moving average equation has been employed to fit the phenological model [22].

$$NDVI_t = \sum\nolimits_{t-(w-1)}^{t} NDVI_i / w \tag{2}$$

where $NDVI_t$ is the moving average value of NDVI for time t, $NDVI_i$ is the smoothed value of NDVI for time i, w is the moving average time interval.

A moving average NDVI time-series is produced by equation (2) with a time lag compared to the smoothed series (Fig. 2). The selection of moving average time interval is adjusted to identify the green-up onset event, when large time-interval lead to less sensitive trend and small time-interval acquired insignificant trend changes. In this study, $w = 18$ is the best identified value of spring phenology based on our preliminary analysis with w values ranging from 6 to 20.

C. GROUND DATE

Phenological data from six sites have been chosen for representing grassland ecological zones in the Inner Mongolia, which are scattered from meadow steppe, typical steppe to desert steppe (Fig. 1, Table 1). These pasture observation stations have been founded by Chinese Weather Bureau to serve livestock production since 1982. The phenological survey provides the date of several grasses' phenological events including green-up as well as tassel, anthesis, mature, and brown-up. The observed species among those stations are different of each station, while Chinese leymus is recorded on all the stations as the primary grass of the Inner Mongolia. The dataset for verification in this study are from year 2002 to 2012, while some sites have incomplete records in this period (Table 2).

TABLE 1. **Main characteristics of ground study sites in the inner mongolia, china.**

Location	Lat. (° N)	Long. (° E)	Elev. (m)	MAT ^{a} (°C)	MAP ^{a} (cm)	Grassland type
Argun	120.18	50.25	582	-1.0	273	Meadow steppe
Bayar Tohushou	120.33	45.07	629	4.5	241	Meadow steppe
Xianghuang Banner	113.83	42.23	1323	5.2	179	Typical steppe
Chahar Right Back Banner	113.18	41.45	1424	4.7	211	Typical steppe
Wushenzhao	109.03	39.10	1313	8.6	222	Typical steppe
Xilingaole	105.38	39.08	1215	8.9	72	Desert steppe

^{a} Mean annual temperature (MAT) and mean annual precipitation (MAP) are from ERA-Interim 2002-2017.

D. CLIMATE DATE

Data of monthly air temperature in 2-m and total precipitation are extracted over the Inner Mongolia study region from a dataset – the European Center for Medium-Range Weather Forecasts ERA-Interim. This reanalysis dataset assimilates observations and has been averaged in the longitudinal direction [43], [44]. Seasonal climate values are calculated for winter season (December to February) and spring season (March to May) from monthly ones. The spatial resolution of climate data is 0.125° × 0.125° grid.

E. STATISTICAL ANALYSIS

We calculate the mean value and standard deviation for satellite derived green-up onset date and corresponding NDVIs among 16 years (Table IV). Besides, verification of green-up onset date between satellite-derived and ground measurement data are evaluated through square of the correlation coefficient (R^2), probability p-value, root-mean-square error (RMSE) and bias between the ground data and satellite values (Fig. 6; Table 2) by the equations (3)-(4).

$$\text{RMSE} = \sqrt{\sum\nolimits_{n=1}^{n} \left(d_s - d_g\right)^2 / n} \tag{3}$$

$$\text{bias} = d_s - d_g \tag{4}$$

where n is sampling number, d_s is satellite-derived date, and d_g is ground measurement date.

The linear regression is implemented for evaluating the effect of individual seasonal climate factor on spring phenology onset. In the meantime, the RMSE is calculated (Fig. 7; Table 3) by equation (5), and 25%, 50%, 75% quartiles of RMSE have been calculated based on pixels in three grassland types.

$$\text{RMSE} = \sqrt{\sum\nolimits_{N=1}^{N} (d_p - d_s)^2 / N} \tag{5}$$

where N is 16 (year from 2002 to 2017), d_p is predicted spring phenology date based on individual climate variable, and d_s is satellite-derived date.

