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Satellite monitoring of boreal forest phenology and its climatic responses in Eurasia

Haibo Li\textsuperscript{a}, Cuizhen Wang\textsuperscript{b}, Lijuan Zhang\textsuperscript{a}, Xiaxiang Li\textsuperscript{a} and Shuying Zang\textsuperscript{a}

\textsuperscript{a}Key Laboratory of Remote Sensing Monitoring of Geographic Environment, College of Geography Sciences, Harbin Normal University, Heilongjiang Province, Harbin, China; \textsuperscript{b}Department of Geography, University of South Carolina, Columbia, South Carolina, USA

ABSTRACT

The fragile ecosystems in boreal Eurasia are sensitive to global climate change. Land surface phenology provides an important tool for us to better understand the current status of boreal forest and its climatic responses in this remote zone. This study utilizes the new-generation AVHRR GIMMS NDVI3g products in 1982–2011 to extract four phenological metrics in the study region, including start of season (SOS), end of season (EOS), season length (LOS), and middle of season (MOS). Linear and Mann–Kendall trend analyses are performed to examine their spatiotemporal patterns and relationships with climatic variables assisted with the Climate Research Unit re-analysis climatic data sets. While advanced spring greening is observed in agreement with past studies, our results reveal that the SOS advance mostly occurs in mixed forests in southern Eurasia. More importantly, this study extracts the opposite trends for the end of season—advanced EOS in coniferous forests above 60°N and delayed EOS in mixed forests below. Overall, temperature in May–October has consecutively increased in the past 30 years. Precipitation has also increased but with a fragmented pattern. The advanced SOS across Eurasia is highly correlated with a warmer spring (April and May) in Eurasia. The EOS has a strong, negative relationship with fall precipitation (September). Further investigation is suggested to examine the opposite EOS trends and their environmental/ecological consequences in different forest zones of boreal Eurasia.

1. Introduction

Land surface phenology is an important indicator of global warming and the corresponding changes of terrestrial environments (Spano et al. 1999; Peñuelas and Filella 2001; de Beurs and Henebry 2004). Phenological changes of vegetation affect the photosynthesis processes and therefore carbon sequestration on Earth surfaces (Myneni et al. 1997). Known as Taiga biome, boreal forests cover the northern high latitudes in North America and Eurasia and comprise 30% of global forest cover (Robinns 2015). Due to harsh environmental conditions, boreal ecosystems are extremely vulnerable to climate change. Temperature in Arctic and boreal region has increased in a rate twice the global average, and climatic zones have been moving north in a rate 10 times faster than forest...
migration (Robinns 2015). Some studies also identified a warmer and drier summer in this region (Buermann et al. 2014), which may result in drought stress and the shift of fire regime in a long run.

Trends of land surface phenology in the northern high latitudes have been examined with frequent satellite observations. Since 1981, the AVHRR 8 km normalized difference vegetation index (NDVI) time series from the Global Inventory Modeling and Mapping Studies (GIMMS) project (15 day interval) and the Pathfinder AVHRR Land (PAL) project (10 day interval) have been utilized in a rich set of studies. For example, Lucht et al. (2002) reported an increased greening trend, earlier spring, and longer growing season. Contrarily, Buermann et al. (2013, 2014) claimed a decreased trend of greening in boreal forests. Moreover, while the advanced spring was commonly observed, slopes of phenological trends in boreal forests varied dramatically in different studies. In earlier efforts with AVHRR data, Myneni et al. (1998) found an 8 day spring advance and 4 day winter delay in 1982–1990 in regions above 45°N. With longer satellite datasets, Tucker et al. (2001) reported an advanced start of season (SOS) of 5.6 days in 1980s and 1.7 days in 1990s in 55°–75°N. In northern Eurasia, the SOS dates were found advanced 3.5 days and the end of season (EOS) dates were delayed 3.6 days in 1982–2004 (Delbart et al. 2006). In Northern Europe, Pudas et al. (2008) identified an advanced SOS in 0.7–1.3 days year−1 and extended season in 1.2–1.6 days year−1.

