Ecological Indicators 70 (2016) 1–9

Contents lists available at ScienceDirect

Ecological Indicators

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

Reflecting conifer phenology using mobile terrestrial LiDAR: A case study of *Pinus sylvestris* growing under the Mediterranean climate in Perth, Australia

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ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form 31 May 2016
Accepted 3 June 2016

Keywords:
Phenological indicator
Conifer
Mobile terrestrial laser scanning (MLS)
Mediterranean climate
Seasonal-scale phenological variation

ABSTRACT

Accurately monitoring of tree phenological dynamics is crucial for understanding how forest ecosystems respond to various climate changes, and a variety of methods recently have been established for accomplishing this task. However, efficient techniques for featuring conifer phenology are still lacking. In fact, characterizing conifer phenological variations have long been an issue, because conifers tend to show hard-to-discern changes in terms of no matter color or crown morphology for different seasons. To address this conventional "conifer issue", this study attempted the state-of-the-art remote sensing technology of mobile terrestrial light detection and ranging (LiDAR) (also termed as mobile terrestrial laser scanning, MLS) to reflect the seasonal-scale phenological variations of conifers, specifically in a case of Scots pines (*Pinus sylvestris*) growing under the Mediterranean climate in Perth, Australia. The MLS-collected data shows that for the conifers growing under different temperature and precipitation conditions, lasers, in a statistical sense, behave with different penetrations into their crowns. In light of this phenomenon, a new seasonal-scale conifer phenological indicator (CsPI) was proposed, i.e. the ratio between the average of the horizontal penetration distances for the entire laser points backscattered from a crown and its diameter calculated along with the horizontal direction of laser incidence. The performance of the newly-proposed CsPI was assessed by the means of meta-analysis, i.e. comparing the CsPI-indicated conifer response to seasonal climate changes in Perth with the derived rule of stem radial growth rates at different seasons in Mesic, Spain, both in the Mediterranean climate scenarios. The correlations with positive results showed that the proposed schematic plan of applying MLS and the developed phenological indicator both are validated, and this study has opened a new way for reflecting the seasonal-scale phenological variations of conifers.

1. Introduction

As a key branch of ecology, phenology concerns periodically recurring biological events and how they are influenced by seasonal or annual variations of environment conditions such as climate and habitat. Phenological observation can supply an important kind of fundamental data for numerous studies in different fields such as ecology, botany, forestry, agronomy and meteorology, since phenological information is so essential for understanding how vegetation responds to the increasingly-intensified climate change (Richardson et al., 2013). Specifically, phenological data proved to facilitate reconstructing historical climate and forecasting future climate (Keatley et al., 2002), revealing various ecological response to recent climate change (Walther et al., 2002), investigating forest carbon balance (Gond et al., 1999) and seasonal transitions of forest carbon exchange (Garrity et al., 2011), quantifying the uncertainties in terrestrial carbon budgets (Jeong et al., 2012), predicting crop productions (Bolton and Friedl, 2013) and classifying forest general habitats (Clerici et al., 2014). Overall, in the face of the 21st-century problem of global change, people have realized the importance of tracking the rhythm of seasons via phenology observation (Morisette et al., 2009). Hence, as an important indicator of environmental variation and climate change impacts, phenology is increasingly highlighted, and efficient techniques for phenology monitoring are widely demanded.

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http://dx.doi.org/10.1016/j.ecolind.2016.06.003
1470-160X/

1.1. Literature review

The most remarkable solutions for phenology monitoring are a set of regional- and even continental-scale phenology networks, and the three representative networks are the European Phenology Network (EPN) (van Vliet et al., 2003), the USA National Phenology Network (USA-NPN) (Schwartz et al., 2012) and the Chinese Phenological Observation Network (CPON) (Dai et al., 2014). The stations comprising these networks have been operated for long and based on their phenological records a lot of knowledge about terrestrial processes and ecosystem-climate interactions can be derived (e.g. Fu et al., 2015; Jeong and Medvigy, 2014; Dai et al., 2014). However, the operating of the networks is mostly based on human observations at the isolated stations, which are commonly distributed in a spatially-scattered way. The shortages of high labor-cost and sparse spatial-distribution restrict the networks from playing their roles in either full-coverage or fine-scale phenological studies.

As a key supplement to the conventional single-site human observation approaches, the remote sensing (RS) technology has been introduced to implement the full-coverage goal of phenology monitoring (Barbosa et al., 2015). The most-notable progress regarding RS-based phenological studies was based on the rich earth observation records by the successive satellite series such as Landsat 1–7 and their derivations such as the Moderate Resolution Imaging Spectroradiometer (MODIS) products (Ganguly et al., 2010), which facilitate implementing regional and even global phenological studies (Cong et al., 2012; Zhang et al., 2003; Stöckli and Vidale, 2004; Soudani et al., 2008; Ganguly et al., 2010; Papeş et al., 2013; Meier et al., 2015). In addition, proposing phenological indicators such as leaf area index (LAI) (Che et al., 2014) and plant species distribution (Bishop et al., 2013) appropriate for different forest compositions and developing more powerful phenology-characterizing methods such as phenological estimators (Moussus et al., 2010) have also been promoted for advancing phenology-relevant studies.

