



Enhanced spring phenological temperature sensitivity explains the extension of carbon uptake period in temperate forest protected areas



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ABSTRACT

Land surface phenology (LSP) and its trend are important for understanding the vegetation–climate relationship. However, whether LSP and LSP trends for different forest communities vary with the intensity of forest disturbance and the main cause of the change is still unclear. In this study, LSP indicators and their temperature sensitivity (Ts) were obtained for coniferous (Larch Coniferous forests (LC) and Spruce Fir Korean Pine forests (SFKP)), mixed (Broadleaf Korean Pine forests (BKP) and Spruce Fir Broadleaf forests (SFB)), and broadleaf (Aspen White Birch forests (AWB) and White Birch forests (WB)) communities in protected (Fenglin National Natural Reserve, FNNR) and unprotected (Lilin Experimental Forest Farm, LEFF) areas in Northeastern China from remote sensing and climate data. Statistical comparisons of the LSP, LSP trends, and Ts were conducted for various forest communities in both FNNR and LEFF. The results show that the values of mean start of the season (SOS) and mean end of the season (EOS) in FNNR were significantly different from those in LEFF, and the SOS, EOS, and the length of season (LOS) trends for various forest communities in FNNR were significantly different from those in LEFF, except for the SFB. In broadleaf forests, both the mean LOS and LOS trends for various forest communities were significantly higher in FNNR. However, significantly higher LOS but lower LOS trends in FNNR were identified for coniferous and mixed forests. In addition, the SOS Ts for various forest communities in FNNR were significantly higher than those in LEFF, and the Ts for broadleaf forests in FNNR were significantly lower than that in other forest communities. The results of this study suggest that the carbon uptake periods of most temperate forest communities are apparently enhanced by the high spring phenological Ts in protected areas, which provides important insights into future carbon sequestration potential and forest management strategies for temperate forests in Northeastern China.

1. Introduction

Human activities have significantly affected the Earth's environment by altering the energy balance and the cycle of matter (Buitenwerf et al., 2018), which has led to global-scale changes in land covers and climates (Steffen et al., 2015). Furthermore, these changes have influenced the compositions and functions of terrestrial ecosystems. As a key component of terrestrial ecosystems, forests are greatly affected by global changes. In particular, the changes in forest phenology under climate change have a great potential to control forest carbon uptake (Broich et al., 2014), which is an important issue for scientists to assess and monitor the global warming impact on ecosystems. Given the increased awareness of the role vegetation phenology plays in regulating

some main ecological functions (Richardson et al., 2013), studies concerning vegetation phenology dynamic under climate change have attracted global attention in recent years.

Phenological indicators generally reflect the timing of recurrent biological events (Migliavacca et al., 2012), and the detailed and fine temporal resolution of those indicators can only be obtained from in-situ observations (Rodriguez-Galiano et al., 2015). However, site-level observations of vegetation phenology are limited and impractical to be applied in phenology dynamics at large spatial scales. Fortunately, satellite-based time series data are increasingly used to monitor land surface phenology (LSP) for its advantages in providing different spatiotemporal scales and filling the absence of ground-based observations (White et al., 2009; Ganguly et al., 2010; Verbesselt et al., 2010; Filipa

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et al., 2018). Due to the close association with vegetation carbon sequestration process, three climate-sensitive LSP indicators (Du et al., 2019), including start of the season (SOS), end of the season (EOS), and length of the season (LOS), are commonly used to represent vegetation phenological processes (Park et al., 2016; Wu et al., 2016; Luo and Yu, 2017). Moreover, the dynamic trends of SOS, EOS, and LOS can also reflect the impact of climate on vegetation phenology (Jeong et al., 2011).

Many studies have documented that the phenology trends of temperate forests have been profoundly influenced by climate change, especially over the past 40 years (Basler and Korner, 2012; Barichivich et al., 2013; Fu et al., 2015; Thurm et al., 2016). The advancing trends of SOS were found in most temperate forests, which are mainly attributed to spring warming temperature (Miller-Rushing and Primack, 2008; Thompson and Clark, 2008). Delaying trends of EOS were also identified in temperate forests, and the increase of temperature in late summer or early autumn was considered as the main reason (Delpierre et al., 2009; Liu et al., 2015; Liu et al., 2016). Although similar LSP trends exist in temperate forests of different areas, the response of vegetation phenology to climates still varies among species and forest communities (Richardson et al., 2013; Keenan et al., 2014). In particular, it is not well understood whether the different responses of LSP among forest communities to climate change vary with disturbance degrees.

Global temperate forests have experienced severe natural and human disturbances and have been lost at a rate of 36,800 km² per year since 2000 (Hansen et al., 2010). Various degrees of forest disturbance cause changes in forest environmental conditions such as microclimate and soil nutrient (Vlassova and Perez-Cabello, 2016; Jean et al., 2017; Toledo et al., 2018), which have been proven to have significant impacts on vegetation phenology (Stromgren and Linder, 2002; Hwang et al., 2011; Keenan et al., 2011; Thurm et al., 2016). However, few studies attempted to compare forest phenology trends under different degrees of disturbances, and how the phenological climate sensitivities of various forest communities change with disturbance degrees is also unclear. Therefore, it is imperative to explore the influence of forest disturbances on vegetation phenology trends and climate sensitivity in different forest communities.

Considering that the intensity of forest disturbances is significantly different between protected areas and unprotected areas (Freudenberger et al., 2013; Feeley and Silman, 2016), the differences of phenological indicators between these two types of areas can reflect the influence of the degree of disturbance on phenology. Time series vegetation gross primary productivity (GPP) dataset and climate data was used to calculate the LSP indicators (SOS, EOS, and LOS) and temperature sensitivity (Ts) of different forest communities every year during 2000–2016 in a protected area and an unprotected area. Based on the comparisons of LSP indicators, their trends, and Ts of different forest communities between the two areas, we aimed to answer three scientific questions: (1) whether the disturbance degrees significantly affected the phenological indicators and their trends of different temperate forest communities, (2) how phenological Ts of different forest communities vary, and (3) whether Ts affects the differences in phenology between disturbance degrees.

2. Materials and methods

2.1. Study area

The Fenglin National Natural Reserve (FNNR) and Lilin Experimental Forest Farm (LEFF), located in the central part of the Lesser Khingan Mountains area (LKM), were selected as the study areas (Fig. 1). The areas of FNNR and LEFF are 166.4 and 74.9 km², respectively. The forest ages of the two regions are quite similar and the forest coverages of the two regions are both higher than 90%. The dominant climate of the entire LKM is the temperate

continental monsoon climate. It has long cold winters and short warm summers, and the average annual precipitation ranges between 550 and 670 mm. The growing season usually lasts from mid-May to mid-August.

The LKM is located in the transitional zone between cold and moderate temperate climate zones. Coniferous, mixed, and broadleaf forests co-exist in this area, and there are mainly 10 forest communities, including Broadleaf Korean Pine forests (BKP), Larch Coniferous forests (LC), Spruce-Fir Korean Pine forests (SFKP), Pinus Sylvestris Korean Pine Coniferous forests (PKC), Spruce-Fir Broadleaf forests (SFB), Planted Pinus Sylvestris forests (PPS), Aspen White Birch forests (AWB), White Birch forests (WB), Aspen forests (AS), and Mixed Broadleaf forests (MB), in our study area (Fig. 1). Based on the areas of each type of forest community in FNNR and LEFF, we only selected the BKP, LC, SFKP, SFB, AWB, and WB (the top six largest community types) as the research targets of this study in order to conduct a better comparison and to avoid confusion. The detailed information about the species composition and relative area percentages of the six community types are listed in Table 1.

