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Monitoring spring phenology with high temporal resolution terrestrial LiDAR measurements

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ABSTRACT

Vegetation phenology studies the timing of recurring seasonal dynamics and can be monitored through estimates of plant area index (PAI). Shifts in spring phenology are a key indicator for the effect of climate change, in particular the start of the growing season of forests. Terrestrial laser scanning (TLS), also referred to as terrestrial LiDAR, is an active remote sensing technique and measures the forest structure with high spatial detail and accuracy. TLS provides information about the 3D distribution of canopy constituents and vertical plant profiles can be derived from these data. Vertical plant profiles describe the plant area per unit volume as a function of height, and can be used to used to monitor seasonal dynamics through PAI. Here, we present a TLS time series based on 48 measurement days of four sampling locations in a deciduous forest in the Netherlands. Vertical plant profiles are derived for each measurement and allow us to quantify not only total canopy integrated PAI, but also monitor PAI at specific horizontal layers. Sigmoidal models show a good fit to the derived total canopy integrated PAI time series (CV(RMSE) <2.4% and CCC >0.99). The start of season (SOS) based on these models occurs between March 29 and April 3, 2014, depending on the species composition. The SOS derived from the TLS data corresponds well with field observations and occurs 7–12 days earlier compared to the SOS estimate from the MODIS NDVI time series. This is mainly caused by the lower relative standard deviation for TLS measurements in leaf-off conditions (0.72% compared to 2.87% for the MODIS NDVI data), which allows us to significantly detect small changes in phenology earlier. TLS allows us to monitor PAI at specific horizontal layers and we defined an understorey, intermediate and upper canopy layer. Even though our study area had only a sparse understorey, small differences are observed in the SOS between the different layers. We expect that these phenological differences will be more pronounced in multi-layered forests and TLS shows the potential to study seasonal dynamics not only as a function of time, but also as a function of canopy height.

1. Introduction

The structure of forests impacts several biological and physical processes. The structural arrangement of canopy constituents within forests influences respiration, transpiration, photosynthesis, carbon and nutrient cycles and rainfall interception. Furthermore, the vertical structure of vegetation is also related to biological diversity and habitat availability (Tanaka et al., 2010; Goetz et al., 2007; Holmes and Sherry, 2001). Phenology studies the periodic biological cycles and seasonal changes in forest structure generally follow a well-defined temporal pattern (Zhang et al., 2003). In general, spring activities (e.g. shooting and flowering of vegetation) have occurred progressively earlier since the 1960s (Walther et al., 2002; Hamunyela et al., 2013). Monitoring phenological dynamics provides information about how these recurring biological cycles are connected to the climate and are responding to climate change (Polgar and Primack, 2011; White et al., 2009).

The leaf area index (LAI) is commonly used to quantify forest structure and monitor seasonal dynamics (Bequet et al., 2011; Garrity et al., 2011). However, because most indirect methods do not differentiate between different constituents in the canopy (e.g. stem, branches, leaves), plant area index (PAI) is a more correct

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term. PAI is defined as the one-sided area of plant material surface per unit ground surface area. The indirect ground-based assessment of PAI in the field has been done with optical instruments (Parker et al., 1989), and, more recently, terrestrial LiDAR (light detection and ranging) instruments. Hemispherical photography is an indirect optical method that is commonly used to estimate PAI to quantify structural information about the canopy architecture (Bequet et al., 2011; Jonckheere et al., 2004). This technique is based on the light attenuation and contrast between elements in the photo to differentiate between sky and canopy elements. Methodological errors can occur at any stage of image capture and analysis and the inferred PAI values are therefore subject to several potential error sources (Jonckheere et al., 2004). The LAI-2000 (Li-Cor, Inc., Lincoln, NE) is another indirect optical method to measure PAI. This method is based on the principle of calculating the transmittance based on the ratio of measurements below and outside the canopy (Jonckheere et al., 2004; Gond et al., 1999). The LAI-2000 tends to underestimate PAI in heterogeneous canopies and its coarse resolution restricts detailed spatial analysis of the canopy constituents distribution (Jonckheere et al., 2004).

LiDAR is an active remote sensing technique that accurately measures distances by transmitting laser pulses and analysing the returned energy as a function of distance or time. Terrestrial laser scanning (TLS), also called terrestrial LiDAR, collects information about the three-dimensional distribution of plant constituents in the canopy and can assess forest structure (Ashcroft et al., 2014; Calders et al., 2014b; Vaccari et al., 2013). Previous studies presented fully automated and objective methods to derive forest structure from terrestrial LiDAR data (Calders et al., 2014a; Newnham et al., 2012; Lovell et al., 2011; Jupp et al., 2009; Danson et al., 2007). The robustness of PAI estimates is critical when comparing temporal measurements for monitoring seasonal dynamics in phenology. PAI estimates from hemispherical photography were found to be less robust and more susceptible to methodological errors than estimates from TLS (Hancock et al., 2014; Jonckheere et al., 2004).

