Assessing consistency of spring phenology of snow-covered forests as estimated by vegetation indices, gross primary production, and solar-induced chlorophyll fluorescence

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ABSTRACT

Accurate phenology characterization is of great importance for measuring ecosystem dynamics, especially for carbon and water exchange between land and the atmosphere. Vegetation indices (VIs), calculated from land surface reflectance, are widely used to estimate phenology from the leaf and canopy structure perspective. Gross Primary Production (GPP) and solar-induced chlorophyll fluorescence (SIF) are used to estimate phenology from the canopy functional (physiological) perspective. To what degree are the spring phenology estimated from these different perspectives consistent with each other? In this study, we evaluated the consistency of the start of the growing season (SOS) in spring for snow-covered evergreen needleleaf forests (ENF) and deciduous broadleaf forests (DBF) using three vegetation indices, in-situ GPP data from the eddy covariance flux towers (GPPEC), GPP data from the Vegetation Photosynthesis Model (GPPVPM), and SIF data from the GOME-2. Results showed that SOSNDVI dates were much earlier than SOS dates from EVI (SOSEVI), land surface water index (LSWI) (SOSLSWI), GPP (SOSGPP; SOSGPP-EC, SOSGPP_VPM) and SIF (SOSSIF) for both snow-covered evergreen needleleaf forest (ENF) and deciduous broadleaf forest (DBF). SOSLSWI dates were more linearly correlated with SOSGPP and SOSSIF than SOS dates from NDVI and EVI. At ENF sites, SOSEVI were 25 (± 34) days later than SOSGPP dates. At DBF sites, SOSEVI dates were 1-week (± 13 days) later than SOSGPP dates. In the snow-covered regions at mid- to high-latitude in the Northern Hemisphere, SOSEVI were 2-3 weeks (± 5 days) later than SOSGPP_VPM and SOSSIF for both ENF and DBF. Our results clearly highlight the need for further investigation of NDVI-based SOS dates, which were likely affected by snowmelt in snow-covered forests, and the potential of LSWI for tracking the effects of snow on SOS dates. Estimations of SOS dates in snow-covered forests should consider the effects of both snow cover and temperature on leaf emergence (green-up) and gross primary production.

1. Introduction

Vegetation (leaf and canopy) phenology significantly affects carbon and water cycles (Hollinger et al., 1999; Peñuelas and Filella, 2009; Richardson et al., 2010) and is often characterized from the perspective of leaf and canopy structure (e.g., leaf flush, green-up) or from the perspective of leaf and canopy function (e.g., photosynthesis or gross primary production (Churkina et al., 2005; Ma et al., 2007; Piao et al., 2007; Richardson et al., 2010). Accurate measurements and the comparison of vegetation phenology from the structural and functional perspectives are significant for improving terrestrial models and exploring ecosystem carbon-water interaction and variability (Wu et al., 2012; Zhang et al., 2003).

Over the past decades, optical remote sensing has been used to identify vegetation phenology and land surface phenology (Matsumoto et al., 2003; Piao et al., 2007; Wu et al., 2013; Zhang et al., 2013). Vegetation indices (e.g., normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), land surface water index (LSWI)) and leaf area index (LAI) provide information on the dynamics of canopy structure and are the primary indices used for estimating the start and end of the growing season (SOS, EOS) from the perspective of canopy structure (Hmimina et al., 2013; Sims et al., 2006; Xiao et al., 2004b; Zhang et al., 2003). The SOS dates estimated by the vegetation indices derived from the Moderate Resolution Imaging
Spectroradiometer (MODIS) varied among land cover types, soil moisture conditions, and even extreme climate events (Liu et al., 2016; Peng et al., 2017a; Shen et al., 2014b; Wu et al., 2014). Our understanding of the unique advantages of each vegetation index in estimating spring phenology and the differences among the VI-based indicators of phenology across vegetation types is still limited (Balzarolo et al., 2016; Chang et al., 2018; Reed et al., 2009).

Gross primary production (GPP) of forests (Baldocchi et al., 2001; Zhang et al., 2006) is also used for estimating SOS and EOS from the perspective of canopy function. Several studies reported that canopy structure phenology from satellites were consistent with the phenology from flux tower GPP observations (Balzarolo et al., 2016) and NEE (Wang et al., 2016), and the net carbon uptake period (CUP) from NEE has been widely used for validation of land surface phenology derived from satellite data analysis (Peng et al., 2017b; Verma et al., 2014; Xiao et al., 2008; Zhang et al., 2016b). However, some other studies reported that no single source of canopy phenology data was able to accurately describe annual patterns of phenology from the eddy flux GPP or NEE data, and the differences are inconsistent across vegetation types (Garrity et al., 2011; Wu et al., 2017). The contrary conclusions could have been caused by snow-cover at the selected sites, which was not addressed in these studies. Thus, further investigation into the consistencies and differences in satellite-based indicators of vegetation canopy structural and functional phenology is needed.

Solar-induced chlorophyll fluorescence (SIF) emitted by vegetation (Joiner et al., 2014; Sun et al., 2018; Wang et al., 2016) was recently used to estimate SOS and EOS from the perspective of canopy function (Joiner et al., 2014). SIF is a kind of photosynthesis-related energy and is directly detected by satellite sensor instead of being modeled based on indirectly satellite datasets (Joiner et al., 2013; Sun et al., 2018). Phenology studies of SIF can help us better understand seasonal dynamics of photosynthesis (Jeong et al., 2017; Walther et al., 2016) and to assess the uncertainties in modeled GPP products (Joiner et al., 2014; Wang et al., 2016). A number of studies have shown that GPP is closely related to SIF (Li et al., 2018; Walther et al., 2016; Zhang et al., 2016b). However, the relationship between GPP and SIF varies from the leaf scale to the canopy scale, and also depends on the time frame (diurnal, daily, seasonal) and biome type (Li et al., 2018; Zhang et al., 2016a). The consistency between the functional phenology metrics derived from GPP and SIF has not yet well studied. Furthermore, structure-based spring phenology dates derived from NDVI, EVI, and LSWI have not yet been compared with phenology from SIF. A comprehensive study is urgently needed for comparing the SOS dates from vegetation indices (NDVI, EVI, LSWI), GPP, and SIF.