2.2. Data acquisition and pre-processing

2.2.1. Distribution map of forest communities

The species distribution data of 2000 in the LKM, produced by the Forestry Planning and Design Bureau of Heilongjiang Province in 2003, was used to classify the forest communities for this study based on the expertise about the species compositions of various forest communities, familiarity with the study region, and local experience (Xiao et al., 2002; Ma et al., 2014). Although forest logging was totally forbidden in the LKM since 2000 (Ma et al., 2017), forest loss and gain were still identified for FNNR and LEFF based on a previous study (Hansen et al., 2013). Therefore, in order to exclude the influence of forest cover change on the estimations of LSP indicators, we only focused on the forest region that did not change after 2000. The unchanged forest distribution map after 2000 (Hansen et al., 2013) was used to mask the original forest types map to obtain the constant distribution map of forest communities.

2.2.2. Time series GPP data

In order to examine the relationship between vegetation phenology and carbon sequestration process, a time series GPP dataset during 2000–2016, with a spatial-temporal resolution of 500-m and 8-day, was employed to calculate LSP indicators for the study area. The GPP dataset was obtained from the vegetation photosynthesis model (VPM), which was driven by surface reflectance dataset (MODIS MOD09A1 product), land cover dataset (MODIS MCD12Q1 product), land surface temperature dataset (MODIS MYD11A2 product), and climate dataset (National Center for Environmental Prediction-Department of Energy reanalysis II, NCEP-DOE reanalysis-II). Gap-filling algorithms were adopted to generate reliable continuous time series vegetation indexes (EVI and LSWI), which are the basic input parameters in the VPM. The detailed simulation processes of the GPP dataset in the VPM were reported in previous studies (Zhang et al., 2017; Ma et al., 2018).

2.2.3. Climate data

Monthly air temperature data of the period 2000–2016, obtained from NCEP-DOE Reanalysis-II climate product, was used to calculate the vegetation phenological temperature sensitivity (Ts) in this study. The temperature data was provided in a gaussian grid (192 × 96; ~1.875° × 2°) format and downloaded from the website <https://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/>. Considering that the FNNR and LEFF were both located in the same grid of the climate data, the time series values of monthly temperature of the relevant pixel were extracted and used in this study.

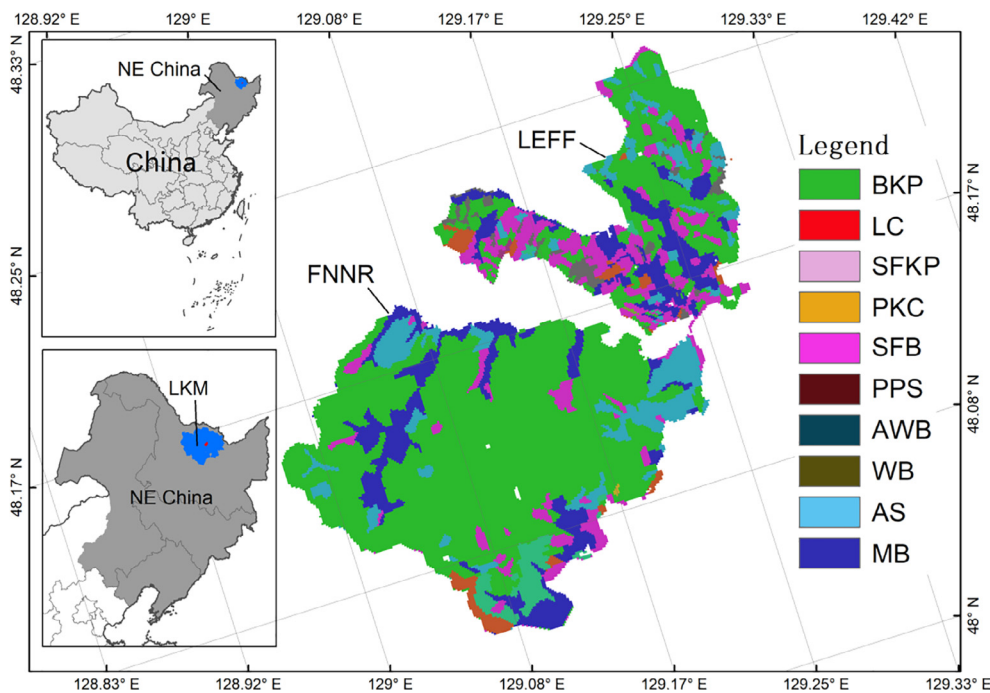


Fig. 1. Location and distribution of forest communities in Fenglin National Natural Reserve (FNNR) and Lilin Experiment Forest Farm (LEFF) of the Lesser Khingan Mountains area (LKM) in Northeastern China. BKP: Broadleaf Korean Pine forests; LC: Larch Coniferous forests; SFKP: Spruce-Fir Korean Pine forests; PKC: Pinus Sylvestris Korean Pine Coniferous forests; SFB: Spruce-Fir Broadleaf forests; PPS: Planted Pinus Sylvestris forests; AWB: Aspen White Birch forests; WB: White Birch forests; AS: Aspen Forests; MB: Mixed Broadleaf forests.

Table 1

Main species compositions, areas, and area percentages of the main forest communities in the Fenglin National Natural Reserve (FNNR) and Lilin Experiment Forest Farm (LEFF). BKP: Broadleaf Korean Pine forests; LC: Larch Coniferous forests; SFKP: Spruce Fir Korean Pine; SFB: Spruce Fir Broadleaf forests; AWB: Aspen White Birch forests; WB: White Birch forests.

Forest communities	Main species	Area (ha)		Area percentage (%)	
		FNNR	LEFF	FNNR	LEFF
BKP	<i>Pinus koraiensis</i> , <i>Fraxinus mandshurica</i> , <i>Juglans mandshurica</i> Maxim., <i>Phellodendron amurense</i>	1215.2	342.2	68.42	45.32
LC	<i>Larix gmelinii</i> , <i>Pinus sylvestris</i> , <i>Betula platyphylla</i>	215.8	139.7	12.15	18.50
SFKP	<i>Picea koraiensis</i> and <i>jezoensis</i> , <i>Abies nephrolepis</i> , <i>Pinus koraiensis</i>	167.1	71.0	9.41	9.41
SFB	<i>Picea koraiensis</i> and <i>jezoensis</i> , <i>Abies nephrolepis</i> , <i>Fraxinus mandshurica</i> , <i>Juglans mandshurica</i> Maxim.	89.1	171.8	5.02	22.75
AWB	<i>Populus davidiana</i> , <i>Betula platyphylla</i>	60.7	5.3	3.42	0.70
WB	<i>Betula platyphylla</i>	28.3	25.0	1.59	3.31

2.3. Retrieval of LSP indicators

The raster-based 500-m and 8-day time series GPP dataset during 2000–2016 was used to extract pixel-wise LSP indicators (SOS, EOS, and LOS) using “PhenologyRaster” function in “greenbrown” package of R software (White et al., 1997; Beck et al., 2006; Elmore et al., 2012). The “Deriv” approach was used to define SOS and EOS based on the GPP dataset, and the retrieval of SOS, EOS, and LOS was conducted after smoothing and interpolation, using a splines method, of the gap-filled time series GPP dataset. The SOS, EOS, and LOS at each pixel for each year during 2000–2016 were obtained. Moreover, the linear regression models were conducted between LSP indicators and year of acquisition for each pixel, and the slope value of the regression for a particular LSP indicator at each pixel location was regarded as its trend. Positive values of SOS and EOS trends suggest the delay of relevant phenology, while negative values of SOS and EOS trends imply the advance of relevant phenology. Moreover, in order to test the reliability of the GPP-derived LSP indicators, MODIS MOD09A1 EVI dataset was also used to calculate the SOS, EOS, and LOS (using the same method) and to compare with those LSP indicators for each year during 2000–2016 of the two study regions. The results of the comparisons of the LSP indicators and their trends between different data source show a good consistency (Figure Supplementary Fig. 1 and Supplementary Fig. 2). This ensures the credibility of the results in this study.