Climatic dependencies of boreal phenology also varied in these studies. Lucht et al. (2002) found the greener trend and spring advance were associated with a warmer climate in past decades. More specifically, some studies claimed the increased temperature in May as the primary contributor of earlier spring (Pudas et al. 2008; Crabbe et al. 2016). Agreeing with a positive relationship between temperature and boreal phenology, Bi et al. (2013) reported that vegetation in Eurasia was more sensitive to increased temperature than that in North America. Some studies attributed the decreased forest greening in boreal forests to warmer and drier summers in both North America (Buermann et al. 2013) and Eurasia (Buermann et al. 2014). Hellmann et al. (2016) suggested that precipitation and temperature jointly contributed to the diverse phenological trends in Eurasia.

Large variations and even discrepancies of these findings in above-mentioned studies may come from the lack of ground details in coarse-resolution satellite time series. Due to large temporal intervals of data series (e.g. the 15 day interval of GIMMS), different approaches to extracting phenological metrics also result in excessive uncertainties. White et al. (2009) reviewed a set of SOS-extraction approaches including global thresholds, local thresholds, mathematical modelling, and curve fitting, and found that the extracted SOS dates varied up to 60 days among these approaches. In a short time span of satellite data sets, climatic impacts to boreal forest phenology may also not be well represented.

The third-generation GIMMS NDVI product, NDVI3g, has improved data quality via advanced cloud masking processes, radiometric and geometric corrections, reduced non-vegetation noises, and expanded its time span to early 2010s (Pinzón and Tucker 2014). This study takes advantage of its improved and longer NDVI time series to extract phenological metrics and to assess their spatiotemporal patterns in boreal Eurasia. These inter-annual trends are important for better understanding of boreal responses to climatic change in the past 30 years.
2. Materials and methods

2.1 Study region

The boreal Eurasia is defined as a 50°–72°N zone in the northern high latitudes (Delbart et al. 2006). Geographically, it extends from Sweden, Finland, Norway to Russia in the east and covers much of Siberia towards the Pacific Ocean (Figure 1). It has a typical sub-frigid climate with annual average temperature below 0°C. This study selects the longitudinal range of 45°–180°E as our study region, which comprises the European Russia in the west and Siberia in the east and borders China, Mongolia, and Kazakhstan in the south end (Figure 1). Boreal forests are the primary vegetation, including a mixture of spruces, pines, and larches in Russian Taiga and larches in eastern Siberian Taiga (Grishin 1995). Given the cold environment, global warming is resulting in strong alteration in forest growth of the study region (Achard et al. 2006).

2.2 Data sets

The 8 km, 15 day AVHRR GIMMS NDVI3g product from January 1982 to December 2011 is the primary satellite observations in this study. Each year it comprises 24 NDVI layers calculated as the maximum NDVI values in a 15 day interval (Pinzón and Tucker 2014). Meteorological data is the 0.5°×0.5° monthly time-series database v3.23 from the Climate Research Unit (CRU), University of East Anglia, UK (Mitchell and Jones 2005). At 0.5° grid size (~50 km), the CRU data set is reconstructed via spatial interpolation of ground observations at meteorological stations across the globe. Data sets utilized in this study include monthly average temperature and monthly cumulative precipitation in 1982–2011, which are resampled to the same grid size (8 km) as the NDVI3g data set.

Land covers in boreal Eurasia biome have been mapped in the 500 m MODIS Terra+Aqua Land Cover Type product (MCD12Q1) under the International Geosphere-Biosphere Programme (IGBP) global vegetation scheme (Friedl et al. 2010). In this remote region, anthropogenic land uses are limited. Since land surface phenology is of our major concern, here we ignored the pixilated small patches of non-vegetation covers and merged the MCD12Q1 classes into four boreal forest types in the study region (Figure 1): open scrublands and shrublands (hereafter referred as scrublands) in the vast north, needle-leaved coniferous forests in the middle, and mixed forests in the south that cover both coniferous and deciduous tree species. As shown in Figure 1, these boreal forests reveal an apparent latitudinal transition. The coniferous forests grow in a narrow zone roughly between 60° and

Figure 1. The study region in Eurasia and the associated vegetation (modified from the 2011 MODIS Land Cover Type map).
65°N, and are split into evergreen conifer in the west and deciduous conifer in the east. Some studies documented that boreal forests in high latitudes have been shrinking and migrating northward (Wielgolaski and Karlsen 2007; Robins 2015). Without detailed ground reference, however, spatial shifts of these four forest types are not considered in our study period of 1982–2011.

