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Remote sensing phenology of two Chinese northern *Sphagnum* bogs under climate drivers during 2001 and 2018

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ABSTRACT

Boreal peatlands, of which *Sphagnum* bogs are one of the main types, play essential roles in the terrestrial soil carbon pool. Vegetation phenology is a sensitive indicator that reveals the underlying processes as well as responses to climate change, while currently there remain knowledge gaps in exploring and monitoring the long-term bog vegetation phenology due to insufficient remote sensing application experiences. In this study, we investigated three remotely sensed vegetation phenological parameters, the start of growing season (SOS), the end of growing season (EOS), and the length of growing season (LOS) in two bogs located in norther China by using double-logistic reconstructed MOD13Q1-EVI from 2001 to 2018, which were evaluated by the flux phenology. Also combing with meteorological data to detect interactions between vegetation phenology and climate change. The results showed that remotely sensed EOS had 8-day time lags with flux phenological date, while that outperformed SOS. Bog vegetation generally with a life pattern of SOS at the 108th day of year (doy) and EOS at the 328th doy, though the life cycle of individual vegetation groups varies among different vegetation communities. There was no significant delayed (or extended) trend in each phenological features in bogs. Precipitation and minimum temperature (monthly and annual) were the driving forces for bog vegetation growth ($R^2 > 0.9$, $P < 0.01$), and other features presented weaker correlations. Overall, this study determined the remote sensing phenology and climate drivers in two Chinese bogs, we suggested that vegetation phenology alternation should be concerned when carry on ecological processes and carbon dynamics researches in peatlands.

1. Introduction

Phenology refers to the periodic growth characteristics of vegetation (such as germination, flowering, fruiting, deciduousness, etc.). It can indicate vegetation productivity, as well as the carbon reserve and carbon dynamics of ecosystems (Myneni et al., 1997), thereby reflecting vegetation responses and adaptations to climate change (Piao et al., 2019). The key parameters of vegetation phenology studies are: the start of growing Season (SOS), which is the date when vegetation starts to grow or photosynthesis resumes; and the end of growing Season (EOS), which is the date when vegetation photosynthesis or the green leaf area begins to decline rapidly. Giving that these two dates determine the length of growing Season (LOS) of vegetation, which is associated with effective photosynthesis periods (Zhang et al., 2003, 2018), and are severely affected by climate changes, especially temperature (Wu, 2012), there are requiring investigate to not only define each phenological phenomena but also clarify climatic influences or drivers.

Peatlands are mainly distributed in northern high latitudes (above 45° N) (Roulet, 2000), which are facing heavier climate threats (IPCC, 2018; Hansen *et al.,* 2006). Although peatland ecosystems account for only 3% of the land area (Maltby and Immirzi, 1993), they do have fixed ~ 20–30 g of CO_2 per year that from a dominated bog vegetation, *Sphagnum* (peat moss) (Fig. 1) (Clymo and Hayward, 1982; Loisel et al., 2012) since the Holocene. Also, peatlands are regarded as a persistent sink of atmospheric carbon (Gorham, 1991; Roulet et al., 2007; Yu, 2012) in a global scale. Due to climate warming, the surface hydrological patterns and trophic status of peatlands, thereby alternating the vegetation phenology, then the amount of carbon sequestration (Lunt

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et al., 2019). Many studies have showed that higher temperatures have advanced the vegetation SOS, delayed the EOS, and prolonged the LOS (Badeck et al., 2004; Penuelas et al., 2009; Wang et al., 2014; Meng et al., 2016). These results mainly from forests and agricultural areas; however, the phenology may differentiate among diverse ecosystems, and their responses to climatic change are also separate (Richardson et al., 2009). Considering that peatland vegetation is sensitive to land surface conditions, where being over wet with a low permeability, and its growth rhythm would be different from that of general terrestrial vegetation (Aerts and Dorrepaal, 2006).

Moreover, there were several studies that linked peatland vegetation phenology to carbon fluxes also the climate. Peichl et al., (2018) discussed peatland vegetation phenology as the main factor caused the seasonal fluctuation of gross primary productivity (GPP). The experiments of Kross et al. (2014) in four boreal bogs showed that peatland vegetation phenologies have strong correlations with climatic features, such as precipitation and temperature, relating to annual CO_2 accumulation of ecosystems. Although the two studies mentioned above experimentally demonstrated the potential relationship among phenology, organic matter accumulation, and climatic threats of peatlands, they did not present the long-term phenology tends of dominant peatland vegetation as well as in a broader scale to explore the linkage between climatic factors and phenological features.

Because *Sphagnum* bogs are distributed in remote boreal areas, traditional phenological observation methods cannot provide long-term, large-area support data. Remote sensing technology has the advantages of traceability, wider spatial range, and high efficiency. It has been widely applied to terrestrial resources monitoring (White et al., 2009; Tan et al., 2011; Hmimina et al., 2013; Melaas et al., 2013; Zhao and Liu, 2014; Tian et al., 2015), also in recent decades more practises were put in ecological processes, like vegetation phenological detection via various satellites platforms revealing responses of vegetation to climate change (White et al., 2009).

Multitemporal remotely sensed images modelized vegetation growth procedures through surface greenness information to derive plant phenological parameters, i.e., SOS, EOS and LOS. Based on studies that proved the ability of satellite products to monitor surface phenology and evaluated pheno-simulating methods across ecosystems (Hufkens et al., 2012), while Double-Logistic (DL) algorithm is more suitable for tracing boreal peatland ecosystems with Moderate Resolution Imaging Spectroradiometer (MODIS) data (Zhanzhang et al., 2017). Moreover, noting that majority research assessed the possibility of using Normalized Difference Vegetation Index (NDVI) to extract surface phenology, while Pang et al. (2019) pointed out that plant cover percentage in peatlands are quite high, and EVI was the ideal indicator for driving peatland vegetation phenology.