2.4. Calculation of phenological Ts

Vegetation phenology is most sensitive to temperature, and vegetation phenological Ts reflects the change in SOS (or EOS) per unit increase in temperature (Du et al., 2019). Hence, phenological Ts was calculated to test whether it differed between the protected and unprotected areas. A linear regression analysis was performed for SOS and EOS against the relevant mean temperatures of pre-seasons, and the corresponding coefficients of determination (R^2) were defined as the Ts of relevant LSP indicators (Fu et al., 2015; Du et al., 2019). According to the initial results of the LSP indicators estimation, SOS and EOS for most pixels in the study area were mainly distributed in May and August. Therefore, the mean temperatures of May (T5) and August (T8) for each year during 2000–2016 were used to calculate SOS Ts and EOS Ts, respectively. In this study, the SOS Ts and EOS Ts were calculated for each pixel of the study area, and they were also calculated for all forest communities and the entire regions of FNNR and LEFF.

2.5. Comparisons of LSP, LSP trends and Ts

In order to test the impact of forest disturbance degrees on LSP, LSP trends, and Ts, we compared the mean LSP indicators, LSP trends, and Ts for each forest community during 2000–2016 between the protected area (FNNR) and the unprotected area (LEFF). One-way ANOVA was adopted to test the significance of the difference in these variables

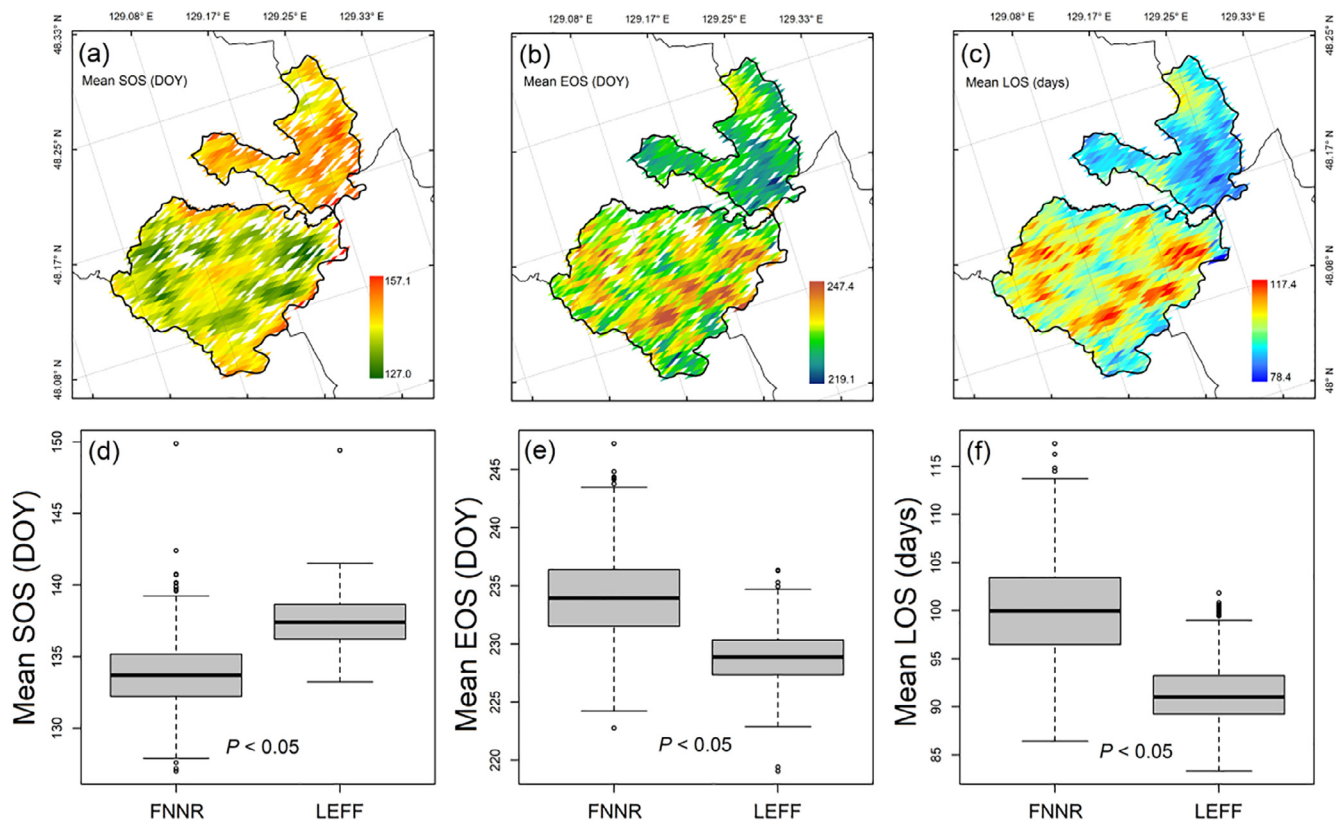


Fig. 2. Spatial distribution and comparisons of the mean start of the season (SOS), end of the season (EOS), and length of the season (LOS) during 2000–2016 between FNNR and LEFF. FNNR: Fengling National Natural Reserve; LEFF: Lilin Experiment Forest Farm.

during 200–2016 between FNNR and LEFF. We also compared the three variables among forest communities using a one-way ANOVA analysis in FNNR and LEFF. The LSD multiple comparison method was used to detect the difference of the three variables during 2000–2016 between any two forest communities.

In addition, in order to test the relationship between LSP indicators and pre-seasons' temperature in protected areas and unprotected areas, linear correlations were conducted between SOS and T5, and between EOS and T8 for both FNNR and LEFF. Correlation coefficients and regression equations were generated to display the degree of correlations qualitatively.

3. Results

3.1. Comparisons of LSP

Significantly ($P < 0.05$) lower mean SOS values during 2000–2016 were found in FNNR (about 133.7 DOY), while the mean EOS and LOS values during 2000–2016, at approximately 234.1 DOY and 100.2 days, respectively, in FNNR was significantly ($P < 0.05$) higher than those in LEFF (Fig. 2). However, compared to most areas of FNNR, the relatively high SOS and low EOS and LOS were identified in some edge and central parts of FNNR. Similarly, compared to most areas of LEFF, relatively low SOS and high EOS and LOS were identified in the northern parts of FNNR (Fig. 2).

In the comparisons of mean LSP indicators during 2000–2016 between the two study regions, the mean LSP indicators in FNNR were significantly ($P < 0.05$) different from LEFF, except the mean SOS for WB (Table 2). The mean SOS (ranging from 133.3 to 137.0 DOY) and mean EOS (ranging from 232.4 to 234.5 DOY) in FNNR were significantly ($P < 0.05$) lower and higher, respectively, than those in LEFF. The mean LOS during 2000–2016 in FNNR (ranged from 96.6 to 100.8 days) was significantly ($P < 0.05$) higher than that of LEFF

(ranged from 89.1 to 93.3 days).

In the comparisons of mean LSP indicators during 2000–2016 among various forest communities, there were significant differences among the mean SOS, EOS, and LOS in various forest communities, except the mean SOS for all forest communities in LEFF and the mean EOS for all forest communities in FNNR (Table 2). The mean SOS value in WB (137.0 ± 2.3 DOY) was significantly higher than that in other forest communities in FNNR, while the EOS in LC (227.1 ± 2.2 DOY) and AWB (227.9 ± 1.8 DOY) were significantly lower than that in other forest communities.