There is a small agricultural zone in the south end of the region, which comprises patches of cultivated croplands in European Russia and arid/semi-arid grasslands in northern Kazakhstan. Crop phenology is heavily affected by cropping activities and varies with different crop types. To simplify the process, these agricultural lands are masked out in this study.

2.3 Approaches

2.3.1 Time-series analysis for phenological extraction

At an 8 km pixel of the NDVI3g product, a 24 point NDVI time series each year is extracted that reveals the seasonal development of vegetation (Figure 2). While cloud covers in NDVI3g have been removed using the maximum value composite technique (Holben 1986), NDVI values are still affected by local atmospheric conditions and cloud noises. Also, precipitation in boreal zone is often in the form of snow in cold and long winters. Extended snow events in early and late growing seasons thus result in lower NDVI along the time series. Adopting a smoothing approach used in our previous efforts (Wang et al. 2013; Wang et al. 2015), this study applied a median filter for removal of cloud or snow spikes, followed by a second-order polynomial Savitzky–Golay filter (Savitzky and Golay 1964) to further smooth the trajectories.

Example NDVI time series of four boreal forests were extracted from randomly selected pixels in each forest type. In Figure 2, the smoothed trajectories better reflect land surface phenology. Mixed forest (Figure 2(a)) grows in the south of the study region with a relatively warmer climate, and therefore, its growing season length is longer than other forests. The needle-leaved evergreen (Figure 2(b)) and needle-leaved deciduous (Figure 2(c)) forests grow in the middle of the study region, and evergreen conifers have

![Figure 2](image)

Figure 2. Example NDVI time series of boreal forests in the study region: mixed forests (a); needle-leaved evergreen (b); needle-leaved deciduous (c); and scrublands (d).
a longer growing season than deciduous conifers. Scrublands occupy the vast area of the cold north, characterized with much lower NDVI and shorter growing season (Figure 2(d)). Except the short summer, excessive snow cover in this rigid zone attributes to the extremely low NDVI values. To simplify the process, all NDVI values less than 0 are assigned to 0 in this study. With snowmelt in spring, boreal forests at northern latitudes benefit from increased water availability and elongated daylight hours for photosynthesis and therefore have explosive plant growth in summer (Grippa et al. 2005). Understory growth also adds into significant increase of NDVI in early growing season. In this sense, NDVI trajectories in Figure 2 reveal the temporal variation of greenness from both boreal trees and ground covers at an 8 km scale.

The TIMESAT program (Jönsson and Eklundh 2004) is applied to extract phenological metrics of boreal forests using a commonly adopted global threshold-based approach. In northern latitudes with heavy snow covers, past studies have found that a threshold of 20% growth was relatively stable to reflect the start and end of a growing season (Suzuki, Nomaki, and Yasunari 2003; Delbart et al. 2006; Wang et al. 2015). Here, we follow the same threshold and extracted the following metrics: SOS (the date-of-year (DOY) when NDVI in spring increases to 20% of the amplitude); EOS (the DOY when NDVI in fall decreases to 20% of the amplitude); Length of Season (LOS, the days between SOS and EOS); and the Middle of Season (MOS, which effectively represents the stage of peak growth in boreal forests). The selection of 20% growth as the threshold is somehow subjective. Apparently a larger threshold value results in later SOS and earlier EOS dates. Since this study explores the spatial patterns and temporal trends of phenology in boreal forests that have simple one-season growth cycles, a global threshold for all NDVI time series maintains the consistency across the study region and the 30 year time span. Noises introduced to the extracted phenological metrics are assumed the same for all pixels and therefore do not heavily affect the patterns in the study region.

**2.3.2 Mann–Kendall trend analysis**

The 30 year trends of phenological metrics in 1982–2011 are examined. Linear trend analysis is not suitable because the phenological measures in adjacent years may not be independent, and the zero-mean normality of residuals may not be satisfied (Wang et al. 2015). Here we use the rank-based, nonparametric Mann–Kendall trend analysis approach that does not require the independency and normality of temporal data series (Hirsch and Slack 1984). Given the 30 point time series of each metric at a pixel, the Mann–Kendall trend analysis defines a sign variable ($s$) to count the signs of comparison between any two points in the time series:

$$s = \sum_{i<j} \text{sgn}(X_j - X_i)$$

where $X_i$ and $X_j$ are the satellite-extracted DOY in year $i$ and $j$ ($i < j$), respectively. The sign function, $\text{sgn}(X_j - X_i)$ is 1 when $(X_j - X_i) > 0$ and $-1$ when $(X_j - X_i) < 0$.