In this study, we aim to apply MODIS EVI timeseries data from 2001 to 2018 that was reconstructed by the DL function to obtain the vegetation phenological information, i.e., SOS, EOS and LOS of two *Sphagnum* bogs. And these remotely sensed phenological features were firstly evaluated by a closely flux tower referred phenology, then linked to meteorological data to explain plants' responses to climate. In special, we tend to address two research questions: (1) what is the remotely sensed phenology of *Sphagnum* bog vegetation and how it alters over the past decades? (2) What are the interannual trends in their phenology, and how do they respond to climate change?

2. Materials and methods

2.1. Study sites

We selected two typical *Sphagnum* bogs, Jinchuan and Hani, in northern China as study areas (Fig. 2). The Jinchuan *Sphagnum* bog (42°20′56″N, 126°22′51″E, 625 m asl) is located in the Longwan National Nature Reserve, Jilin Province, and has an area of approximately 72 ha that is nearly elliptical with a diameter of about 1 km and belongs to a small basin formed by a crater, where the deepest thickness of peat is 7 m (Yu, 2010; Teng, 2016). The Hani *Sphagnum* bog (42°12′20″-42°13′45″N, 126°3′-126°38′E, 900 m asl) is located in the Hani National Nature Reserve, Jilin Province and is the largest peatland in China, with a total area of 1302 ha (Wang et al., 2013).

The surface of the Jinchuan *Sphagnum* bog is flat, and the sedge hollow-hummock microlandscape coverage is 50% −60%. The dominant species of this community are *Betula ellipse* and *Carex schmidtii* on the edge of the bog, and *Sphagnum palustre* is a representative moss distributed under the shrub layer (Yu, 2010). For the Hani *Sphagnum* bog, the vegetation is zonal, and the intercommunity transition phenomenon is obvious (Song et al., 2019). The central part is *Carex-Sphagnum palustre*, accompanied by cotton *Eriophorum-vaginatum*, *Ledum-palustre* var. *dilatatum*, etc.; woody plants are scarce, and the surrounding forests are densely populated with the *Larix olgensis-Betula ovalifolia-Carex schmidtii Meinsh* community (Wang et al., 2013; Song et al., 2019).

2.2. Remote sensing data and phenology extraction

The EVI dataset was derived from the 16-day MODIS EVI composite product (Collection 6 of MOD13Q1) of Jinchuan and Hani *Sphagnum* bogs in 2001–2018 through the *AppEEARS* (Application for Extracting and Exploring Analysis Ready Samples) platform (https://lpdaacsvc.cr.usgs.gov/appeears/) on the LP DAAC website. This dataset has been geometrically and atmospherically corrected, with a time resolution of 16 days and a spatial resolution of 250 m, i.e., covering land area of 6.25 ha in a pixel.

Affected by clouds, snow, water vapor, aerosols, the solar height angle, and other factors, there are irregular fluctuations and abnormal values in the original EVI time series curves (Fig. 3). Studies have showed that in high latitudes, the DL function has a general advantage in eliminating potential noise in remote sensing time series data (Beck et al., 2006), and is more suitable for estimating biophysical parameters

Fig. 1. The Hani peatland (left), and *Sphagnum palustre* (right) in China (photographed during a field investigation on August 20, 2019).