3.2. Comparisons of LSP trends

Significant ($P < 0.05$) difference was only found for the SOS trend between FNNR (-0.28 days year $^{-1}$) and LEFF (-0.46 days year $^{-1}$), while there was no significant difference in the EOS trend and LOS trend between FNNR and LEFF (Fig. 3). However, the spatial heterogeneity of LSP trends in FNNR was much higher than that in LEFF. Compared to most areas of FNNR, relatively high SOS trends, low EOS trends, and LOS trends were identified in the northwestern parts of FNNR.

In the comparisons of the LSP indicators' trends of various forest communities during 2000–2016 between the two study regions, the SOS, EOS, and LOS trends in FNNR were significantly ($P < 0.05$) different from LEFF, except for SFB and the EOS trend for BKP (Table 3). In coniferous (LC and SFKP) and mixed forests (BKP), the SOS trends (ranging from -0.33 to -0.23 days year $^{-1}$) in FNNR were significantly ($P < 0.05$) higher than that in LEFF, while the EOS trends (ranged from 0.12 to 0.35 days year $^{-1}$) and LOS trends (ranged from 0.50 to 0.63 days year $^{-1}$) in FNNR were significantly lower than those in LEFF, except the EOS trend for BKP. Conversely, in broadleaf forests (AWB and WB), the SOS trends in FNNR were significantly ($P < 0.05$) lower than the trends in LEFF, while the EOS trends and LOS trends in

Table 2

The mean value of the start of the season (SOS), end of the season (EOS), and length of the season (LOS) during 2000–2016 of the main forest communities in the Fenglin National Natural Reserve (FNNR) and Lalin Experiment Forest Farm (LEFF). Values are in form of mean \pm SD. Different lower-case letters at the end of values represent the results of the significance of the difference in the mean SOS, EOS, and LOS among forest types in multiple comparisons, and the asterisk after the values mean the significance of the mean SOS, EOS, and LOS between FNNR and LEFF. The significance level is set as 0.05. BKP: Broadleaf Korean Pine forests; LC: Larch Coniferous forests; SFKP: Spruce Fir Korean Pine; SFB: Spruce Fir Broadleaf forests; AWB: Aspen White Birch forests; WB: White Birch forests.

Forest communities	SOS (DOY)		EOS (DOY)		LOS (days)	
	FNNR	LEFF	FNNR	LEFF	FNNR	LEFF
BKP	133.5 \pm 1.9a*	136.9 \pm 1.7a	234.3 \pm 3.5a*	229.7 \pm 2.3b	100.7 \pm 4.9b*	92.6 \pm 3.4b
LC	134.5 \pm 2.4a*	138.3 \pm 1.4a	232.7 \pm 3.9a*	227.1 \pm 2.2a	98.3 \pm 5.6ab*	89.1 \pm 2.2a
SFKP	133.3 \pm 2.9a*	136.8 \pm 1.8a	234.5 \pm 3.9a*	230.1 \pm 2.6b	100.8 \pm 6.4b*	93.3 \pm 3.8b
SFB	134.8 \pm 2.4a*	137.2 \pm 1.4a	233.3 \pm 3.9a*	229.2 \pm 2.4b	98.3 \pm 5.5ab*	91.8 \pm 3.6ab
AWB	135.3 \pm 1.2ab*	137.0 \pm 0.2a	232.4 \pm 2.8a*	227.9 \pm 1.8a	97.1 \pm 3.5a*	90.9 \pm 1.6a
WB	137.0 \pm 2.3b	137.6 \pm 1.0a	233.3 \pm 3.9a*	228.0 \pm 1.6ab	96.6 \pm 4.7a*	90.7 \pm 2.4a

FNNR were significantly higher than those in LEFF.

In the comparisons of LSP indicators' trends during 2000–2016 among various forest communities, significant ($P < 0.05$) differences in the SOS, EOS, and LOS trends were detected for all forest communities in both FNNR and LEFF (Table 3). Generally, the SOS had advanced trends and EOS had delayed trends. In FNNR, the smallest SOS trends (-0.23 days year $^{-1}$) and EOS trends (0.12 days year $^{-1}$) were found in BKP and LC, respectively, while the largest SOS trends (-0.73 days year $^{-1}$) and EOS trends (0.79 days year $^{-1}$) were both found in AWB. In LEFF, the largest SOS trends (-0.48 days year $^{-1}$) and EOS trends (0.56 days year $^{-1}$) were similarly both found in AWB, while the smallest SOS trends (-0.44 days year $^{-1}$) and EOS trends (0.30 days year $^{-1}$) were found in BKP as well as SFB and LC, respectively. Moreover, the LOS trends in AWB were significantly ($P < 0.05$) higher than those in other forest communities in both FNNR and LEFF.

3.3. Comparisons of phenological Ts

The SOS was significantly ($P < 0.05$) linearly correlated with T5 for both FNNR and LEFF, and the R^2 were 0.26 and 0.15, respectively (Fig. 4a). However, there was no significant linear correlation between EOS and T8 for either FNNR or LEFF (Fig. 4b). The SOS Ts in FNNR was significantly ($P < 0.05$) higher than that in LEFF (Fig. 4c), while there was no significant difference in the EOS Ts between FNNR and LEFF (Fig. 4d). In the comparisons of phenological Ts among various forest communities, the SOS Ts and EOS Ts for AWB and WB were significantly ($P < 0.05$) lower and higher, respectively, than those for BKP, LC, SFKP, and SFB in FNNR. However, there was almost no significant difference in phenological Ts for all forest communities in LEFF, except that the SOS Ts and EOS Ts in WB were significantly higher than in other forest communities.