Assigning $n$ as the length of time series ($n = 30$ in this study), the Mann–Kendall’s trend is a rank correlation coefficient ($\tau$) calculated as follows:
\[ \tau = \frac{s}{n(n - 1)/2} \]  

(2)

Equation 2 reveals the trend of each time series with \( \tau \) varying in a range of \([-1, 1]\). \( \tau > 0 \) indicates an increasing trend, and \( \tau < 0 \) is a decreasing trend. Statistical significance of the Mann–Kendall’s trend is tested with a standardized two-sided Z-test (significance level \( \alpha = 0.05 \)). With the sign variable \( s \) and its variance \( \text{var} \), the Mann–Kendall test statistic, \( Z_{mk} \), is calculated as follows:

\[
Z_{mk} = \begin{cases} 
\frac{s-1}{\sqrt{\text{var}(s)}} & \text{when } s > 0 \\
\frac{s+1}{\sqrt{\text{var}(s)}} & \text{when } s < 0
\end{cases}
\]  

(3)

2.3.3 Correlation analysis with climatic variables

Climatic variables (temperature, precipitation) are extracted to examine their annual, seasonal, and monthly trends in the past 30 years. Linear correlation analysis is performed between each phenological metric and climatic factor. The correlation coefficient, Pearson’s \( r \), is calculated and tested against a two-sided student \( t \) test (\( \alpha = 0.05 \)). Statistically significant relationships provide meaningful clues about climatic dependencies of boreal phenology in the study region.

3. Results and discussion

3.1 Temporal trends of phenological metrics

Yearly observations of each phenological metric in the study region were plotted to examine its 30 year variation. In Figure 3, linear trend analysis is performed because points in each trajectory are yearly averages across the study region. The SOS (Figure 3(a)) and LOS (Figure 3(c)) revealed statistically significant trends (\( p < 0.05 \)), agreeing with past studies in the high-latitude Europe (Crabbe et al. 2016). Overall, the SOS advanced 2.7 days and the LOS increased 5.1 days in 30 years. The EOS (Figure 3(b)) and MOS (Figure 3(d)) remained relatively stable in the same time period.

The 30 year linear trends were also examined in different forests. Table 1 lists the Pearson’s \( r \) and annual change rate \( k \) (days year\(^{-1} \)) of four metrics in each forest. For the SOS, only mixed forests revealed significant change (\( r = -0.63 \)), advancing in a rate of 0.43 days year\(^{-1} \), or a total of 12.90 days in the past 30 years. Except needle-leaved evergreen forests, the EOS of all forest types had significant trends. Mixed forests had strong delay (\( r = 0.62 \)) while needle-leaved deciduous forests had strong advance (\( r = -0.74 \)). The EOS of scrublands (\( r = -0.33 \)) also advanced although in a weaker trend. These opposite trends contributed to a relatively stable trend of EOS averaged across the study region (in Figure 3(b)). For LOS, only mixed forests had significant change with an increasing trend of 0.34 days year\(^{-1} \) (\( r = 0.59 \)). The MOS trends were not significant for all forests except scrublands that had a weak advance (\( r = -0.40 \)). From Table 1, mixed forests have the strongest phenological change (advanced SOS and extended LOS) in the past 30 years. Interestingly, mixed forests and needle-leaved deciduous conifers have opposite EOS trends (delaying for mixed forests but advancing for conifers).
Spatial patterns of phenological metrics and 30 year trends

Spatial distributions of the four metrics were extracted. At each pixel, the Mann–Kendall trend analysis was performed to examine its 30 year trend.