III. RESULTS

The onset green-up date in grassland of Inner Mongolia has interannual and spatial variation. As shown by previous

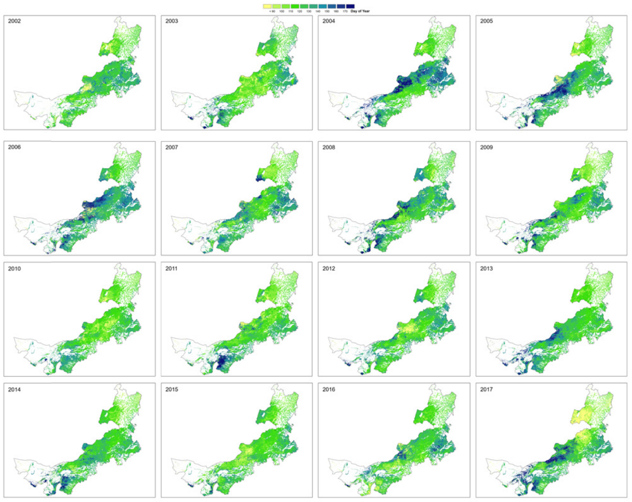

FIGURE 3. Spatial distribution of the onset date of green-up during 2002-2017 over grasslands in the Inner Mongolia.

study [45], the annual green-up date is from DOY 100 to 150 at year 1982 to 2008. Besides, the onset of green-up delayed from 2004 to 2006 among these years [45]. Results from our estimation are fitted well with the range of onset date, and has the extreme spring phenology in the same years (Fig. 3). For years 2002-2017, onset date of green-up varies from early April to early June (DOY 100 and 160, Fig. 3). By comparison with three grassland types, meadow steppe has advanced green-up onset date than that is in typical steppe and desert steppe (DOY $120 < 123 < 131$, Table IV). Biweekly AVHRR NDVI studies show meadow steppe in the Inner Mongolia greens up mostly in late April, while typical steppe greens up by late May and desert steppe in the west green-up occurs later [30], [46]. For comparison, MODIS NDVI in this study has similar result of meadow steppe (late April), but has earlier onset date of typical steppe and desert steppe than that of AVHRR (early to mid-May).

It is obviously that the green-up is delayed overall in 2004. It is even late over typical and desert steppe, whereas the green-up in the meadow steppe is less delayed. A delay of 5-17 days existed in all grassland types in 2004 (Fig. 3; Table S.1). In contrary, green-up onset date in 2010 is estimated to advance approximately 5-9 days contrasted with the mean of 16 years, while the advancement is most apparent in Xilin Gol and Hulunbuir grasslands (Fig. 3). Moreover, the onset of green-up in 2017 has delayed date in the desert steppe, e.g. Ordos grassland and west of Xilin Gol grassland, and advanced date in the meadow and typical steppes, e.g. Hulunbuir grassland and Wulagai grassland (Fig. 3), which the change of spring phenology is differed by regions in this year. The mean green-up onset date of study areas during the 16 years is the earliest in the meadow steppe, which is 3 days advanced than typical steppe and 11 days than desert steppe (Table IV).

The spatial distribution of green-up onset date presents distinct differences over grasslands of the study area (Fig. 3). However, green-up onset date in some locations of meadow steppe and typical steppe can arrive before DOY 100; in some locations of typical steppe and desert steppe can arrive after DOY 160 (Fig. 3). Green-up onset date displays regional variations with location and grassland types. In general, there is a delay of green-up from northeast to southwest, and a remarkable delay is occurred at certain years in middle-north and southwest of the Inner Mongolia (Fig. 3). As for grassland types, onset date of green-up in the meadow steppe is overall advanced compared to others. In the typical steppe, green-up onset has significant spatial variation, with advance in Hulunbuir grassland, followed by Xilin Gol grassland and Horqin grassland. Desert steppe has the most delayed date of green-up onset, while east of Ordos grassland has relatively advanced date than grasslands in west region (Fig. 3).

