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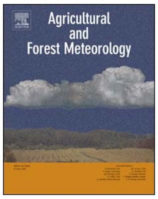

Estimation of plant area index and phenological transition dates from digital repeat photography and radiometric approaches in a hardwood forest in the Northeastern United States

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ABSTRACT

Long-term, continuous digital camera imagery and tower-based radiometric monitoring were conducted at a representative hardwood forest site in the Northeastern United States, part of the AmeriFlux network. In this study, the phenological metrics of the leaf area index (LAI), plant area index (PAI) and associated transition dates (e.g., timing of the onset of leaf expansion and the cessation of leaf fall) were compared using 4-year of data from Bartlett Experimental Forest. We used digital repeat photography (DRP) imagery collected using two different methods ("canopy cover" and "phenocam" approaches), together with above- and below-canopy measurements of photosynthetically active radiation (PAR). The growth-period LAI estimated from canopy cover images (LAI_{CANOPY}) and the above and below canopy PAR measurements (LAI_{fPARt}) were within approximately the same range, in term of magnitude, as previous results for multiple comparative methods, although growing-season LAI_{CANOPY} was slightly lower ($3.11\,m^2\,m^{-2}$ to $3.35\,m^2\,m^{-2}$) than LAI_{fPARt} ($3.19\,m^2\,m^{-2}$ to $3.67\,m^2\,m^{-2}$). In addition, we derived phenological transition dates from PAI_{CANOPY}, PAI_{fPARt}, and color-based metrics calculated from the phenocam imagery (green (G_{CC}) and red (R_{CC}) chromatic coordinates). The transition dates in both spring and autumn differed somewhat according to method, presumably due to the vegetation status detection abilities of each vegetation metric. We found that LAI estimation from canopy cover images may be influenced by automatic exposure settings, which limits the ability to detect subtle changes in phenology during the transition phases in both spring and autumn. Particularly in autumn, the color-based metrics calculated from the phenocam imagery are decoupled from leaf area dynamics and thus PAI. While above and below canopy PAR measurements could yield the better indicators for estimating LAI, its seasonal dynamics, and associated phenological transition dates in long-term monitoring, we argue that there are obvious benefits to the multi-sensor approach used here.

1. Introduction

Plant phenology plays a fundamental role in regulating the seasonal dynamics of ecosystem function and structure, and hence the biogeochemical cycling of carbon and nutrients. Phenology also serves as an important control on energy and carbon exchanges via atmosphere–plant community interactions on local-to-global spatial scales (Richardson et al., 2013a). Thus, phenology drives the biological rhythms of the whole ecosystem under a given climate (Klosterman et al., 2014).

While phenology is sensitive to climate change, it is unclear how it will respond to future warming (Peñuelas et al., 2009). Several researchers have demonstrated the effect of climate change on phenology at an ecosystem scale over past decades and centuries (Ellwood et al., 2013; Primack, 2014). A comparison of recent phenophase measurements with phenology records, collected by hand at a small pond in Northeastern United States more than 15 decades ago by the American naturalist Henry D. Thoreau, revealed major interactive relationships between plants and animals as a result of the occurrence of phenological phases, such as earlier emergence of new leaves in spring that animals preferentially feed on (Ellwood et al., 2013; Primack and Gallinat, 2016). In contrast, several concerns have been raised regarding changes in phenology. For instance, what are the drivers of phenology in different ecosystems? Moreover, if future climate change

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induces changes in phenology, will this impair existing functioning, structure, and biogeochemical cycling in terrestrial ecosystems? A recent report on the relationship between climate change and phenology suggested that phenology might be less sensitive to increasing temperature than previously expected (Fu et al., 2015). However, this issue remains unresolved (Keenan, 2015).

Over the past decades, non-destructive optical or radiometric techniques, so-called "near-surface and remotely-sensed" approaches, have been used widely to evaluate plant phenology at various sites in the AmeriFlux network (e.g., Jenkins et al., 2007; Richardson et al., 2009; Ryu et al., 2010; Sonnentag et al., 2012). Instrument-based approaches can provide high-frequency, long-term data on phenology that are not subject to the inherent uncertainties and subjectivity of human observers (Richardson et al., 2013b). Several remote sensing approaches have been tested to monitor changes in phenological metrics or events, such as bud burst, leaf emergence, color, senescence and defoliation, in a range of terrestrial sites. Simple radiometric measurements – e.g. to quantify the total amount of light absorbed by or transmitted by the canopy – have been used to estimate the seasonality of leaf or foliage area (Turner et al., 2003; Richardson et al., 2012). Other approaches based on digital repeat photography (DRP) have also been applied. Specifically, imagery from upward-looking cameras has been used to quantify variation in canopy cover (Ryu et al., 2012), while imagery from downward-looking cameras has been used to quantify variation in canopy color (Richardson et al., 2007). Furthermore, advances in available satellite measurements have allowed us to assess spatial variability in phenology over a wider geographic range (Zhao et al., 2012; Klosterman et al., 2014).