Phenology studies in snow-covered deciduous and evergreen forests at mid- to high-latitude regions are complex because of snow cover (Botta et al., 2000; Julien and Sobrino, 2009; Zhang et al., 2006). SOS date estimates using vegetation indices are always biased by snow cover, which affects satellite reflectance (Chen et al., 2015; Delbart et al., 2006; Wang et al., 2017; Zhang, 2015). Decoupling the snowmelt signal from vegetative growth is essential for accurate phenology estimation. The effects of snow on spring phenology (SOS estimates) by vegetation indices, GPP, and SIF are not fully investigated. The consistency of spring phenology of snow-covered forests from the perspectives of canopy structure (VIs) and function (GPP, SIF) is not yet well known. Furthermore, as air temperature is the most important environmental factor controlling both SOS (Ensminger et al., 2004; Piao et al., 2015; Wang et al., 2015) and snowmelt processes (Groendahl et al., 2007), there is also a need to understand the effect of air temperature on vegetation indices, GPP and SIF, which would in turn affect their SOS estimates.

In this study, we investigated the consistency of SOS estimates of snow-covered evergreen needleleaf forests (ENF) and deciduous broadleaf forests (DBF) from the perspectives of canopy structure (vegetation indices) and function (GPP and SIF). We used two greenness-related vegetation indices (NDVI and EVI) and one water-related vegetation index (LSWI) from MODIS images, GPP data from the eddy flux tower sites (GPP_EF), GPP data from the Vegetation Photosynthesis Model (GPP_VPM), and SIF data from the GOME-2. We addressed the following questions: (1) what is the consistency of SOS dates from VIs (NDVI, EVI, and LSWI) and from GPP_EF at snow-covered ENF and DBF eddy flux tower sites? (2) what is the consistency of SOS dates from VIs (NDVI, EVI, and LSWI), GPP_VPM, and SIF at snow-covered ENF and DBF forests across the mid- to high-latitude North Hemisphere? (3) what are the responses of VIs, GPP, and SIF to daytime air temperature during the initial growth stage of snow-covered ENF and DBF? We first evaluated the consistency of SOS from vegetation indices (NDVI, EVI, and LSWI) and GPP (GPP_EF, GPP_VPM) at the site level using snow-covered forest flux tower observations, and then explored the consistency of SOS of snow-covered ENF and DBF from VIs, GPP_VPM, and SIF data at regional scale for snow-covered ENF and DBF in the mid- to high-latitude Northern Hemisphere. The relationships between various data sources and air temperature were also analyzed to show the reliability of SOS dates estimated from various datasets at snow-covered ENF and DBF sites.

2. Materials and methods

2.1. Study sites

We selected 17 forest eddy flux tower sites (8 ENF and 9 DBF sites) from the FLUXNET-2015 dataset (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/) (Table 1). Site selection was based on the following criteria: (1) sites must have more than 8 years of observations between 2000 and 2014; (2) sites are relatively homogeneous land cover within the pixels of the MODIS MOD09A1 product (500 m spatial resolution) (Fig. S.1); and (3) sites have snow cover in winter and spring, according to the site description and MODIS normalized difference snow index (NDSI). MODIS NDSI is calculated from green band and short wave infrared band, and is used to assess snow conditions. The MODIS snow-mapping algorithm identifies an observation as snow when NDSI value is equal to or greater than 0.4 (with more than 50% snow cover) (Hall et al., 1995, 2002; Zhang et al., 2003). In our study, only those years identified to have snow cover during the winter (previous December, January, and February) to spring (March, April, and May) for each site were used. For the flux towers listed in Table 1, years with no snow cover were removed. The removed years for the used sites include RU-Fyo (2005, 2008), DK-Sor (2003, 2004, 2007, 2008, 2012, 2014), DE-Hai (2004, 2005, 2007, 2008, 2009, 2012), FR-Fon (2005, 2007–2014), US-Wcr (2000, 2012), US-Ha1 (2000–2007, 2010–2012), IT-Col (2000–2002, 2007, 2008, 2011, 2012, 2014), and US-MMS (2000, 2002–2006, 2008, 2009, 2011–2013).

2.2. Data

2.2.1. Climate and GPP data from the CO2 flux tower sites

The FLUXNET eddy covariance network measures ecosystem CO2, heat fluxes, and meteorological variables at sites across the globe. The FLUXNET-2015 eddy covariance GPP (GPP_EF) datasets were calculated from gap-filled net ecosystem exchange (NEE) data using the standard flux-partitioning method (Lasslop et al., 2010). The GPP product (GPP_DT_VUT_REF) used in this study was calculated with the variable USTAR filtering approach and daytime partitioning method (Kumar et al., 2016). Daily GPP datasets were used in this study to determine SOS. Daily average daytime air temperature datasets (TA_F) from FLUXNET-2015 were also used to explore the relationship between temperature and phenology. Daily observations at the flux tower sites were aggregated to an 8-day and monthly temporal resolutions to match the MODIS VIs and GOME-2 SIF data, respectively.