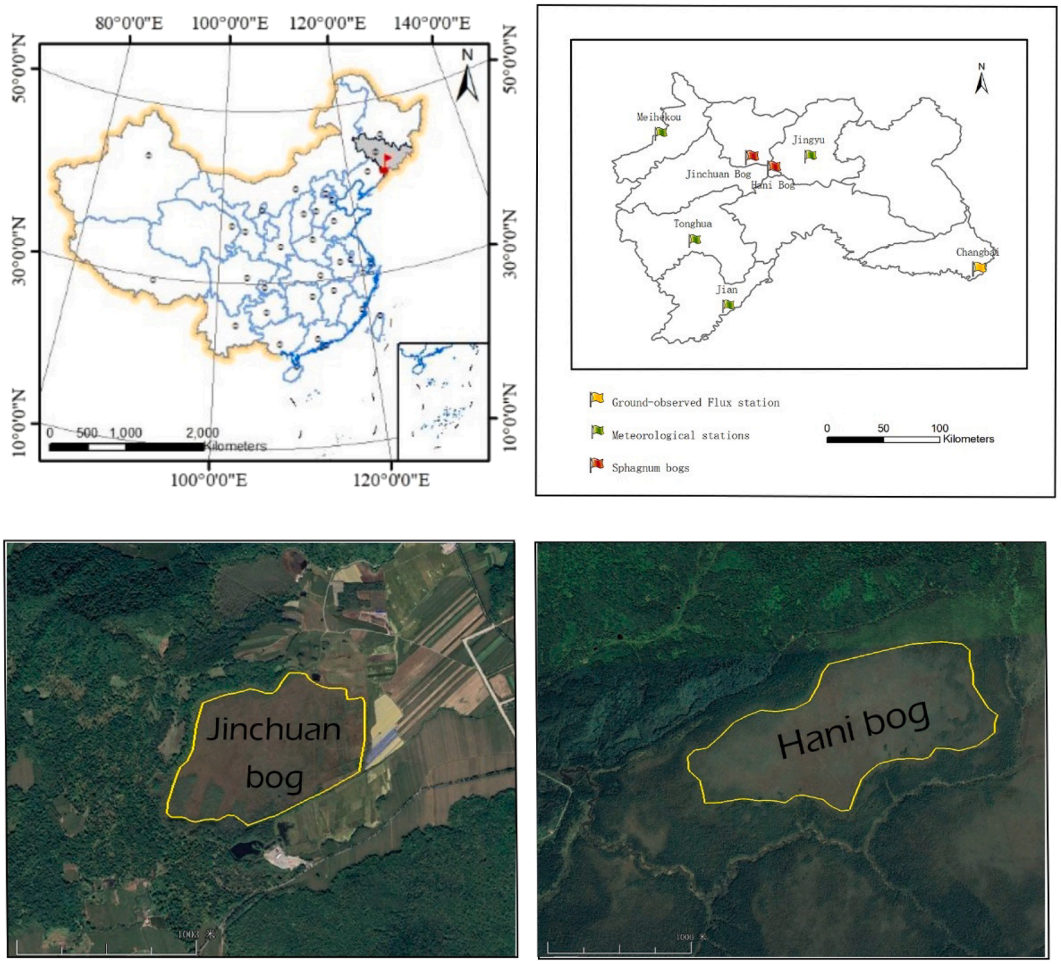

Fig. 2. Map sketch of the research area, with a base map of a true color Sentinel-2A image of minimum cloud synthesis from May to October in 2018.

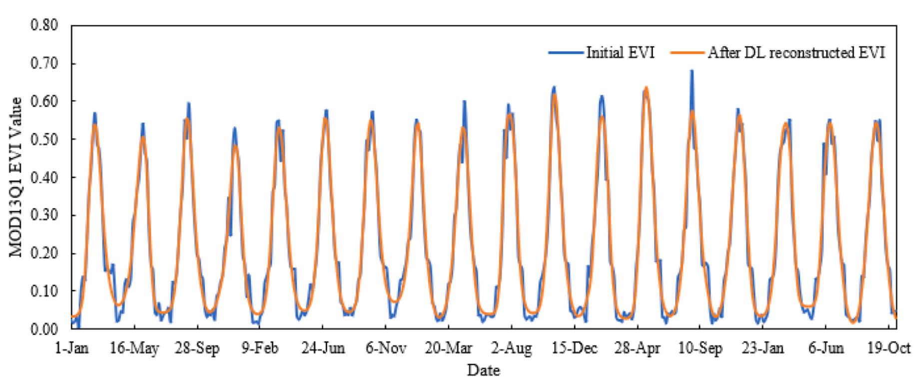

Fig. 3. MOD13Q1 EVI time series curves (2003–2010).

and monitoring vegetation phenology (Hird and McDermid, 2009). Therefore, in this study, the DL method provided by TIMESAT 3.3 was utilized to reconstruct EVI curves (Fig. 3) and to obtain the bog vegetation phenological parameters of SOS, EOS, and LOS.

2.3. Ground-observed phenology data

Because there are no ground phenological observation sites corresponding to the *Sphagnum* bogs, the daily carbon flux data from the Changbai station (Fig. 2, 42°24′E, 128°05′N, 763 m asl.), which is the closest Flux tower to the Jianchuan and Hani bogs, from 2003 to 2010 were collected from the National ecosystem observation and Research Network (http://www.cnern.org.cn/) to verify the extraction accuracy of the remotely sensed phenology.

2.4. Climate data

The global climate is driving changes in the vegetation surface phenology by shifting air temperatures, precipitation, and sunshine hours (Richardson et al., 2013). Representative meteorological data from four stations (Meihekou, Jingyu, Tonghua, Jian, Fig. 2) near the two *Sphagnum* bogs were obtained during the period of 2001 and 2018 from the China Meteorological Data Network (http://data.cma.cn/), and these data include the monthly maximum temperature, monthly minimum temperature, monthly average temperature, monthly precipitation, monthly precipitation days, and monthly sunshine hours. During the analysis, the mean values between the four stations for each meteorological parameter were calculated, and the six meteorological datasets uniformly describing the climatic conditions were obtained.

2.5. Analysis

To evaluate the remote sensing phenology, we calculated the Pearson correlation coefficients and root mean square errors (RMSEs) of the SOS and EOS with ground phenology dates derived from the daily carbon flux, respectively. The monthly EVI dataset was generated using the monthly maximum synthesis method, which corresponded to the monthly climate data from the meteorological station, and the Pearson correlation coefficient was calculated to reveal the effect of climate on the entire growth process of bog vegetation. When assessing the impact of climate on bog surface phenology, due to the interactions among temperature, precipitation and sunshine time, we not only calculated the Pearson correlation coefficients with EVI, EOS, SOS, and LOS but also used partial correlation coefficients to measure the degree of association between the EVI parameter and the GPP parameter in pairs. Additionally, the following univariate linear regression model was calculated using the least squares method, temporal trends of bog phenology, and meteorological variables represented by the slope (k):

$$k = \frac{n\sum_{i=1}^{n}(i \times p) - \sum_{i=1}^{n}(i)\sum_{i=1}^{n}(p)}{n\sum_{i=1}^{n}(i^2) - \left(\sum_{i=1}^{n}(i)\right)^2} \quad (1)$$

where, n is the cumulative number of years, which is 18 in this study; i represents the selected year, taken from 2001 to 2018; p_i is the SOS, EOS, LOS, temperature, precipitation, or sunshine time value in year i; and k is the slope of the regression model, where $k > 0$ indicates that the variable tends to delays (increases), and otherwise, it advances (decreases). All of the above analyses used p-values to evaluate the results, where $p < 0.05$ indicates a significant difference and $p < 0.01$ indicates a very significant difference.