While most instrument-based approaches are based on similar principles (i.e., quantifying how light is processed by the canopy, and how this changes seasonally), they each have individual advantages that allow them to capture unique changes or fine differences in phenology. Photosynthetically active radiation (PAR, 400–700 nm), is absorbed, scattered, and transmitted by plant foliage (as well as woody stems and branches). Broadband radiometric measurements of PAR permit optically-based estimates of leaf or foliage area using the fraction of light transmitted through the canopy. Specifically, in forests with spatially homogeneous foliage arrangement, the gap fraction principle enables accurate assessment of leaf area from a single set of above- and below-canopy measurements. However, more commonly, especially in naturally regenerated or unmanaged forests, the ideal spatial characteristics are rarely achived, The resulting heterogeneous forest structure then requires the deployment of, multiple sensors within the forest to mitigate the effects of spatially heterogeneous below-canopy light environment on the evaluation of foliage area (Jenkins et al., 2007).

Meanwhile, the DRP approach has been shown to be applicable in various tower-flux operation sites across the world because of its user-friendly and weatherproof features (ex., Ryu et al., 2010; Keenan et al., 2014; Zhao et al., 2012; Ma et al., 2014; Toomey et al., 2015; Linkosalmi et al., 2016 Moore et al., 2017). Software tools and methods for processing imagery taken using DRP have been specifically designed to track phenolgy (ex., Leblanc, 2004; Macfarlane et al., 2007; Richardson et al., 2007; Ide and Oguma, 2010; Sonnnentag et al., 2012). With upward-looking camera imagery (e.g., canopy cover photography), the extracted field of view is typically somewhat narrow, and therefore the use of multiple cameras may be desirable to accurately capture spatial heterogeneity (Ryu et al., 2010). For example, in savanna ecosystems where sparsely distributed trees mix with grass, there is a particularly high degree of spatial heterogeneity but longterm canopy cover DRP measurements tracked successfully seasonal and annual variability in vegetation indices such as leaf or foliage area in these ecosystems (Ryu et al., 2012; Ma et al., 2014 Moore et al., 2017). On the other hand, the application to the foliage area evaluation from the corresponding DRP approach in the forests with dense canopy closure has still remained under investigation (Ryu et al., 2012; Macfarlane et al., 2014). In temperate deciduous forests, during the full-leaf period, a scene from the canopy cover DRP approach gets darker due to light occlusion by foliage above the dense canopy. To brighten the image, a digital camera set to automatic exposure will then increase the exposure time or the diameter of the aperture, similar to the process performed for human eye (Macfarlane et al., 2014). It has been acknowledged that as a result, many pixels, including small gaps between leaves, twigs and small branches in dense canopy, might be masked by these exposure effects, leading to underestimation of the maximum foliage area from longterm DRP measurements with automatic exposure setting.

To detect phenology using vegetation metrics of interest, the simultaneous application of multiple near-surface remote sensing approaches has been conducted (Zhao et al., 2011). Previous research has mainly focused on leaf area index (LAI), because this is essential for representing the overall function, structure, and resultant diversity of ecosystems via their photosynthetic activity. However, what is actually measured is plant area index (PAI), representing the aggregated leaf and woody plant materials, such as stems, twigs, and fine branches (Macfarlane et al., 2007; Zhao et al., 2011). The PAI is directly calculated from canopy cover images ($\text{PAI}_{\text{CANOPY}}$) and above- and below-canopy PAR measurements by which the fractional PAR transmitted through the canopy (fPARt) can be obtained ($\text{PAI}_{\text{fPARt}}$). PAI can be also converted into LAI in conjunction with direct sampling technique using litter-trap observations. Another approach to convert PAI to LAI is to subtract off the dormant-season PAI because this represents only woody material. Therefore, PAI might be a beneficial metric when these different approaches are compared in the corresponding time series.

As an additional metric of interest, we focus on the phenological transition dates. The transition dates indicate the phenologic timing associated with specific leaf or foliage developmental phases. Particularly, it is significant to obtain accurate evaluation of the annual difference in these timings in spring and autumn periods for deciduous forests as changes in the phenologic timing have a great potential to alter the whole biological rhythm in the ecosystem over decadal time scales in response to future climate change (Primack and Gallinat, 2016). For the purpose of evaluating the phenologic transition dates, we used the time series data of $\text{PAI}_{\text{CANOPY}}$ and $\text{PAI}_{\text{fPARt}}$, and the green and red chromatic coordinates derived from phenocam imagery (green (G_{CC}) and red (R_{CC}) chromatic coordinates). The phenocam DRP approach captures an oblique view of the canopy from the digital camera mounted on a viewpoint above the canopy, serving as valuable ground truth validation data for satellite remote sensing phenology data products (Klosterman et al., 2014; Ma et al., 2014). The vegetation metrics G_{CC} and R_{CC} from the phenocam DRP approach are calculated from the ratio of green and red digital number (DN) within each image. Changes in these metrics may reflect physiological (or functional) and physical (or structural) characteristics of foliage. Accordingly, phenological metrics derived based on canopy color variations may differ from those based on the structural metric of PAI because canopy color depends on both the amount of leaf area and the color of individual leaves (Keenan et al., 2014).

In this study, we compare the phenologic metrics derived from different near-surface remote-sensing approaches using four years of data (2013–2016) from a temperate deciduous forest. We examine the vegetation features detectable from these and we explore the potential for individual methods to determine the same parameter of interest. Specifically, we compare start- and end-of-season transition dates estimated from light interception from fractional PAR measurements, foliage cover from digital upward-pointing canopy cover images, and greenness from oblique canopy view images.

2. Site information

Field observations were conducted in the Bartlett Experimental Forest (44°3′52.7″ N, 71°17′17.1″ W, 270 m a.s.l), located in the lowlands