2.2.2. MODIS surface reflectance data and vegetation indices

The MODIS surface reflectance product MOD09A1 V6 is provided...
is the fraction of PAR absorbed
is light use e
is the photosynthetic active radiation. 
\( \varepsilon_g \)
is estimated using maximum light
\( \varepsilon \)
and \( \varepsilon_g \)
is calculated from MOD09A1-based bands reflectance products. Prior to calculating the phenology metrics, we processed the time-series VIS using the following three steps. First, observations affected by cloud cover were identified by using the quality assurance (QC) flags for cloud state (‘00’ flags indicate clear sky), and were gap-filled using the multi-year mean of good observations for that day. Second, we used the Best Index Slope Extraction (BISE) method to detect bad-quality observations unidentifiable in the QC layer in NDVI time series, and the bad observations were replaced with the mean value of its nearest two good observations (Viovy et al., 1992; White et al., 1997; Xiao et al., 2009). Spatial distributions of (a) MODIS normalized difference snow index (NDSI) in January in 2010; (b) evergreen needleleaf forest (ENF) and deciduous broadleaf forest (DBF) from MODIS land cover product in 2010; and (c) snow-covered ENF (773 pixels) and DBF (334 pixels) (NDSI > 0.4) in mid- to high-latitudes of Northern Hemisphere.

\[
\text{NDSI} = \frac{\text{GREEN} - \text{SWIR}}{\text{GREEN} + \text{SWIR}}
\]

\[
\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}
\]

\[
\text{EVI} = 2.5 \times \frac{\text{NIR} - \text{RED}}{(\text{NIR} + 6 \times \text{RED} - 7.5 \times \text{BLUE} + 1)}
\]

\[
\text{LSWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}}
\]

with 500-m spatial resolution and 8-day interval temporal resolution (Vermote, 2015). The MOD09A1 dataset was used to calculate four spectral indices including NDSI (Hall et al., 1995, 2002), NDVI (Rouse et al., 1974), EVI (Huete et al., 2002), and LSWI (Xiao et al., 2004a) (see Eqs. (1)–(4)). MODIS bands were used in these equations including: red band (RED) (620–670 nm), near infrared band (NIR) (841–876 nm), blue band (BLUE) (459–479 nm), green band (GREEN) (545–565 nm), and short wavelength near infrared band (SWIR) (1628–1652 nm). NDSI was used to determine snow cover at 500-m spatial resolution. NDSI values for mid- to high-latitude NH are shown in Fig. 1 a.

Vegetation indices (NDVI, EVI, and LSWI) at the flux sites were calculated from MOD09A1-based bands reflectance products. Prior to calculating the phenology metrics, we processed the time-series VIS using the following three steps. First, observations affected by cloud cover were identified by using the quality assurance (QC) flags for cloud state (‘00’ flags indicate clear sky), and were gap-filled using the multi-year mean of good observations for that day. Second, we used the Best Index Slope Extraction (BISE) method to detect bad-quality observations unidentifiable in the QC layer in NDVI time series, and the bad observations were replaced with the mean value of its nearest two good observations (Viovy et al., 1992; White et al., 1997; Xiao et al., 2009).

Third, we used the S–G filter method to remove abnormal values in the time series data (Chen et al., 2004; Savitzky and Golay, 1964).

\[
\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}
\]

\[
\text{EVI} = 2.5 \times \frac{\text{NIR} - \text{RED}}{(\text{NIR} + 6 \times \text{RED} - 7.5 \times \text{BLUE} + 1)}
\]

\[
\text{LSWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}}
\]

2.2.3. GPP data from the VPM simulations

We used the GPP data product simulated from Vegetation Photosynthesis Model (VPM) (GPPVPM) at 500-m spatial resolution. VPM estimates GPP as a function of photosynthetically active radiation (PAR) absorbed by chlorophyll (APAR\text{chl}) and light use efficiency (\( \varepsilon_L \)) (Xiao et al., 2004a). Two basic equations for LUE-based VPM are shown as Eqs. (5) and (6). The global GPPVPM dataset (VPM GPP V20) used different \( \varepsilon_L \) values for C3 and C4 vegetation (Zhang et al., 2017). In VPM model simulations, MODIS-based EVI and NCEP reanalysis climate data were used. When compared with GOME-2 SIF, the 500-m GPPVPM datasets were aggregated from 8-day to monthly and to 0.5° (latitude and longitude).

\[
\text{GPPVPM} = \varepsilon_L \times \text{FPAR}_{\text{chl}} \times \text{PAR}
\]

\[
\varepsilon_L = \varepsilon_0 \times T_{\text{skyline}} \times W_{\text{scalar}}
\]
use efficiency ($\epsilon_r$) downregulated by temperature ($T_{\text{air}}$) and water stress ($W_{\text{stress}}$).

### 2.2.4. GOME-2 SIF data

We used sun-induced chlorophyll fluorescence (SIF) retrievals from the MetOp-A satellite. The GOME-2 MetOp-A satellite has an overpass about 9:30 local solar time and SIF values were retrieved at about 740 nm (Joiner et al., 2013). The GOME-2 instruments have a footprint of about 40 km x 80 km before July 2013, and a 40 km x 40 km footprint after July 2013. We used the GOME-2 SIF V27 level 3 product from 2007 to 2014 at a spatial resolution of 0.5° x 0.5° and monthly resolution.

#### 2.2.5. Land cover data

We used the MODIS land cover dataset (MCD12C1 V051 yearly 0.05°) in 2010 to represent the land cover type (IGBP land cover classification system) throughout the entire study period. We used the majority method to assign the final land cover type when we aggregated the land cover data from 0.05° to 0.5° resolution. Based on MODIS NDSI distribution and land cover data, the snow-covered ENF and DBF pixels were identified at northern mid- to high-latitude regions (30°-90° N) (Fig. 1b). Then, we calculated monthly and average NDVI, EVI, LSWI, GPPVPM, and SIF for all snow-covered ENF and DBF pixels from 0.5° VIs, GPPVPM, and SIF for each year during 2007 to 2016. Then, SOS dates of snow-covered ENF and DBF across the entire mid- to high-latitude NH were estimated based on the monthly VIs, GPPVPM, and SIF time series.