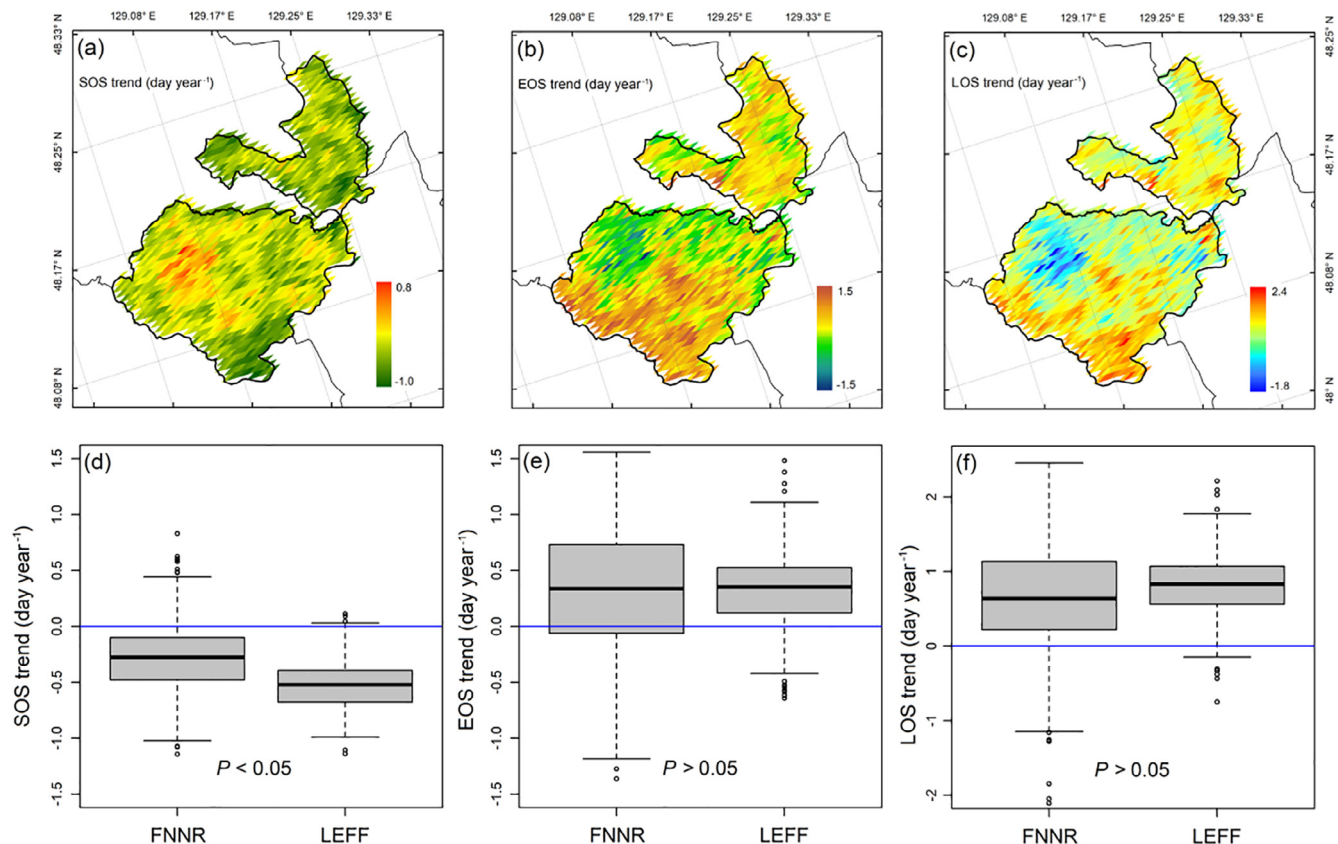


Fig. 3. Spatial distribution and comparisons of the trends of the mean start of the season (SOS), end of the season (EOS), and length of the season (LOS) during 2000–2016 between FNNR and LEFF. The blue lines represent the zero value. FNNR: Fenglin National Natural Reserve; LEFF: Lalin Experiment Forest Farm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

The mean value of the trends of start of the season (SOS trend), end of the season (EOS trend), and length of the season (LOS trend) during 2000–2016 of the main forest communities in the Fenglin National Natural Reserve (FNNR) and Lilin Experiment Forest Farm (LEFF). Values are in form of mean \pm SD. Different lower-case letters at the end of values represent the results of the significance of the difference of the SOS, EOS, and LOS trends among forest types in multiple comparisons, and the asterisk after the values mean the significance of the SOS, EOS, and LOS trends between FNNR and LEFF. The significance level is set as 0.05. BKP: Broadleaf Korean Pine forests; LC: Larch Coniferous forests; SFKP: Spruce Fir Korean Pine; SFB: Spruce Fir Broadleaf forests; AWB: Aspen White Birch forests; WB: White Birch forests.

Forest communities	SOS trend (days year ⁻¹)		EOS trend (days year ⁻¹)		LOS trend (days year ⁻¹)	
	FNNR	LEFF	FNNR	LEFF	FNNR	LEFF
BKP	-0.23 \pm 0.15e*	-0.44 \pm 0.11a	0.35 \pm 0.12b	0.37 \pm 0.10a	0.63 \pm 0.23b*	0.83 \pm 0.20a
LC	-0.33 \pm 0.18d*	-0.51 \pm 0.12b	0.12 \pm 0.15a*	0.30 \pm 0.13a	0.52 \pm 0.23a*	0.82 \pm 0.24a
SFKP	-0.30 \pm 0.17d*	-0.48 \pm 0.11ab	0.15 \pm 0.15a*	0.33 \pm 0.17a	0.50 \pm 0.21a*	0.80 \pm 0.25a
SFB	-0.42 \pm 0.13c	-0.44 \pm 0.11a	0.30 \pm 0.19b	0.32 \pm 0.10a	0.76 \pm 0.30c	0.79 \pm 0.19a
AWB	-0.73 \pm 0.14a*	-0.48 \pm 0.03ab	0.79 \pm 0.26c*	0.56 \pm 0.05b	1.56 \pm 0.24e*	1.03 \pm 0.02b
WB	-0.55 \pm 0.13b*	-0.47 \pm 0.09ab	0.67 \pm 0.36c*	0.35 \pm 0.22a	1.25 \pm 0.33d*	0.80 \pm 0.22a

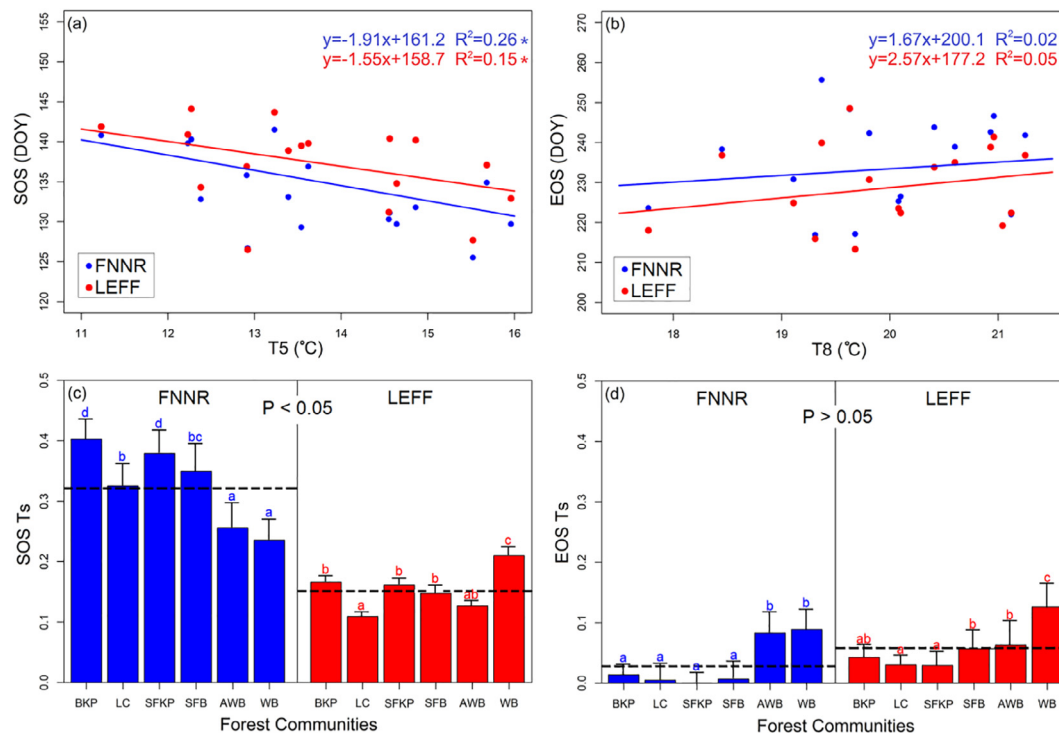


Fig. 4. (a) Relationship between the start of season (SOS) and temperature in May (T5), (b) Correlation between the end of season (EOS) and temperature in August (T8), (c) Comparison of SOS temperature sensitivity (Ts) and (d) Comparison of EOS Ts for various forest communities. Different lower-case letters represent the significance of the difference in the Ts among forest types in multiple comparisons. FNNR: Fengling National Natural Reserve; LEFF: Lilin Experiment Forest Farm. BKP: Broadleaf Korean Pine forests; LC: Larch Coniferous forests; SFKP: Spruce-Fir Korean Pine forests; PKC: Pinus Sylvestris Korean Pine Coniferous forests; SFB: Spruce-Fir Broadleaf forests; PPS: Planted Pinus Sylvestris forests; AWB: Aspen White Birch forests; WB: White Birch forests; AS: Aspen forests; MB: Mixed Broadleaf forests.