3. Results

3.1. Validation of remote sensing phenology

The remotely sensed vegetation phenological features (SOS and EOS) were correlated with the flux phenology based on the Changbai station. As Table 1 showed that the correlation coefficient of the EOS was 0.63 much higher than that of the SOS, i.e., 0.05, and their RMSEs were 8.0 and 33.4 days, respectively. These acceptable accuracies of remote sensing phenology determined that remote sensing could use to can tracing boreal peatland phenology, though the extraction accuracies vary among years and phenological parameters.

Table 1
Remote sensing phenology inspection statistics.

Year	EVI-SOS (doy)	EVI-EOS (doy)	GPP-SOS (doy)	GPP-EOS (doy)
2004	116	301	103	284
2005	122	289	112	288
2006	120	298	125	299
2007	123	315	93	303
2008	126	294	81	293
2009	98	307	66	286
2010	114	320	74	294
Pearson	0.041	0.627		
RMSE	33.415	8.036		

Note: EVI refers to the MOD13Q1 EVI dataset; GPP refers to the flux data from Changbai ground station; GPP-SOS/GPP-EOS refers to the use of the GPP to obtain the surface phenological parameters; and doy means the day of year.

3.2. Characteristics of vegetation phenology in *Sphagnum* bogs

As illustrated in Fig. 4, the range of the EVI of the coniferous and broad-leaved mixed forests was [0.1,0.6]. Before the beginning of April, they were dormant, after that they began to grow in early May and ended in later October. The interannual patterns of the EVI values of mixed forests and their curves were similar in the two bogs, and almost coincided. For the bog vegetation, the EVI value was approximately 0.05 in early spring, which is lower than that of the mixed forests, and reached the maximum value in mid-July. At that time, the EVI value was only slightly lower than that of mixed forests. The similarity of the EVI curve of the bog vegetation was not as good as that of the mixed forests, but the general rules were similar Table 2.

For the growing dates, the SOS of the *Sphagnum* bog vegetation was approximately the 108th of the year (in mid-April) that was 21 days ahead of that of forests; in addition, the EOS was at 328 doy (in early November) that 21 days later than the forests, and both the SOS and EOS contributed to a longer LOS, thereby these all leading to separable growth cycles between inner and outer bog vegetation (Table 1).

Based on the statistics of the monthly interannual variation of the EVI values of the two *Sphagnum* bogs, the growth season of their surface vegetation was from June to August, and May and September were the turning periods for the growth status; in the other months, the vegetation growth was weak, and the vegetation was dormant or waiting for recovery (Fig. 5a). On the whole, the EVI of the Jinchuan bog was higher than that of the Hani bog, while the range of the EVI value of the Hani bog during the vigorous growth season was lagger than that for the Jinchuan bog.

From the perspective of the interannual change of the EVI value, the highest fluctuation of the EVI value in the growing period is also the most obvious. The Jinchuan bog in the transition period has large fluctuations in 2002 and 2015, while the other initial changes are not obvious. Whether it is Jinchuan or Hani Marsh, the EVI value of the dormant period is extremely low i.e., approximately 0.1, and there is almost no fluctuation.

3.3. Temporal trends of bog phenology and climatic conditions

In the past 17 years, the *Sphagnum* bog vegetation phenology surface has been relatively stable, and the trend is not significant, but the phenological value of some years, such as 2003 and 2010, has changed greatly. As showed in Fig. 6, in general, the temporal phenology patterns of the two bogs were similar, but the three parameters of the Jinchuan bogs are delayed (or increased), while the SOS of the Hani bog was delayed, and the EOS and LOS appeared to have been advanced (or reduced). In the past 17 years, the phenology of bogs did not show a trend, which indicates a smoothly running process. However, in 2003, there was a sudden increase in the LOS in the Hani bog; and in 2010, the SOS of both bogs advanced earlier. Additionally, compared to the EOS and LOS, the fluctuation period of EOS does not exceed 20 days. From the perspective of the trend, the phenology of the Hani bog has a stronger trend than that of the Jinchuan bog, especially the LOS, and its annual advance reaches 1.12 ds. For the Jinchuan bog, its EOS was delayed by 0.14 d/a, which was faster than its LOS and SOS. Moreover, the shrinking of the LOS of the Hani bog was a result of the combined influence of the delayed SOS (0.56d/a) and the advanced EOS (0.53d/a).

The climate changing trend of the bogs was stronger than that of their phenology. The linear regression results of five meteorological data variables (annual minimum/maximum/average temperature, annual precipitation, and annual precipitation days) from four meteorological stations show that the temperature has slightly increased in the past 18 years, with an annual minimum and maximum temperatures of 0.144 ℃/a and 0.021 ℃/a, respectively. While the annual average temperature remains stable, the temperature pattern shows higher maximum temperatures and lower minimum temperatures, that is, an increase in extreme weather (Fig. 7). For precipitation, it varies greatly from year to

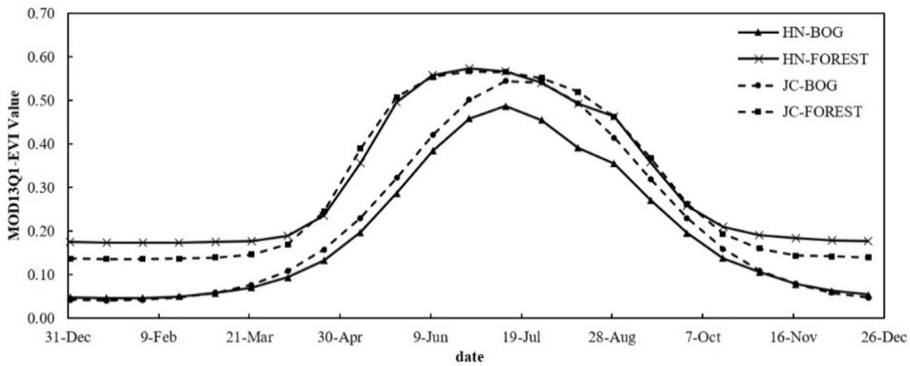

Fig. 4. Bogs surface phenological characteristics of inside and outside.