#### 2.2.6. NCEP temperature data

Daytime temperature data from the National Centers for Environmental Prediction (NCEP) reanalysis project was used in this study. The 6-hour air temperature at 2 m were downloaded (https://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml) and daily daytime mean temperature was calculated (Zhang et al., 2017). The original NCEP air temperature products were in the 2.5° x 2.5° grid (144 x 73). To compare with GPPVPM and SIF, NCEP daily daytime temperatures were composited into monthly data and downscaled to 0.5° spatial resolution using the nearest neighbor method.

### 2.3. Phenology algorithms

The logistic growth model has been widely used in numerous studies of phenology (Fisher et al., 2006; Gu et al., 2003; Zhang et al., 2003). The 8-day 500 m and monthly 0.5° datasets were interpolated to daily before utilizing logistic regression. We used an improved double logistic growth model (Eq. 7) to estimate vegetation phenology metrics from NDVI, EVI, DBF LSWI, GPP, and SIF datasets (Elmore et al., 2012):

$$ A(t) = y_0 \left\{ \left( 1 + \exp \left( -\frac{a_1}{t_1} \right) \right)^{-1} + \left( 1 + \exp \left(-\frac{a_2}{t_2}\right) \right)^{-1} \right\} $$

where $A(t)$ is the observation on day $t$, and $y_0$, $a_1$, $a_2$, $b_1$, $c_1$, $c_2$, $t_1$, and $t_2$ are the model parameters to be estimated from the original given data. Start of the growing season (SOS) was calculated using the DOY at the maximum values of the second derivatives (Bucha and Koren, 2017).

LSWI in snow-covered ENF has no significant increase during the growing season, thus it cannot easily be detected by the traditional logistic algorithm. The specific threshold method described in previous studies (Kang et al., 2016; Xiao et al., 2006) was used to determine SOS by LSWI at ENF. In the current study, SOSLSWI of ENF was defined as the first day during the snow-melt period (LSWI decrease period) when LSWI equaled to or lower than 0.3.

### 3. Results

#### 3.1. Consistency of spring phenology of snow-covered forests at the eddy flux tower sites

The ENF CA-Man site was selected as an example to show the seasonal dynamics of GPPVPM, GPPVPM, NDVI, EVI, and LSWI at the snow-covered ENF sites (Fig. 2a). GPP estimates from the ENF eddy covariance tower (GPPVPM) and GPPVPM had a similar seasonal cycle. Both GPPVPM and GPPVPM at CA-Man site increased rapidly in late May. SOS dates from GPPVPM (SOSGPPVPM) and GPPVPM (SOSGPPVPM) were identified as 136 and 137 day of year (DOY), respectively. However, NDVI sharply increased in late-April (SOSNDVI was 116 DOY) and EVI started to sharply increase in late-May (SOSNDVI was 142 DOY). LSWI was high and peaked at about 0.6 during winter and early spring because of snow cover (NDVI > 0.4), but rapidly decreased in early April due to snowmelt. NDVI was affected by land surface snow cover conditions. When LSWI increased or decreased during the snow cover and snow melting period from winter to early spring, NDVI also decreased or increased. The seasonal dynamics of the other ENF sites had similar results with the CA-Man site; see Fig. S.2 for more information.

The DBF US-UMB site was used as an example to illustrate the seasonal cycles of various variables in the snow-covered DBF sites (Fig. 2b). Both GPPVPM and GPPVPM sharply increased in mid-June, and SOS dates from GPPVPM and GPPVPM were 165 and 163 DOY. NDVI showed the first sharp increase in March along with the sharp decrease of LSWI. The dynamics of NDVI also was distinctly converse with those in LSWI curves during the snow cover (NDVI > 0.4) and snowmelt periods (when NDVI decreased from the maximum value) from winter to early spring. EVI and LSWI showed sharp increases in late May, which was consistent with both GPPVPM and GPPVPM. For similar seasonal dynamics of the other DBF sites, see Fig. S.3.
Linear regression analyses for all the snow-covered ENF sites (Fig. 3a) showed that SOS dates estimated by NDVI (SOSNDVI), EVI (SOSEVI), and LSWI (SOSLSWI) were significantly correlated with SOS dates by GPPEC (SOSGPP-EC) (p < 0.01). However, their RMSE and $R^2$ values varied among these three vegetation indices. SOSNDVI had the largest RMSE value (RMSE = 26 ± 53 days) and lowest $R^2$ ($R^2 = 0.34$) value among the three vegetation indices, while LSWI had smallest RMSE ($R^2 = 17 ± 27$ days) and highest $R^2$ ($R^2 = 0.48$) values. Among all the site-years (Fig. 3c), about 50% of SOSGPP-EC occurred in the range of 104–130 day of year (DOY). The range of SOSLSWI (106–131 DOY) was closer to SOSGPP-EC than the other two greenness-related vegetation indices: SOSNDVI (94–139 DOY) and SOSEVI (123–150 DOY).

Linear regression analyses for all the snow-covered DBF sites (Fig. 3b) also showed that SOS dates estimated by vegetation indices (SOSNDVI, SOSEVI, and SOSLSWI) were significantly correlated with SOSGPP-EC (p < 0.01) (Fig. 5a). Both SOSEVI and SOSLSWI had small RMSE values (7 days), while SOSNDVI had a large RMSE value (21 days). In addition, $R^2$ value for the linear regression models between SOSEVI ($R^2 = 0.84$) and SOSLSWI ($R^2 = 0.86$) and SOSGPP-EC were higher than that for SOSNDVI ($R^2 = 0.31$). Among all the site-years (Fig. 3c), 50% of SOSEVI, SOSLSWI and SOSGPP-EC were distributed in the time range of 120–140 DOY (Fig. 3c). SOSNDVI was much earlier than SOSEVI, SOSLSWI and SOSGPP-EC.