4. Discussion

4.1. LSP and LSP trends in protected and unprotected areas

The mean SOS and mean EOS values during 2000–2016 in the protected area (FNNR) were significantly lower and higher, respectively, than those in the unprotected area (LEFF) (Fig. 2). This indicates that the protection of forests has a considerable potential in extending the growing season of vegetation, which is likely to be attributed to the difference in microclimate conditions under different levels of forest disturbances (Brosofske et al., 1997). It has been reported that vegetation growth is enhanced under higher local temperature in less disturbed forests (Badano et al., 2015). This is also in line with our result that the mean LOS during 2000–2016 in the edge regions of FNNR (Fig. 2) was obviously lower than that in most other parts of FNNR. This

further demonstrates that the high fragmentation level in the edge regions of protected areas since the beginning of the establishment may still have a certain impact on forest phenology, although the same protection policy was applied in the same protected area.

There was almost no significant difference in LSP trends between FNNR and LEFF, except that the SOS trend in FNNR was significantly higher than that in LEFF (Fig. 3). This is in line with a study which reported that the change of vegetation leaf area index, a reflection of vegetation phenology, in the protected areas in Europe was not significantly different from the unprotected areas (Buitenwerf et al., 2018). A possible reason for the nondistinctive responses of phenological trends in different regions in this study is that vegetation phenological trend is more likely to be influenced by general climates (Vitasse et al., 2011; Barichivich et al., 2013; Delpierre et al., 2016). This could also be due to the fact that timber extraction in unprotected areas has

not been allowed since 2000. Moreover, our results also confirm that vegetation spring phenology is more sensitive to external influence, which was also reported by many other studies (Yu et al., 2010; Wolkovich et al., 2012; Shen et al., 2015; Delpierre et al., 2016; Walther et al., 2016).

Compared to the unprotected area, higher spatial heterogeneities of LSP and LSP trends were all identified in the protected area in this study (Figs. 2 and 3). This is mainly caused by the different phenology-climate relationships in various forest communities (Blundo et al., 2018) and various succession stages (Kalacska et al., 2005; Basler and Korner, 2012) under disturbance-free conditions. Moreover, the differences in LSP and LSP trends among various forest communities were relatively smaller in LEFF than in FNNR (Tables 2 and 3). This may be attributed to the mitigating and offsetting effects of high external disturbances on the response of vegetation phenology and phenology trends in response to climates. The impact of disturbances on forest phenology is far greater than that of other factors, and the vegetation phenology of different communities becomes convergent under highly disturbance conditions (Sitch et al., 2003; Moncrieff et al., 2015).

4.2. LSP and LSP trends in various forest communities

In this study, the mean LOS during 2000–2016 for broadleaf forests (AWB and WB) was relatively lower than that of coniferous (LC and SFKP) and mixed forests (BKP and SFB) for both the protected area and the unprotected area, which was directly affected by the high SOS and low EOS for the two regions, respectively (Table 2). This was mainly caused by the different responses to climate in various forest communities. The higher sensitivity of deciduous broadleaf trees to spring and autumn climates may be responsible for the undulant of phenology (Richardson et al., 2010). For the same reason, higher extending trends of LOS were identified for broadleaf forests, especially in protected areas, in this study (Table 3). This is in line with previous studies which documented that broadleaf forests were more beneficial from global warming than other forest communities (Barr et al., 2007; Gazol et al., 2017; Walentowski et al., 2017).

However, in contrast to broadleaf forests, faster-extending trends of LOS were identified for coniferous and mixed forests in unprotected areas, although they had a relatively shorter LOS. This is likely to be attributed to the special protection of forests in unprotected areas. The main coniferous tree species, such as Korean pine, Spruce, and Khingan fir, were listed as rare species and received strict protections no matter whether they were in protected areas or not (Wang et al., 2010), but many broadleaf tree species experienced severe disturbances in history.

4.3. Impact of disturbance degrees on phenological Ts

Our results show that the correlation between SOS and T5 was much stronger than the correlation between EOS and T8 (Fig. 4). This is consistent with many other studies suggesting that vegetation spring phenology, rather than autumn phenology, is more sensitive to temperature (Keenan et al., 2014; Fu et al., 2015; Sun et al., 2015), which was also demonstrated by the significantly higher SOS Ts than EOS Ts in this study. Moreover, in contrast to EOS Ts, the distribution of the values of SOS Ts was quite similar with those of the mean LOS during 2000–2016 for various forest communities, especially in protected areas. This finding demonstrates that SOS Ts is the control factor of LOS variation and explains the advancement of SOS and extension of LOS. Nonetheless, the SOS Ts in WB was significantly higher than that in other forest communities in the unprotected area, which is inconsistent with the LOS distribution pattern among forest communities. This is likely because of the more complex growth conditions of the forest in the unprotected area (Daniels et al., 2011), which also indicates that the vegetation phenology-climate relationship receives certain impacts from forest disturbances. Moreover, although the EOS Ts in broadleaf forests were significantly higher than those in other forest communities,

the distribution of EOS varied among different forest communities. This again demonstrates that forest autumn phenology is less important than SOS in controlling the LOS in the LKM of Northeastern China.

4.4. Implications of carbon sequestration and forest management

In this study, vegetation LSP indicators were extracted using time series GPP in 2000–2016. Considering that the GPP dataset was mainly estimated based on remote sensing vegetation indexes and has been proven to be consistent with satellite-observed vegetation photosynthesis (Zhang et al., 2016; Ma et al., 2018), it thus has a high reliability in calculating LSP indicators. The LSP indicators, especially the LOS, were also closely linked with carbon uptake period. Our results showed that the LOS of forests was generally extended, accompanied by advanced SOS and delayed EOS, during 2000–2016. This indicates that great carbon sequestration potential exists in temperate forests of Northeastern China if climate warming maintains the current level. Moreover, due to the elimination of logging in the LKM since 2000, the two regions in this study were assumed to have different levels of forest disturbances and to represent the different status of two stages in forest protection to some extent. Therefore, forest phenology in FNNR can clearly serve as a future state reference for many unprotected areas, which is crucial for decision-makers dealing with local forest management and planning. Further, in this study, the protected area and the unprotected area was respectively used to represent different forest disturbance levels that were mainly caused by human activities. Our results show that the responses of the LSP and LSP trends to climate change are different between the protected area and the unprotected area, which further demonstrates that anthropic interferences have a certain impact on the carbon cycle in northern temperate forest regions. This will also provide a deep understanding of the response of vegetation to climate change under the influence of human activities.

5. Conclusion

Based on the spatial distribution of forest communities, climate data, and a time series GPP dataset during 2000–2016, vegetation LSP indicators, LSP trends, and the SOS and EOS Ts were obtained for six main forest communities in protected areas and unprotected areas in the LKM of Northeastern China. By comparing the LSP, LSP trends, and Ts for various forest communities in both protected and unprotected areas, we explored whether the disturbance degrees significantly affected LSP and LSP trends of different temperate forest communities and whether Ts could explain the difference of phenology between disturbance degrees. Our results demonstrate that the forest average LOS during 2000–2016 generally extended, and it was especially enhanced in protected areas. However, there was little impact of the disturbance degree on the extension of the general mean LOS trend in space. Moreover, LSP and LSP trends varied among different forest communities. In particular, broadleaf forests had a relatively shorter LOS but a higher LOS extending trend when compared to coniferous and mixed forests. The response of vegetation spring phenology to temperature was more sensitive than the autumn phenology, and SOS Ts is an important factor in controlling the carbon uptake period of temperate forests in Northeastern China. Our study provides important insights into the future carbon sequestration potential of temperate forests and suggests crucial options and decisions for local forest management and planning in Northeastern China.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2019.117679>.