Table 2
JC & HN bogs surface phenological rhythm (doy).

Year	JC-BOG-SOS	HN-BOG- SOS	JC-FOREST-SOS	HN- FOREST-SOS	JC-BOG-EOS	HN-BOG-EOS	JC-FOREST-EOS	HN- FOREST-EOS
2002	110	115	100	113	332	333	305	294
2003	95	81	114	117	311	350	294	309
2004	107	90	121	121	331	330	307	286
2005	95	114	115	130	332	317	300	298
2006	105	118	124	133	336	336	314	331
2007	112	122	123	128	330	323	318	320
2008	106	125	117	130	330	317	314	301
2009	106	110	102	114	331	326	318	304
2010	88	85	112	112	323	315	304	285
2011	128	122	128	128	325	325	302	301
2012	114	128	122	128	333	325	314	299
2013	109	117	118	122	326	333	318	317
2014	118	117	120	128	330	331	318	301
2015	99	104	98	126	339	330	328	307
2016	88	107	102	115	325	328	301	310
2017	99	106	118	123	320	307	310	302
2018	109	115	118	125	336	334	302	302
Average	**105**	**110**	**115**	**123**	**329**	**327**	**310**	**304**

Note: JC& HN stand for Jinchuan and Hani *Sphagnum* bog, respectively; BOG & FOREST refer to the vegetation types inside and outside the bog, respectively.

year, especially in 2010, which was the turning point of the precipitation pattern (Fig. 8). Before 2010, both the precipitation and its days in the bogs showed an increasing trend, and the rates were 30.87 mm/a and 2.95d/a; after 2010, they decreased, with rates of −39.7 mm/a and −2.6 d/a. The development of the bog was controlled by precipitation, which plays a decisive role in bog vegetation growth process by affecting the surface hydrological conditions. Therefore, combining the vegetation phenology and precipitation of the bogs approximately 2010, it was found that the LOS peaked in that year, and the SOS and EOS also reached extreme values.

3.4. Correlation analysis between bog surface phenology and climatic conditions

Temperature and precipitation play a positive role in the growth of bog vegetation, and the lower temperature was the key factor. The correlations and partial correlations between the monthly EVI value and the meteorological factors show that the correlation between the temperature and the EVI value was better than that of precipitation and much stronger than that of sunshine duration (Table 3). All meteorological factors were positively correlated with the EVI values, and the correlation coefficients of precipitation and precipitation days with the EVI value were close. The lower temperature promoted the growth of dominant cold-wet bog vegetation, showing better vegetation conditions. Among them, the monthly minimum temperature was significantly positively correlated with the EVI value (R^2: 0.94 of JC, 0.925 of HN, $p < 0.01$, Table 3). Additionally, the relationship between the monthly average temperature and the EVI value also exceeded 0.9, which was higher than that of the monthly maximum temperature, indicating that higher temperatures have a negative effect on bog ecosystems. The increase in the precipitation and precipitation days were beneficial to the bog environment, and the effect of precipitation was better than the accumulation of precipitation over time. The sunshine duration has the weakest function, with a correlation coefficient of approximately 0.3 ($p < 0.01$), for bog vegetation, which was related to the lower amount of sunshine time in the boreal area (Table 3).

After controlling the monthly minimum temperature and monthly precipitation variables of the highest correlation coefficient, the partial correlation coefficients show that the monthly minimum temperature limits the positive correlation between the temperature and the sunshine duration to the bog vegetation and resulted in negative effects. In other words, low temperatures dominated the growth of bog vegetation, and as the temperature increased, the expansion in the sunshine duration was not conducive to the ecological cycle of the bog. Meanwhile, only precipitation and precipitation days still maintained positive correlations with the EVI value. In the case of controlled monthly minimum temperatures, the correlation coefficient between all other factors and the EVI value was greatly reduced. Conversely, by controlling the precipitation, temperature promoted the growth of bog vegetation; the monthly minimum temperature was still the main driving factor, and its R^2 value exceeded 0.8 ($p < 0.01$) (Table 3). All other factors have positive effects on the bog; in particular, the correlation between sunlight and the EVI value was greatly improved, indicating that the function of sunlight was closely related to that of precipitation (Table 3).