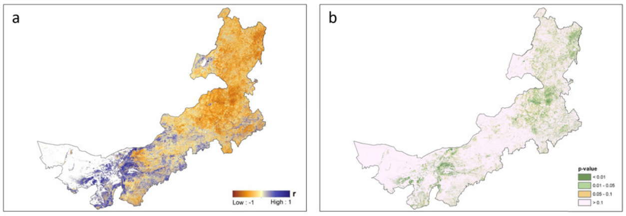

FIGURE 4. Positive to negative trend of correlation (a) and p-value (b) between onset date of green-up and year 2002-2017.

The spatial and inter-annual variations occur in the Inner Mongolia. Overall, the northeast to middle of study area has decreasing date of spring phenology from year 2002 to 2017, while west of study area has the increasing trend (Fig. 4a).

The significance correlation ($p\text{-value} < 0.05$) happened in the east of Hulunbuir grassland, Wulagai grassland and Xilin Gol grassland (Fig. 4b).

Different satellite methods for estimating phenology is a concern for resulting discrepancy from other studies [17], [47]–[49]. For example, at one site over typical steppe in the middle of Inner Mongolia, applying the HANTS-maximum method leads to an early estimation date, while Gaussian-midpoint method produces late estimate at the same site [17]. Nonetheless, the interannual trend of vegetation green-up is relatively consistent from different methods [47], [48].

IV. VALIDATION

Six study sites over different grassland types have been chosen for validation, which can be distinguished by their patterns of NDVI (Fig. 5). Argun and Bayar Tohushou over meadow steppe, has the highest NDVI peak (0.66-0.72) on July, while Xianghuang Banner, Chahar Right Back Banner and Wushenzhao over typical steppe has the medium NDVI peak (0.30-0.36) on late July and early August, and Xilingaole over desert steppe has the least distinguished NDVI elevation and the peak (0.20) is on August (Fig. 5). The amplitude of NDVIs between summer and winter in different grassland types changes from 0.1 in desert steppe, to 0.2 in typical steppe and 0.7 in meadow steppe.

There is significant positive relationship between onset date of green-up from remote sensing approach and ground observations from year 2002 to 2012 ($p\text{-value} < 0.1$).

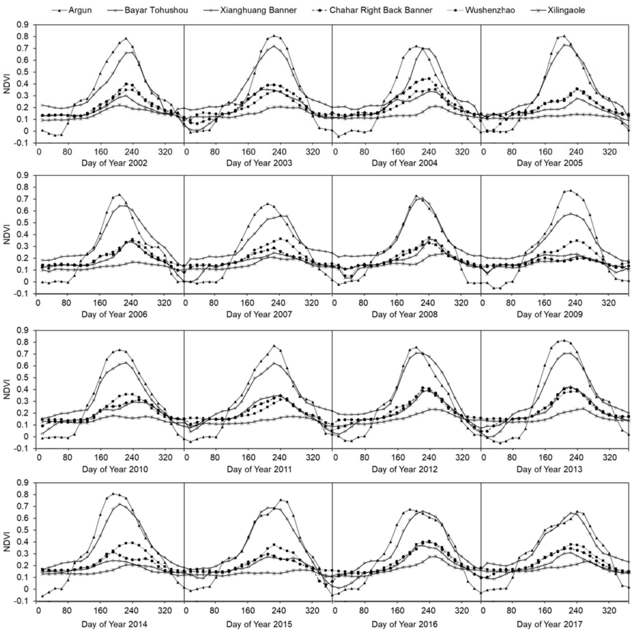

FIGURE 5. Smoothed time series of MODIS-NDVI 16-day composite data from year 2002 to 2017 for six study sites in the Inner Mongolia.