3.3. Consistency of spring phenology of snow-covered forests across the northern mid- to high-latitudes at 0.5° spatial resolution

We calculated average NDVI, EVI, LSWI, GPP and SIF over all the snow-covered ENF and DBF gridcells (0.5° gridcells) over the northern mid- to high-latitudes, and they had strong seasonal dynamics over the study period (Fig. 4a,b,c,d). There were strong agreements between SIF and GPPEC data in terms of seasonal dynamics and interannual variation (Fig. 4b,d), and linear relationships between monthly GPP and SIF (Fig. 4e,f) were significant (p < 0.001).

For snow-covered ENF in northern mid- to high-latitudes, SOSGPP-EC dates were significantly consistent with both SOSGPP-VPM (p < 0.01) (Fig. 5a) and SOSGPP-EC dates (p < 0.01) (Fig. 5c), while SOSNDVI and SOSSEVI dates had no significant linear correlation with SOSGPP-VPM. RMSE values of SOSLSWI dates to SOSGPP-VPM and SOSGPP-EC were 20 ± 5 days and 16 ± 3 days, respectively. Similar to our site-level analysis, SOSNDVI dates were much earlier than SOSGPP-EC, SOSLSWI, SOSGPP-VPM, and SOSGPP-EC for snow-covered ENF region. In addition, we found that SOSGPP-EC and SOSGPP-VPM dates were close to each other (Fig. 5a). The differences between SOSGPP-EC and SOSGPP-VPM ranged from about 0–8 days. As shown in Fig. 5a, SOSGPP-EC was on average 5 ± 3 days earlier than SOSGPP-VPM.

For snow-covered DBF in northern mid- to high-latitudes, both SOSLSWI (p < 0.001) and SOSEVI (p < 0.01) had a significant linear correlation with SOSGPP-VPM (Fig. 5b). However, there was a higher $R^2$ value between SOSLSWI and SOSGPP-VPM ($R^2 = 0.8$) than between SOSEVI and SOSGPP-VPM ($R^2 = 0.62$). RMSE values between SOSLSWI and SOSEVI and SOSGPP-VPM were 20 ± 2 days and 15 ± 6 days, respectively. SOSLSWI was consistent with SOSGPP-EC (p < 0.1) with a RMSE value of 18 ± 6 days while SOSNDVI and SOSEVI didn’t significantly correlate with SOSGPP-EC (Fig. 5d). SOSGPP-EC was also much earlier than SOS from EVI, LSWI, GPP-EC, and SIF. In addition, SOSGPP-VPM were also similar to SOSGPP-EC for snow-covered DBF forest. Differences between SOSGPP-EC and SOSGPP-VPM were about 0–7 days (Fig. 5e). On average, SOSGPP-VPM was 2 ± 3 days earlier than SOSGPP-EC.

3.3. The effect of air temperature on spring phenology of snow-covered forests at both site and regional scales

For the snow-covered ENF and DBF sites, responses of GPP-EC, GPP-VPM, NDVI, EVI, and LSWI to average daytime air temperature (TemDT) were analyzed (Fig. 6). ENF GPP-EC and GPP-VPM had similar dynamics in response to TemDT (Fig. 6a,b), which started to increase at 0 °C. ENF NDVI, EVI, and LSWI also increased rapidly at 0 °C (Fig. 6c,d,e). DBF GPP-EC and GPP-VPM had similar dynamics in response to TemDT (Fig. 6f,g), which started to increase at 5 °C. DBF NDVI, EVI, and LSWI also increased rapidly at 5 °C (Fig. 6h,i). We calculated the average TemDT for various SOS dates in snow-covered ENF and DBF sites (Fig. 6k, Table 2). For ENF sites, average TemDT of the SOS dates from GPP-EC, GPP-VPM and LSWI were close to each other (5 ± 6 °C), but higher than that from NDVI and lower than that from EVI (Table 2). For DBF sites, average TemDT of SOS for GPP-EC, GPP-VPM, EVI, and LSWI were similar (12 °C), and higher than from NDVI (9.60 °C ± 4.11) (Table 2).

For the snow-covered ENF and DBF gridcells (0.5°) in northern mid- to high-latitudes, responses of GPP-VPM, SIF, NDVI, EVI, and LSWI to TemDT were analyzed (Fig. 7). ENF GPP-VPM and SIF had similar...
dynamics in response to TemDT (Fig. 7a, b), starting to increase at \( \sim 5^\circ C \).

ENF NDVI, EVI, and LSWI also increased rapidly at 5 °C (Fig. 7c, d, e).

DBF GPPVPM and SIF had similar dynamics in response to TemDT (Fig. 7f, g), which started to increase at \( \sim 5^\circ C \). DBF NDVI, EVI and LSWI also increased rapidly at 5 °C (Fig. 7h, i, j). We calculated the average TemDT for various SOS dates in snow-covered ENF and DBF gridcells (Fig. 7k, Table 3). For the ENF gridcells, average TemDT of the SOS dates from GPPVPM, SIF and NDVI were close to each other (\( \sim 3 \) to 4 °C), but lower than those from EVI and LSWI (Table 3). For the DBF gridcells, average TemDT of SOS for GPPVPM and SIF were similar (\( \sim 6^\circ C \)), but higher than NDVI (\( \sim 3^\circ C \)) and lower than EVI and LSWI (Table 3).

4. Discussion

4.1. The limitations of greenness-related vegetation indices for identifying spring phenology (SOS) of snow-covered forests

Greenness-related vegetation indices (NDVI and EVI) have been used to monitor the spring phenology of ENF (Hmimina et al., 2013; Peng et al., 2017a; Shen et al., 2014a). A previous study found that MODIS NDVI is not an accurate indicator of phenology in evergreen forest in France because MODIS NDVI had smaller values than in-situ NDVI (Hmimina et al., 2013). Two additional studies reported that the lag between ENF SOSNDVI and SOSSIF was about 40–60 days for the United States, and thus EVI can also not be used for accurate SOS estimation (Peng et al., 2017a; Shen et al., 2014a). Consistent with previous studies, our study showed that SOSNDVI and SOSEVI were about 3–4 weeks different from SOSSIF at the snow-covered ENF sites. The inconsistency of canopy greenness and canopy photosynthesis for snow-covered ENF is due to the fact that the start of photosynthesis in ENF relies on temperature and water availability rather than the emergence and growth new leaves (canopy structural development) (Ensinger et al., 2004; Melaas et al., 2013; Monson et al., 2005).