Precipitation was the main driving force for the bog phenology. The statistical results of the correlation coefficient between the bog

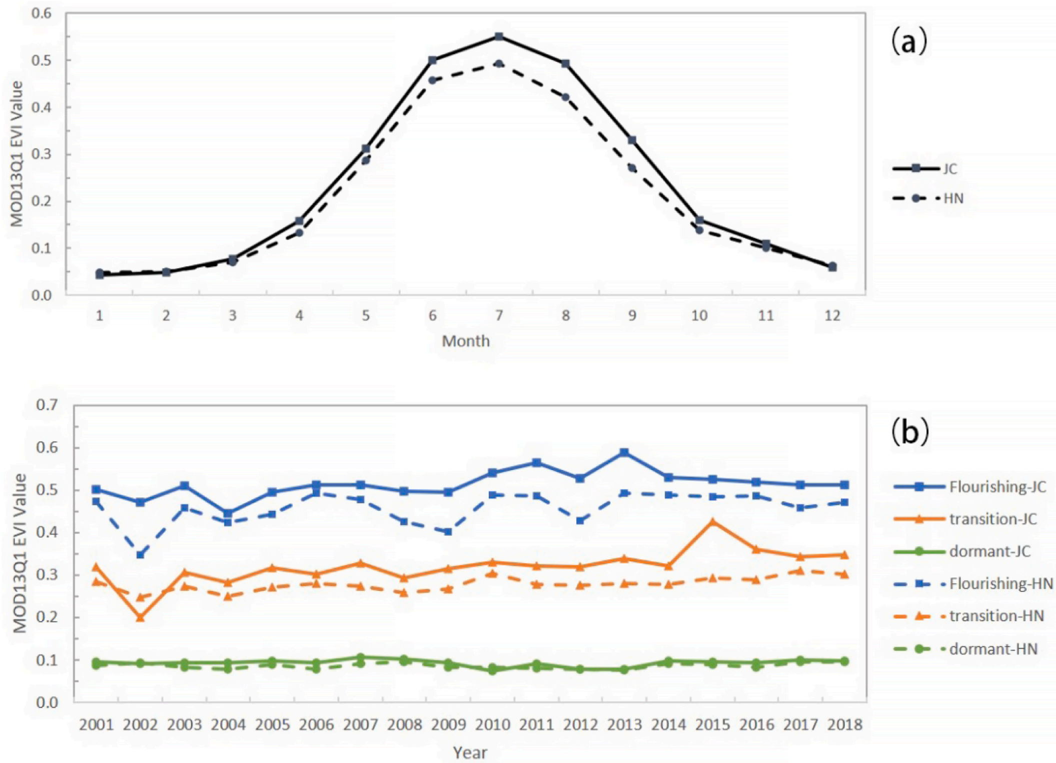

Fig. 5. The interannual variation of EVI in flourishing period, transition period and dormant period of the vegetation growth state of *Sphagnum* bogs.

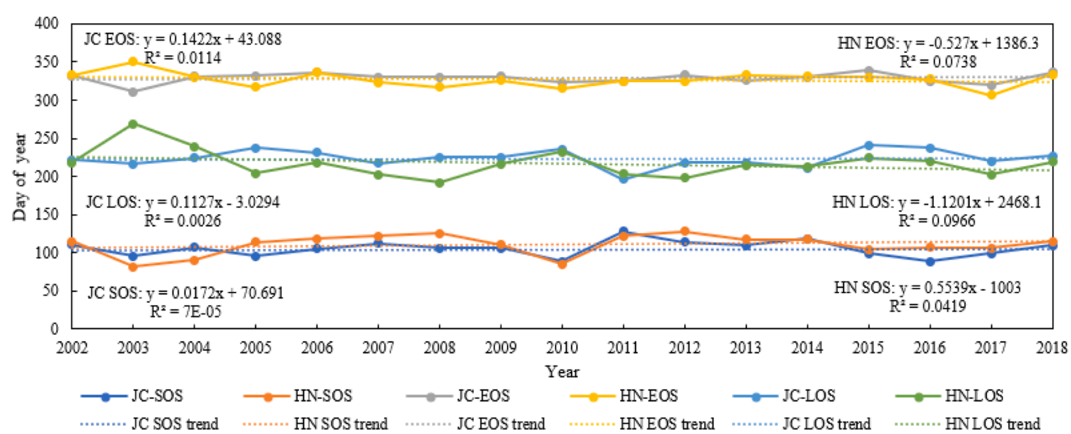

Fig. 6. Temporal trends of bogs phenology.

phenology and the meteorological factors show that vegetation growth rhythm, especially the SOS, had the best correlation with the average annual precipitation and the annual precipitation days, followed by the annual minimum temperature (Table 4). The SOS was regulated by precipitation and precipitation days, and there was a significant negative relationship ($R^2 = -0.52$, $p < 0.05$), indicating that increasing precipitation contributed to an earlier SOS; however temperature had no significant relationship with the SOS. In contrast, the EOS were controlled by both the annual minimum temperature and the precipitation, with negative correlations. As the temperature decreased, the EOS was delayed. Both the SOS and the EOS were sensitive to climate change, and the LOS determined from them were also mainly affected by precipitation. As showed in Table 4, the temperature had different effects on the LOS of the two bogs. The temperature had a weaker relationship with the LOS of the JC bog, but there were negative and positive correlations between the annual extreme temperatures (maximum and minimum) and the average temperature with the LOS of the HN bog, respectively. Therefore, based on the regional climate background, an increase in the average temperature could promote the LOS and improve carbon accumulation in bogs.