References

- Badano, E.I., Samour-Nieva, O.R., Flores, J., Douterlungne, D., 2015. Microclimate and seedling predation as drivers of tree recruitment in human-disturbed oak forests. *For. Ecol. Manage.* 356, 93–100.
- Barichivich, J., Briffa, K.R., Myneni, R.B., Osborn, T.J., Melvin, T.M., Ciais, P., Piao, S.L., Tucker, C., 2013. Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO₂ at high northern latitudes from 1950 to 2011. *Global Change Biol.* 19, 3167–3183.
- Barr, A.G., Black, T.A., Hogg, E.H., Griffis, T.J., Morgenstern, K., Kljun, N., Theede, A., Nesic, Z., 2007. Climatic controls on the carbon and water balances of a boreal aspen forest, 1994–2003. *Global Change Biol.* 13, 561–576.
- Basler, D., Korner, C., 2012. Photoperiod sensitivity of bud burst in 14 temperate forest tree species. *Agric. For. Meteorol.* 165, 73–81.
- Beck, P.S.A., Atzberger, C., Hogda, K.A., Johansen, B., Skidmore, A.K., 2006. Improved monitoring of vegetation dynamics at very high latitudes: a new method using MODIS NDVI. *Remote Sens. Environ.* 100, 321–334.
- Blundo, C., Gasparri, N.I., Malizia, A., Clark, M., Gatti, G., Campanello, P.I., Grau, H.R., Paolini, L., Malizia, L.R., Chediack, S.E., MacDonagh, P., Goldstein, G., 2018. Relationships among phenology, climate and biomass across subtropical forests in Argentina. *J. Trop. Ecol.* 34, 93–107.
- Broich, M., Huete, A., Tulbure, M.G., Ma, X., Xin, Q., Paget, M., Restrepo-Coupe, N., Davies, K., Devadas, R., Held, A., 2014. Land surface phenological response to decadal climate variability across Australia using satellite remote sensing. *Biogeosciences* 11, 5181–5198.
- Broszofski, K.D., Chen, J.Q., Naiman, R.J., Franklin, J.F., 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. *Ecol. Appl.* 7, 1188–1200.
- Buitenwerf, R., Sandel, B., Normand, S., Mimet, A., Svenning, J.C., 2018. Land surface greening suggests vigorous woody regrowth throughout European semi-natural vegetation. *Global Change Biol.* 24, 5789–5801.
- Daniels, L.D., Maertens, T.B., Stan, A.B., McCloskey, S.P.J., Cochrane, J.D., Gray, R.W., 2011. Direct and indirect impacts of climate change on forests: three case studies from British Columbia. *Can. J. Plant Pathol.* 33, 108–116.
- Delpierre, N., Dufrene, E., Soudani, K., Ulrich, E., Cecchini, S., Boe, J., Francois, C., 2009. Modelling interannual and spatial variability of leaf senescence for three deciduous tree species in France. *Agric. For. Meteorol.* 149, 938–948.
- Delpierre, N., Vitasse, Y., Chuine, I., Guillemot, J., Bazot, S., Rutishauser, T., Rathgeber, C.B.K., 2016. Temperate and boreal forest tree phenology: from organ-scale processes to terrestrial ecosystem models. *Ann. For. Sci.* 73, 5–25.
- Du, J., He, Z.B., Piatek, K.B., Chen, L.F., Lin, P.F., Zhu, X., 2019. Interacting effects of temperature and precipitation on climatic sensitivity of spring vegetation green-up in arid mountains of China. *Agric. For. Meteorol.* 269, 71–77.
- Elmore, A.J., Guinn, S.M., Minsley, B.J., Richardson, A.D., 2012. Landscape controls on the timing of spring, autumn, and growing season length in mid-Atlantic forests. *Global Change Biol.* 18, 656–674.
- Feeley, K.J., Silman, M.R., 2016. Disappearing climates will limit the efficacy of Amazonian protected areas. *Divers. Distrib.* 22, 1081–1084.
- Filippa, G., Cremonese, E., Migliavacca, M., Galvagno, M., Sonnentag, O., Humphreys, E., Hufkens, K., Ryu, Y., Verfaillie, J., di Cella, U.M., Richardson, A.D., 2018. NDVI derived from near-infrared-enabled digital cameras: Applicability across different plant functional types. *Agric. For. Meteorol.* 249, 275–285.
- Freudenberger, L., Hobson, P.R., Rupic, S., Pe'er, G., Schluck, M., Sauermann, J., Kreft, S., Selva, N., Ibsch, P.L., 2013. Spatial road disturbance index (SPROADI) for conservation planning: a novel landscape index, demonstrated for the State of Brandenburg, Germany. *Landscape Ecol.* 28, 1353–1369.
- Fu, Y.H., Zhao, H., Piao, S., Peaucelle, M., Peng, S., Zhou, G., Ciais, P., Huang, M., Menzel, A., Uelas, J.P., Song, Y., Vitasse, Y., Zeng, Z., Janssens, I.A., 2015. Declining global warming effects on the phenology of spring leaf unfolding. *Nature* 526, 104–+.
- Ganguly, S., Friedl, M.A., Tan, B., Zhang, X.Y., Verma, M., 2010. Land surface phenology from MODIS: Characterization of the Collection 5 global land cover dynamics product. *Remote Sens. Environ.* 114, 1805–1816.
- Gazol, A., Camarero, J.J., Anderegg, W.R.L., Vicente-Serrano, S.M., 2017. Impacts of droughts on the growth resilience of Northern Hemisphere forests. *Global Ecol. Biogeogr.* 26, 166–176.
- Hansen, M.C., Stehman, S.V., Potapov, P.V., 2010. Quantification of global gross forest cover loss. *PNAS* 107, 8650–8655.
- Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342, 850–853.
- Hwang, T., Song, C.H., Vose, J.M., Band, L.E., 2011. Topography-mediated controls on local vegetation phenology estimated from MODIS vegetation index. *Landscape Ecol.* 26, 541–556.
- Jean, M., Alexander, H.D., Mack, M.C., Johnstone, J.F., 2017. Patterns of bryophyte succession in a 160-year chronosequence in deciduous and coniferous forests of boreal Alaska. *Can. J. For. Res.* 47, 1021–1032.
- Jeong, S.J., Ho, C.H., Gim, H.J., Brown, M.E., 2011. Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008. *Global Change Biol.* 17, 2385–2399.
- Kalacska, M., Calvo-Alvarado, J.C., Sanchez-Azofeifa, G.A., 2005. Calibration and assessment of seasonal changes in leaf area index of a tropical dry forest in different stages of succession. *Tree Physiol.* 25, 733–744.
- Keenan, T.F., Grote, R., Sabate, S., 2011. Overlooking the canopy: the importance of canopy structure in scaling isoprenoid emissions from the leaf to the landscape. *Ecol. Model.* 222, 737–747.
- Keenan, T.F., Gray, J., Friedl, M.A., Toomey, M., Bohrer, G., Hollinger, D.Y., Munger, J.W., O'Keefe, J., Schmid, H.P., SueWing, I., Yang, B., Richardson, A.D., 2014. Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nat. Clim. Change* 4, 598–604.
- Liu, Q., Fu, Y.S.H., Zhu, Z.C., Liu, Y.W., Liu, Z., Huang, M.T., Janssens, I.A., Piao, S.L., 2016. Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology. *Global Change Biol.* 22, 3702–3711.
- Liu, L.L., Liang, L., Schwartz, M.D., Donnelly, A., Wang, Z.S., Schaaf, C.B., Liu, L.Y., 2015. Evaluating the potential of MODIS satellite data to track temporal dynamics of autumn phenology in a temperate mixed forest. *Remote Sens. Environ.* 160, 156–165.
- Luo, Z.H., Yu, S.X., 2017. Spatiotemporal variability of land surface phenology in China from 2001–2014. *Remote Sens.* 9.
- Ma, J., Hu, Y., Bu, R., Chang, Y., Deng, H., Qin, Q., 2014. Predicting impacts of climate change on the aboveground carbon sequestration rate of a temperate forest in Northeastern China. *PLoS ONE* 9.
- Ma, J., Xiao, X.M., Bu, R.C., Doughty, R., Hu, Y.M., Chen, B.Q., Li, X.P., Zhao, B., 2017. Application of the space-for-time substitution method in validating long-term biomass predictions of a forest landscape model. *Environ. Modell. Software* 94, 127–139.
- Ma, J., Xiao, X.M., Zhang, Y., Doughty, R., Chen, B.Q., Zhao, B., 2018. Spatial-temporal consistency between gross primary productivity and solar-induced chlorophyll fluorescence of vegetation in China during 2007–2014. *Sci. Total Environ.* 639, 1241–1253.
- Migliavacca, M., Sonnentag, O., Keenan, T.F., Cescatti, A., O'Keefe, J., Richardson, A.D., 2012. On the uncertainty of phenological responses to climate change, and implications for a terrestrial biosphere model. *Biogeosciences* 9, 2063–2083.
- Miller-Rushing, A.J., Primack, R.B., 2008. Global warming and flowering times in Thoreau's concord: a community perspective. *Ecology* 89, 332–341.
- Moncrieff, G.R., Hickler, T., Higgins, S.I., 2015. Intercontinental divergence in the climate envelope of major plant biomes. *Global Ecol. Biogeogr.* 24, 324–334.
- Park, T., Ganguly, S., Tommervik, H., Euskirchen, E.S., Hogda, K.A., Karlsen, S.R., Brovkin, V., Nemani, R.R., Myneni, R.B., 2016. Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data. *Environ. Res. Lett.* 11.
- Richardson, A.D., Black, T.A., Ciais, P., Delbart, N., Friedl, M.A., Gobron, N., Hollinger, D.Y., Kutsch, W.L., Longdoz, B., Luyssaert, S., Migliavacca, M., Montagnani, L., Munger, J.W., Moors, E., Piao, S.L., Rebmann, C., Reichstein, M., Saigusa, N., Tomelleri, E., Vargas, R., Varlagin, A., 2010. Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philos. Trans. R. Soc. B-Biol. Sci.* 365, 3227–3246.
- Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O., Toomey, M., 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agric. For. Meteorol.* 169, 156–173.
- Rodriguez-Galiano, V.F., Dash, J., Atkinson, P.M., 2015. Intercomparison of satellite sensor land surface phenology and ground phenology in Europe. *Geophys. Res. Lett.* 42, 2253–2260.
- Shen, M.G., Piao, S.L., Cong, N., Zhang, G.X., Janssens, I.A., 2015. Precipitation impacts on vegetation spring phenology on the Tibetan Plateau. *Glob. Change Biol.* 21, 3647–3656.
- Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venesky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Glob. Change Biol.* 9, 161–185.
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the anthropocene: the great acceleration. *Anthropocene Rev.* 2, 81–98.
- Stromgren, M., Linder, S., 2002. Effects of nutrition and soil warming on stemwood production in a boreal Norway spruce stand. *Global Change Biol.* 8, 1195–1204.
- Sun, W.Y., Song, X.Y., Mu, X.M., Gao, P., Wang, F., Zhao, G.J., 2015. Spatiotemporal vegetation cover variations associated with climate change and ecological restoration in the Loess Plateau. *Agric. For. Meteorol.* 209, 87–99.
- Thompson, R., Clark, R.M., 2008. Is spring starting earlier? Holocene 18, 95–104.
- Thurm, E.A., Uhl, E., Pretzsch, H., 2016. Mixture reduces climate sensitivity of Douglas-fir stem growth. *For. Ecol. Manage.* 376, 205–220.
- Toledo, R.M., Santos, R.F., Baeten, L., Perring, M.P., Verheyen, K., 2018. Soil properties and neighbouring forest cover affect above-ground biomass and functional composition during tropical forest restoration. *Appl. Veg. Sci.* 21, 179–189.