Many studies suggested that both NDVI (Wu et al., 2017) and EVI (Shen et al., 2014a) can provide an accurate estimation of spring phenology in DBF. For example, Peng et al. (2017a) showed that DBF SOS detected from NDVI and EVI were different from SOSGPP by about 12 days in the United States. However, our study found that NDVI cannot detect SOS in DBF under snow-covered conditions accurately. SOSNDVI in our study had the lowest R square and highest RMSE among these three vegetation indices when compared with SOSSIF in snow-covered DBF. SOSSWFI was about 3–4 weeks earlier than SOSSIF. Earlier experiments in the snow-covered region of the Northern Hemisphere have shown that both snowmelt and vegetation growth can increase NDVI values (Moore et al., 1997). Consequently, spring phenology derived from NDVI is always biased due to the snowmelt process, and earlier NDVI increases could be due either to earlier vegetation growth or earlier snowmelt (Delbart et al., 2005; Huete et al., 2002). Our results indicated that removing snow effects from NDVI signals is of great importance for accurate phenology characterization in snow covered forest regions, even for DBF. So far, some studies have tried to develop thresholds for removing the effects of snow from NDVI timeseries data. For example, Suzuki et al. (2003) assumed that snow will not exist when NOAA NDVI exceeds 0.2, while Gamon et al. (2013) suggested that the land surface was snow-free when MODIS NDVI reached 0.3. However, we found that MODIS NDVI was above 0.2 for the whole year at the snow-covered DBF sites, and snow was not completely melted at NDVI value of 0.3 as LSWI was decreasing dramatically (Fig. 1b). Our research indicated that new approaches for accurate estimates of spring phenology of snow-covered forests are required.

4.2. The potential of water-related vegetation index for identifying spring phenology (SOS) of snow-covered forests

From both the site-level and regional analysis, we found that SOSLSWI was closer to SOSSIF and SOSSIF for both snow-covered DBF and ENF than SOSSWFI and SOSEP. Meantime, SOSLSWI had lower RMSE values than SOSSIP and SOSEP. Our results suggested that SOS from LSWI was mostly consistent with functional SOS dates from GPP and SIF at snow-covered forest, and LSWI could be a good indicator for snow-covered ENF and DBF spring phenology detection when referenced by SOSSIP and SOSEP. Since LSWI values increase with vegetation growth and decrease with snowmelt, it is able to decouple snowmelt signal...
from vegetation growth (Ceccato et al., 2002; Xiao et al., 2009). Some new indices also have been developed using water-related spectral bands and have shown promise for improving the detection of phenology in snow-covered regions (Delbart et al., 2005; Wang et al., 2017). For example, the Normalized Difference Water Index (NDWI), calculated with the near-infrared band (0.78–0.89 μm) and short-wave infrared band (1.58–1.75 μm) from SPOT-VGT, was used for spring phenology detection (Delbart et al., 2005, 2006). The results showed that NDWI can provide better estimations of the start of green-up than NDVI in Eurasia when compared with in-situ phenological records. SPOT-VGT NDWI has also been used in northeastern China for identifying the start and end of the growing season of evergreen forest (Xiao et al., 2002). Normalized Difference Infrared Index (NDII) was calculated from the red band and short-wave infrared band and reflected canopy water content effectively (Hardisky et al., 1983). MODIS NDII was found to be more efficient in estimating the date of onset of greening than methods based on NDVI throughout the central and northern Rocky Mountains of the United States and Canada (Dunn and de Beurs, 2011). Wang et al. (2017) developed a new index named Normalized Difference Phenology Index (NDPI) using three bands of MODIS: near-infrared band, red band, and short-wave infrared band. Analysis at 11 eddy-covariance tower sites in snow-covered deciduous ecosystems showed that NDPI was more reliable than NDVI for spring phenology detection when compared with spring phenology metrics derived from daily GPP.

However, the ability to monitor phenology using water-related vegetation indices remains limited. The specific threshold method was the most popular method for phenology detection based on water-related vegetation indices. For instance, Kang et al. (2016) defined SOS in Tibetan Plateau as the date when LSWI reached -0.1. The threshold selection is relatively subjective, with different thresholds being set by different researchers and study areas. For the sites in our study, the linear relationship between SOSLSWI and SOSGPP-EC varied significantly among the results from different threshold values (Fig. 8). The results suggest that further study is needed to develop a constant algorithm for characterizing phenology of snow-covered ENF. Also note that the average SOSSIF dates were close to SOSGPP-VPM, but relatively far away from SOSNDVI, SOSGPP and SOSLSWI (Table 3), which clearly suggested that at the coarse spatial resolution (0.5° in this study) vegetation index data are not appropriate for identifying spring photosynthesis phenology of snow-covered ENF and DBF, because of mixed land cover types within the grid cells. It is more reasonable to characterize spring phenology with time series image data at moderate to high spatial resolutions (e.g., MODIS 500-m; see Table 2).