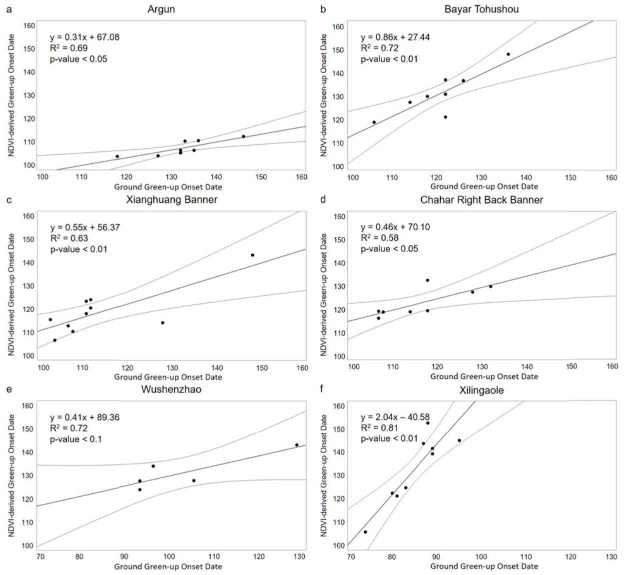

FIGURE 6. Regression of green-up onset date from satellite estimation and ground observation from year 2002 to 2012 at six study sites in the Inner Mongolia (lines show the linear regression, curves show the limits of 95% confidence interval).

TABLE 2. Statistics of linear regression between satellite-estimated green-up onset date and ground data from 2002 to 2012 at six study sites in the inner mongolia.

	Argun	Bayar Tohushou	Xianghuang Banner	Chahar Right Back Banner	Wushenzhao	Xilingaole
n	8	9	10	8	5	9
R^2	0.69	0.72	0.63	0.58	0.72	0.81
p-value	< 0.05	< 0.01	< 0.01	< 0.05	< 0.1	< 0.01
RMSE	1.8	4.6	6.2	4.0	4.3	6.6
Bias^a	-24	10	5	7	28	48

The correlations for all sites are medium to high ($R^2 > 0.58$). It is worth pointing out that gradient of linear regression between ground- and MODIS-NDVI derived dates are differed from sites (0.31-2.04), except that Xianghuang Banner and Chahar Right Back Banner have similar linear equations, might due to their nearby location (Fig. 1; Fig. 6). Besides, most of the remote sensing derived dates are larger than the ground values, except for Argun. There is a negative bias of 24-day at Argun between satellite-estimated green-up onset date and ground observations, while small positive biases of 5-10 days are at Xianghuang Banner, Chahar Right Back Banner and Bayar Tohushou, and large positive biases of 28-48 days are at Wushenzhao and Xilingaole. However, RMSE is small at study sites from 4-6 days, and a minimal RMSE of 1.8 days is occurred at Argun (Table 2).

Evidence derived from MODIS-NDVI estimation indicates the trend on green-up onset date from this approach is in accordance with ground observation, though advanced estimation may occur in snow-cover site. The unsolved problem is what developmental stage of grass can be corresponded to the onset date of green-up derived from satellite methodology. It has been noticed green-up onsets detected with satellite signal reflect the start of active vegetation growth, which is close to the point when gross primary productivity (GPP) rapidly rises up from zero, but later than the first leaf unfolding or budburst – the signal of the start of spring in the ground [32]. The GPP also can be modeled from satellite images and CO_2 flux data [49]. It is worth to notice that ground observation is specie level while satellite-derived phenology is biome-level. The biological meaning of them is not identical. Nonetheless, the green-up onset dates obtained from remote sensing in multi-years are positive correlated with ground observations at the six study sites (R^2: 0.58 – 0.81, Fig. 5). The stability of this method was reliable, and RMSEs at all sites are less than 7 days (Table 2). However, bias between dates derived from remote sensing and observations is highly depended on site locations. Negative bias can exist due to snow-cover, and large bias may happen at sites with sparse vegetation.