3.2.1 Start of season (SOS)
Across the study region, the SOS distributions revealed an apparent latitudinal gradient delay to the north (Figure 4(a)). Mixed forests in 50°–60°N had the earliest SOS dates of 100–120 DOY (mid to late April). Needle-leaved evergreen forests, located below 65°N in the west, had an SOS range similar to mixed forests although showing a transition of delay to the north. The needle-leaved deciduous forests, while covering a broad latitudinal zone, had relatively stable SOS dates of 120–130 DOY (early May). The scrublands, with sparse and less vigorous vegetation, had a wide span of SOS dates ranging from early May to late June (120–170 DOY). Majority area of the study region did not show an apparent Mann–Kendall trend of SOS in the past 30 years (Figure 4(b)). Areas with statistically significant SOS advance only covered 2.8% of the study region, mostly in mixed forests while extending into the evergreen zone in the north. The SOS trends in scrublands were also limited.

Figure 3. Temporal variations and 30 year linear trends of SOS (a), EOS (b), LOS (c), and MOS (d), averaged across the study region.

Table 1. The 30 year phenological trends of different forest types.

<table>
<thead>
<tr>
<th>Forest type</th>
<th>SOS k (days year⁻¹)</th>
<th>SOS r</th>
<th>EOS k (days year⁻¹)</th>
<th>EOS r</th>
<th>LOS k (days year⁻¹)</th>
<th>LOS r</th>
<th>MOS k (days year⁻¹)</th>
<th>MOS r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrubland</td>
<td>−0.001</td>
<td>−0.018</td>
<td>−0.038</td>
<td>−0.327*</td>
<td>−0.009</td>
<td>−0.063</td>
<td>−0.090</td>
<td>−0.400**</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>−0.430</td>
<td>−0.630***</td>
<td>0.155</td>
<td>0.620***</td>
<td>0.340</td>
<td>0.590***</td>
<td>−0.017</td>
<td>−0.050</td>
</tr>
<tr>
<td>Needle-leaved deciduous</td>
<td>−0.036</td>
<td>−0.155</td>
<td>−0.230</td>
<td>−0.740***</td>
<td>0.011</td>
<td>0.050</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>Needle-leaved evergreen</td>
<td>0.011</td>
<td>0.027</td>
<td>−0.040</td>
<td>−0.096</td>
<td>0.117</td>
<td>0.146</td>
<td>−0.107</td>
<td>−0.199</td>
</tr>
</tbody>
</table>

*p < 0.1; **p < 0.01; ***p < 0.001. Both annual change rate (k) and Pearson’s r are calculated for each metric.
3.2.2 End of season (EOS)

In Figure 4(c), the EOS distributions vary latitudinally and delay to the south. As expected, scrublands in the north had the earliest EOS dates of 270–285 DOY (early October). The needle-leaved forests, especially those in the narrow zone above 60°N, had the latest EOS dates of 300–330 DOY. Theoretically, evergreen forests are not senescent in fall and therefore do not have apparent EOS dates. Boreal forests, however, are highly affected by snow covers in late season. Remote-sensing studies have confirmed that the late EOS dates in high-latitude forests had good agreement with snow days (Kobayashi et al. 2016). Given the mixed condition of deciduous and coniferous trees, the EOS of mixed forests occurred in 290–310 DOY (late October to early November). The 30 year EOS trend in Figure 4(d) is stronger than SOS trend in...
Both trend directions were observed in the study region. Mixed forests in the south had most significant EOS delay, covering 5.96% of the study region. Needle-leaved forests above 60°N (both evergreen and deciduous) had significant EOS advance (7.54% of the study region). The sparse scrublands did not show significant EOS change.

### 3.2.3 Length of season (LOS)

The LOS distribution in Figure 4(e) also varies latitudinally. Scrublands in the north had the shortest growing season of 120–160 days, and those in the east had relatively longer season than the west. Needle-leaved forests actually had a longer season of 175–225 days. Mixed forests had growing season about 175–210 days, slightly shorter than conifers. For the LOS trends in Figure 4(f), the shorter LOS above 60°N is mostly affected by the advanced EOS in coniferous forests. The significantly longer LOS in the south was jointly affected by advanced SOS and delayed EOS, mostly in mixed forests.

### 3.2.4 Middle of season (MOS)

Spatial patterns of the MOS also revealed a latitudinal gradient, from 190–210 DOY (mid-July) in mixed forests to 215–230 DOY (early to mid-August) in the cold scrublands (Figure 4(g)). The 30 year trends of MOS were not significant across the study region. In Figure 4(h), only spotted clusters in mixed forests and scrublands reveal significant advance (0.71% of the study region).