Fig. 5. Comparison of start of growing season (SOS) extracted from NDVI, EVI, LSWI, GPP$_{VPM}$, and GOME-2 SIF for snow-covered ENF and DBF distributed in northern mid- to high-latitudes during 2007-2016. (a) Comparison of ENF SOS VIs to SOS GPP$_{VPM}$; (b) Comparison of DBF SOS VIs to SOS GPP$_{VPM}$; (c) Comparison of ENF SOS VIs to SOS SIF; (d) Comparison of DBF SOS VIs to SOS SIF; (e) Comparison between SOS from GPP$_{VPM}$ and GOME2-SIF of ENF and DBF.
4.3. The role of air temperature for identifying spring phenology (SOS) of snow-covered forests

Air temperature analysis at the time when SOS occurs provides strong evidence for snow-cover conditions in different forest ecosystems. As indicated by GPP_{EC}, photosynthesis at snow-covered ENF sites started at about 5 °C daytime temperature when snow has not yet completely melted (Table 2). Our results match the previous conclusions that the photosynthetic spring recovery in ENF (north of 50 °N) occurs as soon as daily mean temperature temperatures exceed 2–3 °C (Walther et al., 2016). In addition, air temperature is an important factor that directly affects photosynthesis and has been widely used in land surface phenology models (Richardson et al., 2006; Wu et al., 2012). The minimum daily mean temperature for the growth of trees in cold environments was determined to be about 5 °C in the commonly used accumulate temperature phenology model (Prentice et al., 1992). So, our results match the previous assumptions and conclusions in land surface phenology models that are based on temperature. Since evergreen trees do not need to sprout new leaves prior to each growing season, photosynthesis rapidly increases as soon as the required minimum air temperature shows (5 °C), and thus we detected SOS at this time point for ENF. However, we should note that daytime temperature was used in our study, which was different from the above-mentioned phenology models with daily mean temperature. As our results detected ENF SOS_{GPP} (Table 2) and SOS_{SIF} (Table 3) at about 5 °C daytime temperature, the daytime temperature is an important factor for plant growth. Piao et al. (2015) also suggested that leaf onset in the northern hemisphere was triggered more by daytime temperature than nighttime temperature and daily mean temperature based on both satellite and in-situ observation datasets. Using daytime temperature instead of daily mean temperature in future land surface phenology models can make the models more reliable.

Even though the minimum air temperature for tree growth is 5 °C, we detected DBF SOS at about 12 °C when snow has melted completely (He et al., 2014), because unlike ENF, DBF photosynthesis in the spring relies on new leaves. Basically, the SOS we detected in DBF was the time when new leaves expanded rapidly. When air temperature reaches the minimum required for growth (5 °C), buds start to develop. After that, it takes some days to accumulate temperature so that the buds can expand into leaves in DBF. For example, in-situ observation in North America found that the progression from bud swelling noticeably to 75% leaves expanded takes about 24 calendar days for tree species (Richardson et al., 2006). Obviously, temperature requirements for SOS in ENF and DBF are completely different. However, temperature conditions were set as the same for SOS measurement in both ENF and DBF in previous studies. For example, SOS was always defined as the time when degree-days above 5 °C had accumulated to at least 40 for all kinds of land cover types in previous studies (Liu et al., 2016; Wu et al.,

Table 2

<table>
<thead>
<tr>
<th>ENF</th>
<th>ENF GPP_{EC}</th>
<th>ENF GPP_{VPM}</th>
<th>ENF NDVI</th>
<th>ENF EVI</th>
<th>ENF LSWI</th>
</tr>
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<tbody>
<tr>
<td>SOS (DOY)</td>
<td>117 ± 20</td>
<td>121 ± 18</td>
<td>112 ± 32</td>
<td>136 ± 18</td>
<td>129 ± 22</td>
</tr>
<tr>
<td>TemDT at SOS (°C)</td>
<td>4.9 ± 3.71</td>
<td>6.01 ± 4.98</td>
<td>3.02 ± 4.69</td>
<td>8.65 ± 3.65</td>
<td>5.82 ± 2.87</td>
</tr>
<tr>
<td>DBF GPP_{EC}</td>
<td>DBF GPP_{VPM}</td>
<td>DBF NDVI</td>
<td>DBF EVI</td>
<td>DBF LSWI</td>
<td></td>
</tr>
<tr>
<td>SOS (DOY)</td>
<td>134 ± 12</td>
<td>130 ± 12</td>
<td>117 ± 13</td>
<td>128 ± 11</td>
<td>128 ± 12</td>
</tr>
<tr>
<td>TemDT at SOS (°C)</td>
<td>12.76 ± 2.96</td>
<td>12.07 ± 2.66</td>
<td>9.60 ± 4.11</td>
<td>11.91 ± 2.36</td>
<td>11.86 ± 3.04</td>
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</table>

Fig. 6. Relationships between daytime temperature (TemDT) and GPP_{EC}, GPP_{VPM}, NDVI, EVI, and LSWI at ENF and DBF snow-covered sites. All the data during January - August (8-day interval) were used. (a) - (e) are relationships to daytime mean temperature at ENF; (f)-(j) are relationships to daytime mean temperature for DBF. The smooth curves represent the dynamic trends of samples, which were derived from the cyclic penalized cubic regression spline smooth model in R Studio. (k) average TemDT of those SOS dates.
Based on the same temperature model, the results showed that growing season length based on accumulated temperature model was less consistent with carbon uptake length in ENF and mixed forest than DBF (Wu et al., 2012). Thus, future phenology models with temperature which developed respectively for various land cover types are necessary.