V. APPLICATION TO INNER MONGOLIA GRASSLAND

Direct evidence is needed for determining what time is "safe" to start grazing, given that the local policy of seasonal grazing is purely relied on the empirical mode [51]. For example, Wulagai grassland in the east of Inner Mongolia has an open season for grazing since May 20th (DOY 140). However, compared to this fixed date, our result demonstrates there is a time range from early April to early June of green-up onset date at Wulagai grassland (Fig. 3).

TABLE 3. RMSE of linear regression between green-up onset date and meteorological factors.

	Meadow steppe			Typical steppe			Desert steppe		
	25 %	50 %	75 %	25 %	50 %	75 %	25 %	50 %	75 %
Winter precipitation	6.8	8.7	11.6	8.6	11.8	16.6	0	9.9	2069
Spring precipitation	6.6	8.5	11.3	8.2	11.3	16.1	0	9.9	1507
Winter temperature	6.8	8.7	11.5	8.6	11.8	16.7	0	9.8	70.0
Spring temperature	6.8	8.8	11.7	8.7	11.9	16.7	0	9.8	66.7

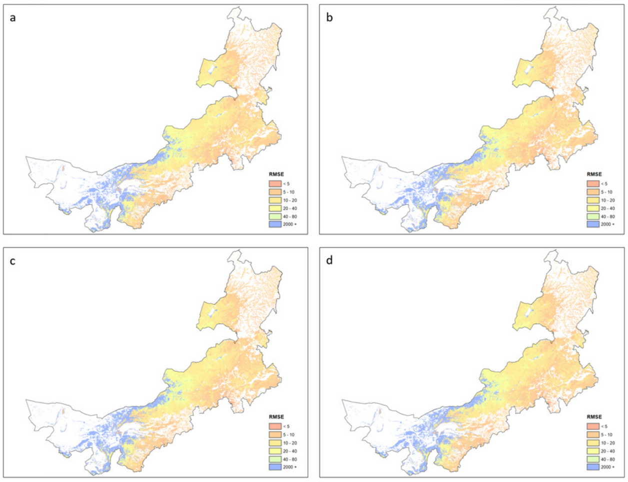

FIGURE 7. Values of the RMSE between the green-up onset date and precipitation (a–b) or temperature (c-d) from 2002 to 2017 over grasslands in the Inner Mongolia: (a) winter precipitation (December-February); (b) spring precipitation (March-May); (c) winter temperature (December-February); and (d) spring temperature (March–May).

Satellite retrieval of spring phenology is intended for use as an objective evidence for grassland management in the Inner Mongolia. In this part, we will use a long-term green-up onset date based on satellite method to demonstrate the interannual and spatial variation and also examine how climate variables affected the spring phenology during the 2002 to 2017 period. The winter and spring precipitation and temperature as independent climate controls for explaining the temporal change in green-up onset date have been evaluated by RMSE value. Spatial distribution of RMSEs have similar patterns within the climate factor in this study (Fig. 7). We also notice that grassland types respond different to climate controls on green-up onset date shift. The linear regressions are fitted best in meadow steppe, with the least RMSE around 7 to 12 days (1st to 3rd quarters), typical steppe has relatively large RMSE around 9-17 days, and desert steppe has extremely large RMSE in the most study areas especially for precipitation as regression variable (Table 3).

TABLE 4. Green-up onset date and corresponding NDVI values from year 2002 to 2017 over three grassland types in the inner mongolia.