- Verbesselt, J., Hyndman, R., Zeileis, A., Culvenor, D., 2010. Phenological change detection while accounting for abrupt and gradual trends in satellite image time series. *Remote Sens. Environ.* 114, 2970–2980.
- Vitasse, Y., Francois, C., Delpierre, N., Dufrene, E., Kremer, A., Chuine, I., Delzon, S., 2011. Assessing the effects of climate change on the phenology of European temperate trees. *Agric. For. Meteorol.* 151, 969–980.
- Vlassova, L., Perez-Cabello, F., 2016. Effects of post-fire wood management strategies on vegetation recovery and land surface temperature (LST) estimated from Landsat images. *Int. J. Appl. Earth Obs. Geoinf.* 44, 171–183.
- Walentowski, H., Falk, W., Mette, T., Kunz, J., Brauning, A., Meinardus, C., Zang, C., Sutcliffe, L., Leuschner, C., 2017. Assessing future suitability of tree species under climate change by multiple methods: a case study in southern Germany. *Ann. For. Res.* 60, 101–126.
- Walther, S., Voigt, M., Thum, T., Gonsamo, A., Zhang, Y.G., Kohler, P., Jung, M., Varlagin, A., Guanter, L., 2016. Satellite chlorophyll fluorescence measurements reveal large-scale decoupling of photosynthesis and greenness dynamics in boreal evergreen forests. *Global Change Biol.* 22, 2979–2996.
- Wang, X.G., Ye, J., Li, B.H., Zhang, J.A., Lin, F., Hao, Z.Q., 2010. Spatial distributions of species in an old-growth temperate forest, northeastern China. *Can. J. For. Res.* 40, 1011–1019.
- White, M.A., Thornton, P.E., Running, S.W., 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochem. Cycles* 11, 217–234.
- White, M.A., de Beurs, K.M., Didan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'Keefe, J., Zhang, G., Nemani, R.R., van Leeuwen, W.J.D., Brown, J.F., de Wit, A., Schaepman, M., Lin, X.M., Dettinger, M., Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T., Lauenroth, W.K., 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. *Global Change Biol.* 15, 2335–2359.
- Wolkovich, E.M., Cook, B.I., Allen, J.M., Crimmins, T.M., Betancourt, J.L., Travers, S.E., Pau, S., Regetz, J., Davies, T.J., Kraft, N.J.B., Ault, T.R., Bolmgren, K., Mazer, S.J., McCabe, G.J., McGill, B.J., Parmesan, C., Salamin, N., Schwartz, M.D., Cleland, E.E., 2012. Warming experiments underpredict plant phenological responses to climate change. *Nature* 485, 494–497.
- Wu, C.Y., Hou, X.H., Peng, D.L., Gonsamo, A., Xu, S.G., 2016. Land surface phenology of China's temperate ecosystems over 1999–2013: Spatial-temporal patterns, interaction effects, covariation with climate and implications for productivity. *Agric. For. Meteorol.* 216, 177–187.
- Xiao, X.M., Boles, S., Liu, J.Y., Zhuang, D.F., Liu, M.L., 2002. Characterization of forest types in Northeastern China, using multi-temporal SPOT-4 VEGETATION sensor data. *Remote Sens. Environ.* 82, 335–348.
- Yu, H.Y., Luedeling, E., Xu, J.C., 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. *PNAS* 107, 22151–22156.
- Zhang, Y., Xiao, X., Jin, C., Dong, J., Zhou, S., Wagle, P., Joiner, J., Guanter, L., Zhang, Y., Zhang, G., Qin, Y., Wang, J., Moore III, B., 2016. Consistency between sun-induced chlorophyll fluorescence and gross primary production of vegetation in North America. *Remote Sens. Environ.* 183, 154–169.
- Zhang, Y., Xiao, X.M., Wu, X.C., Zhou, S., Zhang, G.L., Qin, Y.W., Dong, J.W., 2017. Data Descriptor: A global moderate resolution dataset of gross primary production of vegetation for 2000–2016. *Sci. Data* 4, 13.