In fact, satellite-based phenology still highlights field monitoring, which is needed to supply the ground truth data for analyzing phenological mechanisms (Stockli et al., 2007) or training phenological models. Correspondingly, the concept of "near-surface" or "terrestrial" monitoring of phenology was pushed forward (Richardson et al., 2007), and a variety of RS solutions aiming at this goal have been developed. For example, the common digital cameras or their modified forms have been attempted to repeatedly take images of the landscapes of interest at high frequencies over months or years for phenological researches (Richardson et al., 2007; Graham et al., 2010; Granados et al., 2013; Nijland et al., 2014; Petach et al., 2014). Digital repeat photography has the potential to become an important long-term data source for phenological research, given its advantages in terms of logistics, continuity, consistency and objectivity over traditional assessments of vegetation status by human observers (Sonnentag et al., 2012). Some other kinds of techniques in different measurement principles, such as continuous flux measurements (Wu and Chen, 2013) and spectral reflectance sensors (Ryu et al., 2014), have been validated for phenology monitoring. The plan of integrating satellite and near-surface RS measurements has also been validated and applied for deciduous broadleaf forest phenology (Hufkens et al., 2012).

The previous mainstream studies as listed above were briefly based on the characteristics of vegetation optical reflectance. Actually, in addition to this kind of traits such as tree organ colors, tree structural variations can serve as another essential category of indicators of tree phenological dynamics. For the task of capturing tree structures, airborne light detection and ranging (LiDAR) (also termed as airborne laser scanning, ALS) has proved to be an efficient RS technology (Lovell et al., 2003), and it can somehow overcome the shortages of passive optical cameras (e.g. brightness instability caused by illumination changes). The introduction of ALS into phenology monitoring has emerged (Rinaldi et al., 2013), but this technology is often restricted to its inefficiency in the derivations of tree structural variables at fine scales. For fine-scale tree structure representation, static terrestrial LiDAR (also referred to as static terrestrial laser scanning, TLS) mostly capable of characterizing structure details, such as vegetation density profiles (Ashcroft et al., 2014), was attempted to quantify and monitor ecosystem structural dynamics (Eitel et al., 2013). Portillo-Quintero et al. (2014) utilized a TLS system to in-situ measure the dynamics of phenology. Calders et al. (2015) operated spring phenology monitoring by manipulating high temporal resolution TLS measurements.

1.2. Conifer issue

However, the solutions proposed in the previous studies, based on no matter images or 3D point clouds, were primarily aimed at deciduous trees (Richardson et al., 2007; Fu et al., 2012; Zhao et al., 2012; Granados et al., 2013; Nijland et al., 2014; Calders et al., 2015). In other words, although a large number of techniques as mentioned above have already been developed for tree phenology monitoring, the traditional "conifer issue" has not been fully solved. That is, for evergreen conifers typically with needle-shaped leaves, extracting their features in terms of no matter color or detailed structure for the purpose of inspection of their seasonal-scale phenological variations turned out to be a difficult task. The reason is that sunlight difference or rain-flushing effect may disturb the recognition of the tiny changes on color and structure.

In fact, coniferous forests play important roles in adapting climate change (Kramer et al., 2000), and accurately monitoring of conifer phenology is of considerable implications. Tang and Bechage (2010) found that the commonly-projected global warming in the twenty-first century will cause more extensive loss of coniferous forests than hardwood deciduous forests in New England. Swidrak et al. (2014) compared the timing of key phenological dates of xylem and phloem formations and determined their adaptability to dry environments. Du et al. (2014) tracked the local changes in a coniferous forest dynamics and learnt how the conifers adapt to the semi-arid mountain environments. A limited number of phenology-associated endeavors have taken conifers into account, but no fully-effective solutions for monitoring of conifer phenology have been established. For example, Richardson et al. (2009) reported that spring increases and autumn decreases in canopy greenness can be detected in both deciduous and coniferous stands, but conifers display weaker morphological variations than deciduous trees. Jönsson et al. (2010) pointed out that evergreen forests do not have a sharp increase in greenness during spring. In other words, the measures such as in the principle of thresholding vegetation index (VI) curves, often used for determining the timing of different phenological phases, are not applicable for coniferous forests.

The situation may become more complicated when directly manipulating LiDAR-based measurements of 2.5–5 cm long and 1–2 mm broad needle leaves, because it is difficult for so tiny tree organs to effectively trigger laser backscattering. Inevitably, the single needle leaves are easily omitted in the resulting point clouds. For the case of evergreen trees growing under the Mediterranean climate, this problem becomes more serious, because there is generally no apparent effect of coldness hampering tree growth in winter. In other words, the phenomenon of almost no distinguishable needle leave shrinkages or other changes in winter may make it full of errors in the LiDAR-based measurements. To our best knowledge, there have yet been no LiDAR-based approaches proposed for characterizing seasonal-scale conifer phenological variations in terms of crown morphology. Instead, TLS has the potential of