Year	Meadow Steppe		Typical Steppe		Desert Steppe	
	Date[a] (DOY)	NDVI[a]	Date (DOY)	NDVI	Date (DOY)	NDVI
2002	121±15	0.26±0.07	122±18	0.19±0.04	115±24	0.13±0.03
2003	120±14	0.25±0.07	116±16	0.20±0.04	121±24	0.14± 0.03
2004	127±18	0.25±0.06	130±21	0.20±0.04	143±32	0.14±0.03
2005	121±15	0.26±0.06	126±22	0.20±0.04	140±35	0.14±0.03
2006	128±15	0.25±0.07	134±20	0.19±0.04	133±35	0.13±0.03
2007	121±17	0.26±0.07	123±20	0.20±0.04	127±24	0.14±0.03
2008	123±17	0.26±0.08	126±18	0.20±0.04	136±31	0.14±0.03
2009	118±16	0.26±0.07	122±16	0.21±0.04	130±26	0.15± 0.04
2010	115±12	0.25±0.07	114±16	0.19±0.04	123±22	0.14±0.03
2011	115±14	0.25±0.07	119±16	0.19±0.04	128±28	0.13±0.03
2012	121±14	0.26±0.07	119±16	0.20±0.04	119±22	0.14± 0.03
2013	117±11	0.26±0.06	121±12	0.21±0.04	137±21	0.15±0.04
2014	117±14	0.29±0.07	123±12	0.23±0.05	130±25	0.15±0.04
2015	117±13	0.27±0.07	119±14	0.21±0.05	115±24	0.14±0.04
2016	121±14	0.27±0.08	121±17	0.20±0.05	118±25	0.13±0.04
2017	110±21	0.28±0.08	118±25	0.22±0.05	138±31	0.15±0.04
Avg.	120±10	0.26±0.07	123±10	0.20±0.04	131±17	0.14±0.04

[a] The statistic are average ± standard deviation values.

We realize there is not a universal approach can be suitable for the entire study area. Satellite-derived data are determined by selection of platform, sensors and phenology retrieval methods. The SG technique performs best for different satellite sensors to reconstruct long-time series datasets [49]. However, it has the limitation for reducing cloud and aerosols' noise, when identifying the maxima and minima of NDVI with small amplitudes [52]. In our study, the low NDVI amplitude is found in the desert steppe due to small amount of vegetation (Fig. 5). Besides, the beginning of the greatest increase phase of NDVI acquiring from moving average method is probably time of snowmelt, instead of green-up onset event [20]. For example, the NDVI curve of Argun has two obviously increase processes (Fig. 5), and its estimates of green-up onset date are much advanced than ground data (Fig. 6; Table 2). Besides, it is hard to have consistent trends in spring phenology based on the different NDVI datasets and retrieving methods for spring phenology [53]. The improvement of satellite-derived spring phenology need eliminating the snow effects on NDVI signal. Another approach is using enhanced vegetation index (EVI), with a reduction of noise contamination, for detecting vegetation phenology [54]. Consequently, the SG filter with moving average method in this study is probably best fitted in medium to dense vegetation and snow-free grasslands, but has a poor performance in sparse and snow-cover grasslands.

VI. CONCLUSION

One of purposes of this study was to apply a robust satellite method on the identification of spring phenology onset based on MODIS NDVI dataset. It appears that results are satisfied in general, which had medium to high positive correlation with ground observations, and clear presented the trend of interannual and spatial changes. But this approach may have limitation of absolute accuracy of the spring phenology onset date, especially at sparse vegetation and snow-cover study areas. Except for those areas, the bias for ground site observations are 5-10 days. More pre-processing for avoiding snow effect will need to perform before this method are accurate for snow-cover grassland areas.

There are significances for application of this method. Importantly, in vast grasslands, detailed information of green-up is hardly available. The consideration of seasonal grazing for present has to sacrifice the spatial variation. This research provided effective information of spring phenology with the time and spatial variation. The deviation of interannual and spatial change of green-up onset had been documented from 2002 to 2017 over grasslands in the Inner Mongolia. Moreover, research tested the impact of climate factors on spring phenology shifting. In short, this study is an initial process presenting the satellite detectable spring phenology in the vast grasslands of the Inner Mongolia, and providing independent verification between green-up and climate variables.

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APPENDIX

See Table 4.

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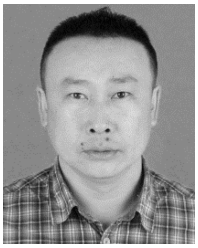

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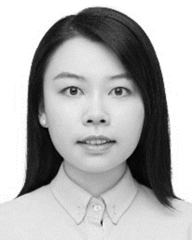

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