Vertical profiles of gap fraction and plant area are important structural metrics to quantify the canopy structure and can be derived from TLS (Calders et al., 2014a; Ni-Meister et al., 2010; Jupp et al., 2009). The vertical distribution of plant area volume density (PAVD) as a function of canopy height was calculated through estimates of the vertically resolved gap fraction. Vertical plant profiles can be used to derive PAI, but also other various metrics such as tree height, height of maximum density or the canopy base height. LiDAR derived plant profiles provide a means not only to calculate integrated canopy metrics, such as PAI, but also a means to quantify the PAI of a specific horizontal canopy layer. This can be important for monitoring multi-layered forests, where the start of the growing season in the lower canopy layers can occur at an earlier time than the upper canopy layers (Richardson and O'Keefe, 2009; Gond et al., 1999).

Previous studies used a limited number of samples to monitor spring phenology using PAI (Bequet et al., 2011; Calders et al., 2011). To our knowledge, the work presented in this paper is the first that analyses spring phenology with high temporal resolution 3D measurements. In this paper we collect terrestrial LiDAR time series data in a broadleaf deciduous forest to monitor leaf development during the period February-July. We will create vertical plant profiles from TLS and monitor the forest structure and the phenological changes during this period. The main objectives of this paper are

1. Monitoring changes in total canopy integrated PAI using TLS from leaf-off conditions in winter to a fully developed canopy in summer;
2. Exploring the use of TLS derived vertical plant profiles to monitor PAI dynamics in specific horizontal canopy layers; and
3. Comparing the start of season inferred from TLS against the start of season derived from meteorological data, MODIS NDVI time series and field observations.

This work provides insight in the stability of TLS measurements in the context of repeatable measurements, which is important to monitor subtle changes in forest structure. We explore the potential of terrestrial LiDAR for monitoring changes in phenology at plot level scale, which may contribute to more objective calibration and validation of large scale remote sensing product.

2. Study area and data collection

2.1. Study area

Terrestrial LiDAR data were acquired in *Dassenbos*, a broadleaf deciduous forest in Wageningen, the Netherlands (51.9829° N, 5.6558° E). The terrain had little to no topographic relief. Four sample locations (locations A, B, C and D) were established and data were collected on 48 measurements days during the period February–July 2014. The forest was oak-dominated (*Quercus* spp.) with a presence of birch (*Betula* spp.) in the upper canopy, and was approximately 40 years old. The upper canopy of locations A and B consisted of approximately 85% oak and 15% birch, whereas locations C and D consisted of approximately 95% oak and 5% birch. The sparse understorey mainly consisted of *Sambucus nigra*, *Sorbus aucuparia*, *Prunus* spp., *Amelanchier* spp. and *Ilex aquifolium*.

2.2. LiDAR data

The TLS sampling intensity varied according to the expected changes in phenology, with more weekly measurements days in periods of larger phenological changes. The measurement period started at day of year (DOY) 55 (February 24, 2014) with three measurements per week for a period of 12 weeks. During the following four weeks (starting from DOY 139, May 19) two weekly measurements were done. TLS data was collected once a week for the final four weeks (starting from DOY 167, June 16) of the measurement campaign.

TLS data were acquired with a RIEGL VZ-400 terrestrial laser scanner (RIEGL Laser Measurement Systems GmbH), mounted on a tripod at approximately 1.45 m height. The instrument has a beam divergence of nominally 0.35 mrad and operates in the infrared (wavelength 1550 nm) with a range up to 350 m. The instrument also measures the yaw (through an internal compass), pitch and roll (through inclination sensors) and records up to four returns per emitted pulse. Lovell et al. (2003) and Calders et al. (2014a) discussed the advantage of multiple returns over single returns. Their studies concluded that multiple return instruments will lead to an improved sampling at greater heights in the canopy. The scanner settings were the same across all scans with a pulse repetition rate of 300 kHz and a minimum range of 0.5 m. We used a 0.06° angular sampling resolution, which resulted in an acquisition time of 1 min 23 s for a single scan. When the instrument is level, the RIEGL VZ-400 instrument has a zenith angle range 30–130°. Therefore an additional scan was acquired at each sampling location with the scanner tilted at 90° from the vertical to complete sampling of the full hemisphere. These two scans were registered by using retro-reflecting targets that were distributed around the scan positions using the RiSCAN PRO software (provided by RIEGL). We converted the raw TLS data to the sorted pulse data (SPD) format with the open source sorted pulse data software library (Bunting et al., 2013b,a) for further analysis.