As demonstrated in the phenological patterns (Figure 4(a,c,e,g)), in certain year there are erroneously no-data pixels (grey tone in the figures). Along their NDVI trajectories, the phenological stages at these pixels were not clear and the TIMESAT program cannot extract the valid outputs. There were apparently more no-data areas in EOS (Figure 4(c)) than SOS (Figure 4(a)). Aside from cloud noises, it may also be related to gradual decrease of greenness and snow fall in late season. In contrast, boreal forests are characterized with rapid growth in spring and early summer triggered by snowmelt. The rapid increase of NDVI can be easily detected in TIMESAT, and therefore, the no-data areas in SOS (Figure 4(a)) and MOS (Figure 4(g)) are limited. The no-data pixels in LOS (Figure 4(e)) come from those in both SOS and EOS.

Phenological extraction from satellite time series could also be highly affected by smoothing approaches. Given the relatively simple one-season growth cycle of boreal forests, this study applies a local curve fitting method. Comparing with the complicated model simulations such as the Asymmetric Gaussian (Wang et al. 2013) and double logistic (Beck et al. 2006) functions, local fitting method maximally maintains trajectory features in relatively homogeneous land covers. Modifications of local filters have also been published. For example, Hird and McDermid (2009) defined a least-square smoothing approach to fitting the upper envelope of NDVI time series. Advanced smoothing techniques could potentially improve the spatial and temporal patterns in Figure 4.

### 3.3 Climatic patterns and the 30 year trends

The annual average temperature (Figure 5(a)) and cumulative precipitation (Figure 5(b)) in 1982–2011 were extracted for the study region. The average temperature was −6.28°C and precipitation was 416.63 mm in this rigid/sub-rigid climatic zone. Both variables revealed significant increase ($p \leq 0.01$). In the past 30 years, temperature increased 1.17°
and precipitation increased 28.8 mm. Two extreme weather events were observed: the coldest and driest one in 1987 (−7.89°C and 380.14 mm) and the warmest and moistest one in 2007 (−4.82°C and 450.22 mm). In between there was an extremely warm year in 1995 and moist year in 1990.

Climatic trends in the study region revealed seasonal differences (Table 2). Climatic conditions remained relatively stable in winter (December to February), in which both average temperature and cumulative precipitation did not show significant change. Temperature in summer (June to August) and fall (September to November) had the strongest increase \((p < 0.01)\) with a rate of 0.038°C year\(^{-1}\) and 0.064°C year\(^{-1}\), respectively. Spring temperature showed weaker correlation \((p < 0.1)\), but it had the highest increase rate of 0.065°C year\(^{-1}\). Precipitation in spring-fall also had weak correlation \((p < 0.1)\). Interestingly, precipitation in summer-fall had an increase rate almost doubled than spring precipitation.

Breaking down to monthly trends, both monthly average temperature and monthly cumulative precipitation had positive Pearson’s \(r\) values, indicating their overall increasing trends. In Figure 6(a), temperature in May–October has consecutively significant increase \((p < 0.05)\) in the 30 year period. The change rate ranged from 0.031°C year\(^{-1}\) in July to 0.077°C year\(^{-1}\) in October. Therefore, it is reasonable to interpret that, in both start and end of seasons, boreal forests have experienced higher temperature increase, which could attribute to the corresponding phenological changes in the study region. In Figure 6(b), monthly precipitation change is less dramatic, only showing significant increase in March, June, and September \((p < 0.05)\).

Climatic patterns varied geographically (Figure 7). Using the 2011 climatic data as example, the annual average temperature decreased from southwest to northeast, matching well with the transition of mixed forests, conifers to scrublands (Figure 7(a)). Precipitation showed a longitudinal transition that decreased from east to west (Figure 7(b)). In general,

### Table 2. The 30 year seasonal trends of climatic variables.

<table>
<thead>
<tr>
<th>Climatic variable</th>
<th>Spring (March–May)</th>
<th>Summer (June–August)</th>
<th>Fall (September–November)</th>
<th>Winter (December–February)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(k \text{ (°C year}^{-1})</td>
<td>(r)</td>
<td>(k \text{ (°C year}^{-1})</td>
<td>(r)</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.065</td>
<td>0.450*</td>
<td>0.038</td>
<td>0.610***</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.190</td>
<td>0.370*</td>
<td>0.330</td>
<td>0.360*</td>
</tr>
</tbody>
</table>