4. Discussion

4.1. Verification analysis of remote sensing phenology

At present, the satellite vegetation indices are widely used to deduce the vegetation phenology (Hmimina et al., 2013). Giving that these remotely sensed phenological features are modulizations of surface conditions, verification assessments are based on field measurements, although such phenological observation networks, such as phenocams (Brown et al., 2016) have been gradually established at the beginning of the 21st century (Wu et al., 2017), or higher resolution remote sensing datasets are required. Additionally, in some ecosystems, such as northern peatland and tundra, there are a lack of the long-term ground

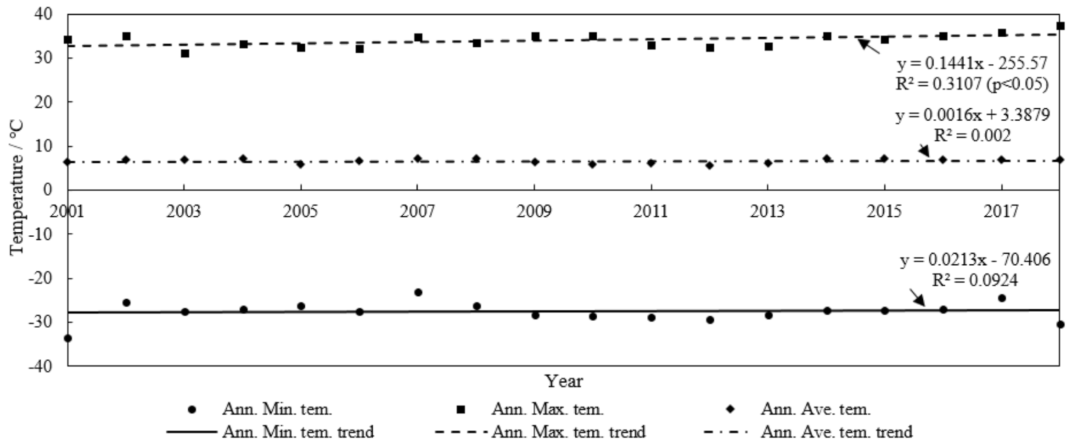

Fig. 7. Temporal trends of temperature.

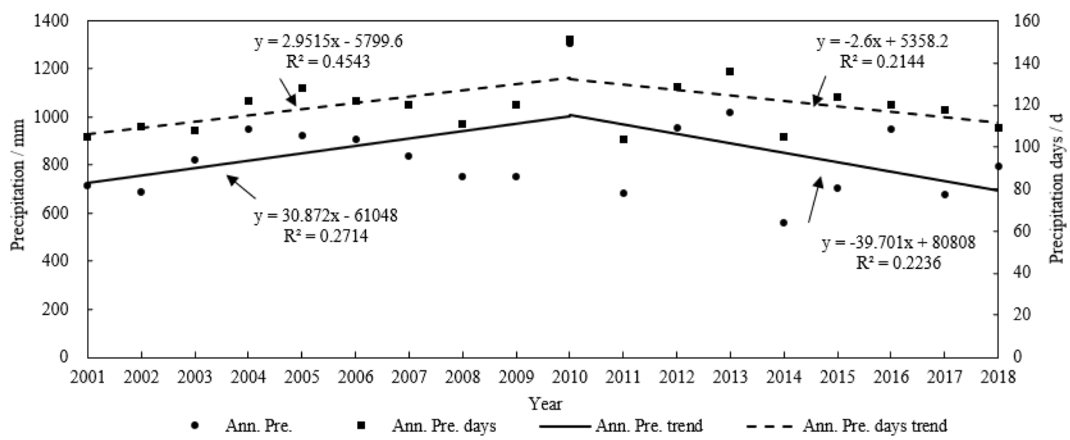

Fig. 8. Temporal trends of precipitation and precipitation days.

Table 3
Statistical correlation between the EVI value and the meteorological factors.

Mete. factors		Monthly Max. Tem. (°C)	Monthly Min. Tem. (°C)	Monthly Ave. Tem. (°C)	Monthly Pre. (mm)	Monthly Pre. Days (d)	Monthly sunshine duration (h)
JC	Cor. Co.	0.852**	**0.94****	0.919**	**0.774****	0.66**	0.313**
	Partial Cor. Co.	−0.357**	Controlled	−0.121	0.337**	0.318**	−0.207*
		0.75**	0.863**	0.838**	Controlled	0.184	0.562**
HN	Cor. Co.	0.831**	**0.925****	0.901**	**0.774****	0.662**	0.296**
	Partial Cor. Co.	−0.371**	Controlled	−0.134*	0.343**	0.325**	−0.215*
		0.708**	0.827**	0.801**	Controlled	0.192*	0.535**

Note: JC refers to the Jinchuan *Sphagnum* bog; HN refers to the Hani *Sphagnum* bog; Max., Min., Ave., Tem., Pre., and Cor. Co. are abbreviations for maximum, minimum, average, temperature, precipitation, and correlation coefficient, respectively.
**Indicates a significant correlation (two-sided) at the 0.01 level, and. * indicates a significant correlation (two-sided) at the 0.05 level.

observation data, which restrict the accuracy evaluation of remote sensing phenology (Garrity et al., 2011). Researchers, in recent decades, have been used the flux tower data to evaluate remote sensing phenology that at the landscape scale (Gonsamo et al., 2012; Wu et al., 2017), though there were scale differences and adaptation errors (D'Odorico *et al.,* 2015), and in norther ecosystems been proved have acceptable performance (Zhao et al., 2020) than other areas and other alternative methods (Garrity et al., 2011). Some update studies (Zhao and Liu, 2014), have used photosynthetic phenology (chlorophyll fluorescence) instead of green index phenology to reflect the ecological process, and they have good conclusions in forest systems (Xiaoliang et al., 2018), while whether this method can be efficiently applied to boreal regions requires further explorations (Wang et al., 2017).

