Remote Sensing of Environment 176 (2016) 152–162

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Improved modeling of land surface phenology using MODIS land surface reflectance and temperature at evergreen needleleaf forests of central North America

Yuxia Liu [a,b], Chaoyang Wu [a,*], Dailiang Peng [c,*], Shiguang Xu [a], Alemu Gonsamo [d], Rachhpal S. Jassal [e], M. Altaf Arain [f], Linlin Lu [c], Bin Fang [g], Jing M. Chen [d]

[a] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[b] University of the Chinese Academy of Sciences, Beijing 100049, China
[c] Key Laboratory of Digital Earth, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[d] Department of Geography and Program in Planning, University of Toronto, 100 St. George St., Toronto, ON M5S 3G3, Canada
[e] Faculty of Land and Food Systems, University of British Columbia, Vancouver, BC, Canada
[f] School of Geography and Earth Sciences and McMaster Centre for Climate Change, McMaster University, Hamilton, Ontario, Canada
[g] Department of Earth & Environmental Engineering, Columbia University, 500 W 120th St., New York, NY 10027, USA

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form 16 January 2016
Accepted 22 January 2016
Available online xxxx

Keywords:
Remote sensing
Phenology
MODIS
Needleleaf forests
NDVI
EVI

ABSTRACT

Plant phenology plays a significant role in regulating carbon sequestration period of terrestrial ecosystems. Remote sensing of land surface phenology (LSP), i.e., the start and the end of the growing season (SOS and EOS, respectively) in evergreen needleleaf forests is particularly challenging due to their limited seasonal variability in canopy greenness. Using 107 site-years of CO_2 flux data at 14 evergreen needleleaf forest sites in North America, we developed a new model to estimate SOS and EOS based entirely on the Moderate Resolution Imaging Spectroradiometer (MODIS) data. We found that the commonly used vegetation indices (VI), including the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI), were not able to detect SOS and EOS in these forests. The MODIS land surface temperature (LST) showed better performance in the estimation of SOS than did a single VI. Interestingly, the variability of LST (i.e., the coefficient of variation, CV_LST) was more useful than LST itself in detecting changes in forest LSP. Therefore, a new model using the product of VI and CV_LST was developed and it significantly improved the representation of LSP with mean errors of 11.7 and 5.6 days for SOS and EOS, respectively. Further validation at five sites in the Long Term Ecological Research network (LTER) using camera data also indicated the applicability of the new approach. These results suggest that temperature variability plays a previously overlooked role in phenological modeling, and a combination of canopy greenness and temperature could be a useful way to enhance the estimation of evergreen needleleaf forest phenology of future ecosystem models.

1. Introduction

Phenology is one of the most important controls of interannual variability of gross/net ecosystem productivity (GEP/NEP) (Fu, Campioli, Vitasse, et al., 2014; Gonsamo, Chen, Wu, & Dragoni, 2012; Jin et al., 2013; Richardson et al., 2013; Sakamoto, Gitelson, & Arkebauer, 2013; Wu, Chen, Black, et al., 2013; Zhang, Cheng, Lyapustin, Wang, Gao, et al., 2014; Zhang, Cheng, Lyapustin, Wang, Xiao, et al., 2014). Therefore, increasing efforts have been made to model phenological variations using remote sensing data, which is considered as the most convenient and efficient way in understanding vegetation dynamics at regional to global scales (Hmimina et al., 2013; Melaas, Richardson, et al., 2013; White et al., 2009; Wu, Hou, Peng, Gonsamo, & Xu, 2016).