*\(p < 0.1; **p < 0.01; ***p < 0.001. Both annual change rate \((k)\) and Pearson’s \(r\) are calculated for each season.*
mixed forests and evergreen conifers in the west were warm and wet, scrublands in the east were cold and dry, and deciduous conifers were in between. In Figure 7(c), spatial patterns of the 30 year temperature trends reveal significant increase. However, areas with increased annual temperature were mostly in the scrublands in the east of the region. Majority of mixed and coniferous forests actually did not experience significant increase of annual average temperature. Precipitation also had an increasing pattern although spotted across the study region (Figure 7(d)). This agrees with Figure 6(b) in which only three discrete months show significant precipitation change.

### 3.4 Correlations between climate and boreal phenology

At each pixel, the Pearson’s $r$ was calculated between each metric and annual average temperature in 30 years. At significance level $\alpha = 0.05$, areas with significant correlations
are extracted in Figure 8. The SOS was negatively correlated with temperature, covering 13.67% of the study region, especially in mixed forests and scrublands (Figure 8(a)). Given the advancing trends of SOS in Figure 4(b) and unidirectional increase of climatic variables in Figures 6 and 7, it is reasonable to interpret that the advanced SOS could be triggered by increased temperature and earlier snow melting from climatic warming in early growing season. Spatial correlations between the EOS and temperature were spatially limited but revealed geographically opposite patterns (Figure 8(b)). Only 3.31% of the study region was in positive and 3.32% in negative correlations. More specifically, mixed forests had advanced EOS while clustered coniferous forests in the narrow zone of 60°–65°N had delayed EOS. Higher temperature in May–October (Figure 6(a) above) may attribute to the extended late growth in mixed forests, but may also trigger earlier senescence of coniferous forests. From the joint contribution of SOS and EOS, a high percentage (11.29%) of the study region had positive correlations between LOS and temperature (Figure 8(c)). The MOS had a unidirectional, negative correlation in 16.31% of boreal forests especially scrublands (Figure 8(d)). Overall, the increased annual temperature has more impacts on phenological advances in earlier seasons (SOS and MOS), but less on late seasons (EOS) in boreal forests. Among all forest types, scrublands were most sensitive to annual temperature change, followed by mixed forests. Except a few clusters with negative relationships for SOS and EOS, boreal conifers in central region were actually not very sensitive to temperature change.

Spatial patterns of correlations between phenological metrics and annual cumulative precipitation were less dramatic. In Figure 9, only spotted local patterns are observed, which may be related to localized trends of precipitation in the past 30 years (as shown in Figures 6(b) and 7(d) above). The SOS generally had negative relationship with precipitation in the west and positive in the east (Figure 9(a)). For EOS, an overall negative correlation was observed across the region (Figure 9(b)). The LOS also showed opposite correlation directions, i.e. negative patterns in the west and positive in of east

Figure 8. Spatial patterns of correlations (p < 0.05) between annual average temperature and SOS (a), EOS (b), LOS (c), and MOS (d).
The MOS in Figure 9(d) reveals a positive correlation in most areas except the scrublands in the north and a small cluster in the south end. Given the highly fragmented patterns in this figure and precipitation trends in Figure 7(d), caution should be paid in interpreting the dependencies of boreal phenology to precipitation.

The 30 year correlation analyses in Figures 8 and 9 are performed in yearly basis. Forest phenology, however, is more sensitive to seasonal climatic conditions. For example, the SOS would be more sensitive to weather dynamics in early spring but may not be related to those in fall. Here, we examined the inter-relationships between monthly climatic variables and phenological metrics. For monthly time series of temperature and precipitation, pixels of each metric with significant correlation were counted and its areal percentage over the study region was extracted.