4.4. The contribution of comparing spring phenology from NDVI, EVI, and LSWI with SOS SIF

Our study provided a comprehensive comparison among SOS dates from NDVI, EVI, GPPVPM, and SIF for the snow-covered ENF and DBF region in mid- to high-latitude Northern Hemisphere. SIF has recently been used for exploring land surface ecosystem seasonal dynamics in several studies (Jeong et al., 2017; Walther et al., 2016). Jeong et al. (2017) used GOME-2 SIF data to examine physiological activity over northern high-latitude forests (40°–55° N), and their results indicated a large-scale seasonal decoupling of structural growing season length from NDVI and physiological growing season length from SIF (by about 46 days). Walther et al. (2016) also found that MODIS GPP and SIF showed similar seasonality in both ENF and DBF ecosystems in the northern hemisphere, and photosynthesis SOS indicated by SIF is about 1 month earlier than canopy greenness SOS indicated by EVI in ENF. Consistent with previous studies, we also found SOS_{GPPVPM} and SOS_{SIF} air temperature to be similar. Quantitatively, our study concluded that difference between the dates of SOS_{GPPVPM} and SOS_{SIF} is about 5 ± 3 days for snow-covered ENF and 2 ± 3 days for snow-covered DBF in the mid- to high-latitude NH, which can be a good reference for future phenology studies. Our study found that SOS from NDVI and EVI was not significantly correlated with SOS from GOME-2 SIF for snow-covered ENF and DBF sites (Fig. 6c,d). SOS from the water-related vegetation index (LSWI) were found to be most consistent with SOS_{GPPVPM} and SOS_{SIF} for snow-covered ENF and DBF for the first time. In addition, SOS_{NDVI} dates were earlier than the structural phenology of SOS_{EVI} and SOS_{LSWI}, as well as earlier than the functional phenology of SOS_{GPPVPM} and SOS_{SIF}. Our conclusions for regional analysis were consistent with the conclusions for sites analysis.

However, we should note that when exploring the consistency between SOS from satellite-based GPP and SIF is that GPP and SIF represent the fate of absorbed PAR at different time scales. We used instantaneous GOME-2 SIF measurements while GPP_{VPM} simulates daily average rate of photosynthesis every 8 days. Even though daily SIF products have been developed using instantaneous SIF observations and have a better consistency with daily GPP (Joiner et al., 2013; Zhang et al., 2018), the robustness of the results will be affected by the quality of the model used to calculate daily SIF and the interpolation of 8-day GPP to daily values. In addition, the SIF data is especially noisy and there are less frequent measurements in some regions (Joiner et al., 2012). It is critical that future studies utilize SIF and reflectance data with high spatial and temporal resolution so that we can reach a greater understanding about the phenology worldwide.

<table>
<thead>
<tr>
<th>ENF (DOY)</th>
<th>ENF GPPVPM</th>
<th>ENF SIF</th>
<th>ENF NDVI</th>
<th>ENF EVI</th>
<th>ENF LSWI</th>
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<tbody>
<tr>
<td>120 ± 5</td>
<td>125 ± 6</td>
<td>111 ± 13</td>
<td>159 ± 8</td>
<td>140 ± 4</td>
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</tr>
<tr>
<td>TemDT at SOS (°C)</td>
<td>3.37 ± 0.35</td>
<td>3.93 ± 0.58</td>
<td>3.13 ± 0.71</td>
<td>9.39 ± 1.39</td>
<td>6.27 ± 0.41</td>
</tr>
<tr>
<td>DBF (DOY)</td>
<td>DBF GPPVPM</td>
<td>DBF SIF</td>
<td>DBF NDVI</td>
<td>DBF EVI</td>
<td>DBF LSWI</td>
</tr>
<tr>
<td>116 ± 3</td>
<td>118 ± 3.35</td>
<td>87 ± 4</td>
<td>131 ± 6</td>
<td>136 ± 4</td>
<td></td>
</tr>
<tr>
<td>TemDT at SOS (°C)</td>
<td>5.54 ± 0.54</td>
<td>5.78 ± 5.24</td>
<td>2.75 ± 0.44</td>
<td>8.14 ± 1.05</td>
<td>9.11 ± 0.6</td>
</tr>
</tbody>
</table>

Fig. 7. Response of GPP_{VPM}, GOME-2 SIF, NDVI, EVI, and LSWI to average daytime air temperature gradient (TemDT) over the snow-covered ENF and DBF gridcells (0.5°) in northern mid- to high latitudes (Fig. 1). (a) - (e) ENF gridcells; (f)-(j) DBF gridcells, (k) average TemDT of those SOS dates.
5. Conclusions

Snow cover and snowmelt affect land surface reflectance leading to bias SOS estimates in snow-covered forests. We comprehensively compared the consistency of SOS dates derived from MODIS vegetation indices (NDVI, EVI, LSWI), GPPEC, GPPVPM, and GOME-2 SIF for snow-covered DBF and ENF ecosystems. In addition, we analyzed daytime air temperature so that we can not only better understand when snowmelt and SOS occur in various datasets but also evaluate the reliability of SOS results from various datasets. Based on our analysis, comparison of estimated SOS dates, and the relationship between SOS and air temperature, we found that VIs (NDVI, EVI, and LSWI) performed differently in snow-covered ENF and DBF ecosystems. Furthermore, GPPVPM was significantly correlated with SIF, and thus canopy functional SOS detected from the two datasets were similar. Our results highlight that the remote-sensing of phenology at higher latitudes needs further development to account for the impacts of snow cover on greenness-related vegetation indices (NDVI and EVI). We suggest SOS estimates should make full use of water-related vegetation indices and consider daytime air temperature so that we may better understand the relationship between the changes in greenness and photosynthesis.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2019.06.002.

References


Fig. 8. Relationship between SOS extracted with different threshold values of LSWI (ENF SOS,LSWI threshold) and SOS extracted from eddy covariance GPP (ENF SOS,GPPEC) at snow-covered ENF eddy covariance sites. The threshold values were selected from 0.4 to 0.15, with 0.05 decreasing interval (0.4, 0.35, 0.3, 0.25, 0.2, 0.15).
Environ. 84 (3), 471–475.
chlorophyll fluorescence and gross primary production for remote sensing applica-
Zhang, Y., et al., 2016b. Consistency between sun-induced chlorophyll fluorescence and
gross primary production of vegetation in North America. Remote Sens. Environ. 183,
154–169.
Zhang, Y., et al., 2017. A global moderate resolution dataset of gross primary production
Zhang, Y., et al., 2018. On the relationship between sub-daily instantaneous and daily
total gross primary production: implications for interpreting satellite-based SIF re-