Growing season phenology from remote sensing is determined by detecting the seasonal dynamics of vegetation greenness using spectral signals from sensors onboard satellite platforms (Melaas, Friedl, & Zhu, 2013; Sonnentag et al., 2012; Wu, Gonsamo, Gough, Chen, & Xu, 2014). A widely used remote sensing-based phenological data source is the Moderate Resolution Imaging Spectroradiometer (MODIS), and several vegetation indices (VIs) were reported to have potential in indicating phenological transitions (Friedl et al., 2010; Ganguly, Friedl, Tan, Zhang, & Verma, 2010; Gonsamo, Chen, Price, Kurz, & Wu, 2012; Hmimina et al., 2013; Jin & Eklundh, 2014; Sakamoto et al., 2010; Xiao, Hagen, Zhang, Keller, & Moore, 2006; Zhang et al., 2003). For example, both the normalized difference vegetation index (NDVI, Tucker & Sellers, 1986) and the enhanced vegetation index (EVI, Huete et al.,

* Corresponding authors.
E-mail addresses: hefery@163.com (C. Wu), pengdl@radi.ac.cn (D. Peng).

http://dx.doi.org/10.1016/j.rse.2016.01.021
0034-4257/

2002) are extensively used in reconstructing phenological transitions for various plant functional types, including forests, grasslands, and croplands (Hmimina et al., 2013; Jeganathan, Dash, & Atkinson, 2014; Wu et al., 2014; Zhang & Goldberg, 2011; Zhang et al., 2003). One of the most widely used algorithm to model phenological changes is to detect the local maxima/minima in the rate of change of curvature (i.e., local inflection points) in a fitted curve from time-series of remote sensing signals (Friedl et al., 2010; Ganguly et al., 2010; Zhang et al., 2003; Zhang, Friedl, & Schaaf, 2006). More recently, signals from seasonal (e.g., spring and autumn) mean VIs have been shown to be useful in detecting changes in land surface phenology (Wu et al., 2014).

Forests are the most important ecosystems in terrestrial carbon budget (Pan et al., 2011), and their phenology consequently has played a significant role in explaining interannual variability of NEP (Richardson et al., 2010, 2013; Wu, Chen, Black, et al., 2013). However, there are several challenges in modeling forest phenology from remote sensing data. The most confounding issue related to phenological modeling to date is the limited potential of VIs to estimate LSP in needleleaf forests because of small seasonal VI variation (Guyon et al., 2011; Hufkens et al., 2012; Melaas, Friedl, et al., 2013; Shen, Tang, Desai, et al., 2014). For example, Hmimina et al. (2013) showed that MODIS is unable to accurately infer phenological patterns for needleleaf forests. In comparison, with evident variations in canopy greenness, changes in phenology of deciduous forests is much easier to detect (Garrity, Maurer, Mueller, Vogel, & Curtis, 2011; Gonsamo, Chen, Price, et al. 2012; Luo, Chen, Wang, Xu, & Tian, 2014; Melaas, Richardson, et al., 2013; Melaas, Friedl, et al., 2013; Ryu, Lee, Jeon, Song, & Kimm, 2014; Wu et al., 2014). This problem becomes more severe for detecting the end of growing season (EOS) in autumn since this period sustains a much longer and slower change of canopy greenness compared to that of the start of growing season (SOS) in spring (Richardson et al., 2013; White, Pontius, & Schaberg, 2014; Wu et al., 2014).

Remote sensing of phenology using time-series of VIs is based on the intra-annual changes of canopy greenness. Essentially, this is an external expression of plant dynamics to plant growth determinants (e.g., temperature, soil water content) which strongly regulate the growth dynamics of boreal and temperate forests. For example, temperature has been long recognized as a main driver of plant growth, and spring air temperature was found to trigger the recovery of photosynthesis in most boreal and temperate ecosystems (Barr, Black, & McCaughey, 2009; Chen et al., 2003; Suni, Berninger, Vesala, et al., 2003). Apart from temperature itself, it is also possible that the temperature variability may have an unrecognized role on phenology and its modeling. For example, Wheeler, Craufurd, Ellis, Porter, and Prasad (2000) showed a strong evidence for the importance of variability in temperature, independent of any substantial changes in mean seasonal temperature, for the yield of annual crops. In particular, seed yields are particularly sensitive to brief episodes of hot temperatures if these coincide with critical stages of crop development. Furthermore, Reyer et al. (2013) indicates that distinguishing between impacts of changing mean climatic conditions and changing climatic variability on terrestrial ecosystems is generally underrated in current studies. They found that phenology is largely affected by changing mean climate but also that impacts of climatic variability are much less studied. The problem is that how temperature, in particularly remote sensing based observations (e.g., MODIS Land Surface Temperature product (LST)), can be incorporated to better depict evergreen needleleaf forest phenology? For example, Gonsamo, Chen, Wu, et al. (2012) has shown that the combination of remotely sensed VI and LST is a good indicator of the start and end of net positive carbon uptake period of broadleaf forests. Therefore, using continuous CO_2 flux measurements at 14 evergreen needleleaf forests and five additional PhenoCam sites in North America, this study explores the potential of a new model that incorporates MODIS VIs and LST products to estimate the boreal and temperate evergreen needleleaf forest phenology. The questions we address include: (i) can MODIS NDVI and EVI be used to model SOS and EOS of needleleaf forests?; (ii) Is temperature variability more important than average temperature itself in detecting plant greenness dynamics?; (iii) if so, does the combination of MODIS VI and LST improve the accuracy of modeled SOS and EOS?