In Figure 10, the SOS is more sensitive to temperature in April and May, with 20% of the study area revealing negative correlation in April and 32% in May. In other words, increased temperature in April and May was highly related to the advanced SOS of the study region. Its correlation with precipitation was limited in all months (< 5%). Climatic relationship with the EOS was in an opposite way. Its correlation with monthly temperature was limited, but that with precipitation in September was significantly negative (> 10%). As there was a trend of increased precipitation in September (in Figure 6(b)), most likely in form of snow, it is reasonable to indicate that increased snow in late fall triggered an early end of season. Correspondingly, the LOS was related to both temperature in April and May and precipitation in September. The MOS was strongly negatively related to spring temperature especially May and June (about 30%–40% each month). It had much weaker relationship with monthly precipitation except snow in January (8%). Interestingly, the MOS had consecutively positive relationships with precipitation in winter–spring (December–July). The consecutively positive relationships were also observed between SOS and precipitation in January–April, although the areal coverage was less dramatic in these months.
In summary, this study confirmed that boreal phenology in Eurasia had significant changes in the past 30 years. Agreeing with our common understanding, spatial patterns of phenological metrics followed a latitudinal transition. Different from many studies that reported advanced spring and longer growing season in boreal Eurasia (e.g. Lucht et al. 2002; Bi et al. 2013; Buermann et al. 2013), we found that the 30 year phenological trends actually varied in different forest types. Mixed forests in southern Eurasia had advanced SOS and delayed EOS. In contrast, Boreal conifers in the 60°–65°N zone had advanced EOS but relatively stable SOS. Therefore, the season length of mixed forests extended but that of boreal conifers shortened. Sparse scrublands in the north, defining the north end of Taiga biome, did not show widespread phenological change. The opposite trends in boreal conifers and mixed forests deserve further investigation.

Figure 10. Areal percentages with significant correlation between each metric (SOS, EOS, LOS, MOS) and monthly climatic variable (temperature, precipitation). Plots against temperature are in the left column, and those against precipitation are in the right.
Increased temperature was often assumed the primary contributor of phenological changes in Eurasia (as reported by Pudas et al. 2008; Crabbe et al. 2016). By exploring multi-level (annual, seasonal, monthly) climatic variables, our findings agreed with these past studies that the SOS and MOS were highly correlated with spring–summer temperature (April–June). Beyond past studies, we found that the EOS was more sensitive to fall precipitation (September). Moreover, it was clear that cumulative snow cover in winter–early spring played a positive role to the SOS and MOS. Although spatial patterns of correlation between precipitation and phenological metrics were fragmented, results of this study did not agree with Buermann et al. (2014) which claimed a drier summer in boreal Eurasia. Instead, this study revealed an increasing trend of precipitation in March, June, and September, and its increase in summer–fall was almost doubled than that in spring. Although spatially isolated, patches of this trend were observed across the study region.

This study contributes to boreal phenology literature in its long-term evolution under the big picture of global climate change. The opposite trends of EOS between coniferous and mixed forests reflect their different climatic responses in Eurasia that deserves further investigation. Understanding these unique climatic dependences of boreal forests will help us better predict forest succession and migration in this vast, fragile ecosystem.

4. Conclusion

This study extracted four phenological metrics from the AVHRR GIMMS NDVI3g time series of the boreal Eurasia in 1982–2011, and explored their spatiotemporal patterns and correlations with climatic variables. Our findings include the following:

1. Phenological patterns reveal apparent latitudinal transition that varies from mixed forests in the south, needle-leaved forests in the middle, and scrublands in the north.
2. The 30-year phenological trends vary geographically and in different forest types. The advanced SOS mostly occurs in mixed forests (−13 days in 30 years). The EOS has opposite trends across 60°N, i.e. advanced in coniferous forests (−7 days) but delayed in mixed forests (5 days). This results in their similarly opposite trends of LOS.
3. Except winter, both temperature and precipitation have been increased in boreal Eurasia. Temperature increases consecutively in May–October while precipitation increase is isolated in March, June, and September. Temperature has stronger relationship with boreal phenology than precipitation.
4. Climatic correlations of boreal phenology show seasonal variations: increased spring temperature is strongly related to the advanced SOS and MOS, while increased fall precipitation is primarily related to EOS. Although the winter–spring snow does not have significant change, it has consecutively positive correlations with SOS and MOS.

This study suggests that the opposite EOS trends across 60°N could come from joint impacts of increased spring–fall temperature and fall precipitation. Further investigation is needed to better understand these different climatic responses from mixed and coniferous forests in boreal Eurasia.
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ORCID

Cuizhen Wang @ http://orcid.org/0000-0002-0306-9535

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