In our study, we obtained flux-based phenology that applied to assess remotely sensed phenological features, though this flux station has typical norther plant communities and away from the bog sites, and our pheno-results resemble other boreal peatland areas where have similar land surface covering conditions and also evaluated their satellite phenology by a forest flux tower (Eklundh et al., 2011). Our results present that on the phenological rhythm of *Sphagnum* bogs, the SOS was in the middle of April (the 108th day of year), and the EOS was in the end of November (the 328th day of year), both of which were supported by the GPP seasonal patterns of peatlands vegetation recorded by the phenology cameras exhibitions of Peichl *et al.* Furthermore, Eklundh et al. (2011) compared the relationship between ground phenology detecting and satellite data calibration at 5 sites (two of which are

Table 4
Correlation between the bog phenology and the meteorological factors.

Mete. factors	Ann. Min. Tem. (°C)	Ann. Max. Tem. (°C)	Ann. Ave. Tem. (°C)	Ann. Pre. (mm)	Ann. Pre. Days (d)	Ann. Sunshine Duration (h)
JC-SOS	−0.14	−0.059	0.016	**−0.52***	−0.506*	0.425
HN-SOS	0.035	0.046	−0.137	**−0.373**	−0.265	0.054
JC-EOS	−0.132	0.219	0.058	−0.145	0.039	0.197
HN-EOS	**−0.352**	−0.333	0.279	−0.118	−0.344	−0.04
JC-LOS	0.037	0.182	0.018	0.428*	**0.528***	−0.287
HN-LOS	−0.208	−0.211	0.226	**0.239**	0.033	−0.057

Note: The abbreviations are consistent with Table 3.

peatlands) and pointed out that MODIS-NDVI are proper for phenology monitoring of peatlands; the phenological parameters obtained in this study were similar to their results, that is, the peatland vegetation growing season begins on the 100th day and ends on the 315th day.

4.2. Relationship between bogs vegetation phenology and climate

Although we merely associated monthly meteorological data with the bog remote sensing phenology, there existed several studies that successfully determined climate drivers and relationships between satellited phenology and station climate measurements in norther ecosystems (Yu et al., 2014). As meteorological observations normally interpolated, which are promising to combine regional bioprocesses, to be associated with regional-scale phenology and to track long-term ecosystem trajectories (Yang et al., 2012; Kaspar et al., 2015). In our case, we linked phenological features to climate factors, though there were quite studies investigated the collaboration between water tables and vegetation activities (Breeuwer et al., 2009), and temperature and participation more likely to alter the life cycle of bog vegetation (Mäkiranta et al., 2018). However, the effect of climate on the ecological processes of vegetation is complex, and we cannot describe these complex processes through simple variables. Hence, we pointed out that the correlation between climate and phenology was weaker from both single-factor and multifactor perspectives. Therefore, future studies can include climate models or vegetation dynamics models to analyse the interaction of biology and energy for the ecosystem as a whole.

In the study, we stated that the minimum temperature (monthly or annual) and precipitation were the driving forces for bog vegetation growth, though these linages not quite significant. Likewise, in other ecosystems, the long-term phenological alternations impossible well explained with only a few meteorological factors (Wang et al., 2019). On the one hand, the temperature around the bogs has had no significant tendency in the past 18 years, while the precipitation abruptly changed approximately 2010, and together, these factors led to no tendency for change in the bog phenology. On the other hand, the prominent changes of precipitation in some years, such as 2003 and 2010, could quickly response to phenology (Fig. 6), indicating that climate regulates the bog vegetation growth process. Furthermore, among we selected climatic factors, the effect of sunshine time was the weakest, which may due to the stronger radiation and longer durations during summer or vegetation growing seasons in the boreal area (Baldocchi et al., 2000), declining the vegetation sensitivities to light changes, and the fact that peatlands are mostly in basins where the surrounding vegetation is mixed broadleaf-conifer forests, leading to the amount of solar radiation absorbed by mosses is scarce (Liu et al., 2019).

Many previous studies have concluded that the SOS advanced in the boreal due to temperature increases (Piao et al., 2011; Zhang et al., 2017), and the SOS of *Sphagnum* bogs obtained in this study also exhibited signs of delay, which contributed to the unusual growth trends of *Sphagnum* compared to vascular plants (Peichl et al., 2018), such as forests, crops, and grasslands (Bu et al., 2011). Nevertheless, few studies have tested the distinguishment between *Sphagnum* phenology and that of other community plants (Eklundh et al., 2011; Kobayashi et al., 2016). Comparing the phenology inside and outside the bogs, we found that the internal vegetation SOS was earlier than that of in external, and the bog EVI value was quite low, i.e., around 0.1, during dormancy.

5. Conclusions

We derived the vegetation remote sensing phenology of two norther bogs in China, which exhibited acceptable accuracies compared with flux phenological features. Our results determine that the growth pattern of bog vegetation and external forests are separated that means internal bog plants have shorter growth periods with seven months in the dormant, while the phenological characteristics of the two bogs were similar. In last two decades, there were no significant alternation trends in bog phenology, also that trends diffracted in two bogs.

Although it is difficult also impossible to concentrate phenological changes to individual climatic factors, because there are always jointly impacts, we could point out that temperature (especially the monthly minimum or annual minimum temperature) and precipitation are the keys to driving bog vegetation growth. There are also several uncertainties between remotely sensed and flux phenological features, and insufficient climatic analysis. Hence, in future, through the assimilation of ground observation networks, such as Phenocams, and fine-scale remote sensing inversion data, our knowledge of the material and energy cycles of boreal ecosystems can be improved.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

All authors conceived the ideas underlying the study. The experiments were designed by Yuwen Pang and Junfeng Xu. Yuxin Huang and Yinying Zhou co-processed parts of the remote sensing data, Li He and Jun Sui assisted in the field inventory of the Hani bog. Finally, this manuscript was written by Yuwen Pang.

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