2. Methods

2.1. Flux sites and CO_2 flux data

To support the phenological analysis of this study, we used CO_2 flux data from 14 evergreen needleleaf forest (ENF) flux tower sites in North America from the AmeriFlux and Canadian Carbon Program (CCP) formerly known as Fluxnet-Canada networks with at least 5 years of complete data with less than 20% gap-filled in each year (Fig. 1). Detailed descriptions of these sites are given in Table 1.

Half-hourly CO_2 fluxes were continuously measured at each site using the eddy-covariance technique (Baldocchi et al., 2001). Regional flux networks adopt several standard procedures to partition the directly measured net ecosystem exchange (NEE) into gross primary productivity (GPP) and total ecosystem respiration (R_e). Because these study sites belong to two different regional flux networks within North America, gap-filling and NEE partitioning approach is different. For CCP sites, the NEE portioning was conducted using the network's standard approaches described in Barr et al. (2013). For the AmeriFlux sites, the Artificial Neural Network (ANN) method (Papale & Valentini, 2003) and/or the Marginal Distribution Sampling (MDS) method (Reichstein et al., 2005) were adopted to conduct level-4 products that contain gap-filled and u^* filtered records of CO_2 fluxes at varying time intervals. Though various flux networks applied different decomposition techniques to flux data, they generally have a negligible impact on modeled GPP (Desai et al., 2008; Wu, Chen, Black, et al., 2013; Wu, Chen, Desai, Lafleur, & Verma, 2013).

2.2. Canopy phenology from PhenoCam network

Digital repeat photography makes consistent visual assessment of phenology possible over broad geographic ranges and has played an important role in phenological analysis recently (Sonnentag et al., 2012; Klosterman et al., 2014). The PhenoCam network is a continental-scale phenological observatory, spanning a wide range of biogeoclimatic zones and vegetation types, across the northeastern US and adjacent Canada (Imagery and data products are available at the PhenoCam website http://phenocam.sr.unh.edu/webcam/). Over the thirteen geographically distinct research sites in PhenoCam network, we identified five sites dominated by the evergreen forests species that are suitable for our analysis (Table 2).

2.3. MODIS data

In this study, we used two MODIS land surface products acquired from the Oak Ridge National Laboratory Distributed Archive Center (DAAC) website (http://daac.ornl.gov/cgi-bin/MODIS/GR_col5_1/mod_viz.html). The first product was the 8-day Terra MODIS Surface Reflectance product (MOD09A1, 500 m, quality control was done for cloud, view angle, and aerosol), which was used to compute NDVI and EVI in this study. For each site, both NDVI and EVI were extracted from 3 × 3 MODIS pixels centered on the flux tower similar to the approach used by Sims et al. (2008). The 3 × 3 MODIS pixels method was also confirmed to represent each site with respect to both footprints (flux-tower fetch) (~1 km) and land cover (Chen et al., 2011).

The second product is the MODIS 8-day Land Surface Temperature (LST) and Emissivity product (MOD11A2, 1 km) derived by applying the generalized split-window algorithm. In the split-window algorithm, emissivity in spectral bands 31 and 32 is estimated from land cover types, and atmospheric column water vapor and lower boundary air