Monitoring multi-layer canopy spring phenology of temperate deciduous and evergreen forests using low-cost spectral sensors

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ABSTRACT

Emerging near-surface remote sensing techniques have advanced our ability to monitor forest canopy phenology. Thus far, however, little effort has been made to monitor the phenologies of the various canopies of multi-layer forests separately, despite their importance in regulating forest biogeochemical cycles. Here we report phenological changes in multi-layer canopies of deciduous broadleaf and evergreen needleleaf forests in the Republic of Korea during the spring of 2013. We installed light-emitting diode (LED) sensors at four different canopy heights at two sites to measure the normalized difference vegetation index (NDVI) using red and near-infrared (NIR) spectral reflectance and to estimate leaf area index (LAI) using the blue band gap fraction. LED-sensors identified leaf-out dates of over- and understory canopies at both sites; leaves unfolded 8–11 days earlier in the understory canopy than the overstory canopy. At the deciduous forest site, LED-NDVI failed to capture the leaf-out date in the overstory canopy, because all four LED-sensors started to see green-up from the understory canopy while the overstory canopy was leafless. LED-LAI identified different leaf-out dates for the over- and understory canopy, because the gap fraction was measured explicitly for each canopy layer. In the evergreen forest site, LED-NDVI signals between the top of the tower and beneath the overstory canopy were decoupled because of the dense evergreen overstory canopy. Both LED-NDVI and LED-LAI identified new needle expansion in the overstory canopy and understory canopy development. MODIS NDVI agreed well with LED-NDVI data (R² = 0.96, RMSE = 0.04) at the deciduous forest site, and we discovered that understory canopy development determined the onset of greenness based on MODIS NDVI data. LED-LAI data agreed well with independent estimates from the other instruments, indicating that LED-sensors could be used to monitor multi-layer canopy LAI. Continuous, in-situ observation of multi-layer canopy phenology will aid in the interpretation of satellite remote sensing phenology products and improve land surface models that adopt a multi-layer canopy model.

1. Introduction

Forest structures, which typically form multi-layer canopies, are complex in space and time. Multi-layer canopies exhibit different phenological patterns that modify species composition, light capture, carbon, water, and nutrient cycles in the forest (Baldocchi, Xu, & Kiang, 2004; Pearcy, 1990; Seiwa, 1998). For example, understory species maximize annual mass gain and survival by unfolding leaves earlier than overstory species in deciduous broadleaf forests (Seiwa, 1998). Although field observations can be used to monitor multi-layer canopy phenology (Richardson & O’Keefe, 2009), it is unclear how to monitor multi-layer canopy phenology automatically and continuously. Strengths and limitations of different vegetation metrics, such as Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) and leaf area index (LAI) for monitoring multi-layer canopy phenology also have to be established.

To monitor forest canopy phenology, researchers generally obtain spectral data from the sky toward the forest canopy, spectral data from the forest floor toward the sky, and use quantum sensors to measure light attenuation through the canopy. Numerous studies have focused on monitoring canopy phenology from the sky. Instruments used include radiometric sensors (Huemmrich, Black, Jarvis, McCaughey, & Hall, 1999; Schmid, Grimmond, Copley, Offerle, & Su, 2000; Soudani et al., 2012), digital cameras (Nagai, Nasahara, Muraoka, Akiyama, & Tsuchida, 2010; Richardson et al., 2007; Sonnentag et al., 2012), and satellite remote sensing (Ganguly, Friedl, Tan, Zhang, & Verma, 2010; White et al., 2009; Zhang et al., 2003). Looking at the forest from the sky enables forest phenology...
to be monitored from the plot level to continental scales. However, those sensors mostly see the top of canopies, and it is unclear how in-depth the sensors look at the forests, as this depends on forest openness and sun-target–sensor geometries (Pisek & Chen, 2009). Thus observing the forest from the sky is unlikely to capture multi-layer canopy phenology in forests, particularly dense forests.

Another approach to monitor forest phenology is to look upwards at the forest from the forest floor. This method has the advantage that details of the forest inside can be obtained. In an open forest, such as that found in a savanna ecosystem where the tree canopy height is 10 m, upward-pointing digital cameras accurately monitored tree canopy phenology despite slight variations in LAI over the seasons (0 to 0.9) (Ryu et al., 2012). A recent study of tall, dense, closed canopies reported that hemispherical photographs taken from the forest floor did not capture the canopy phenomenology of a coniferous forest well, although the same technique captured the canopy phenomenology of a deciduous forest well (Nagai et al., 2013). To the best of our knowledge, no study has evaluated if upward-pointing digital cameras can capture multi-layer canopy phenology.

Light attenuation through canopies is a good indicator of canopy phenomenology. One century ago, Salisbury (1916) observed that changing light environments at the forest floor are related to phenomenology. In the 1970s, an innovative field campaign was conducted to measure the forest light environment using traversing radiometer systems that horizontally moved through Sitka Spruce forest canopies at different canopy depths (Norman & Jarvis, 1974, 1975). A similar system was established in an Oak–Hickory forest in the 1980s to monitor multi-layer canopy phenomenology (Baldocchi, Hutchinson, Matt, & McMillen, 1984, 1985; Chason, Baldocchi, & Huston, 1991; Hutchinson et al., 1986). Traversing radiometer systems have been shown to be able to capture spatial variations in light environments in forests (Brown, 1973; Herrington, Leonard, Hamilton, & Heisler, 1972).

However, these types of system require regular and careful maintenance of sophisticated infrastructures such as rails, motors, cables, masts and radiometers, which hampers continuous observation of multi-layer phenomenology over seasons and years. As an alternative, researchers have observed light attenuation through canopies by placing photosynthetically active radiation (PAR) sensors at fixed locations above and below canopies to monitor over- and understory canopies, not separately (Nagai et al., 2013; Novick et al., 2004; Richardson et al., 2007). In spite of the advancements in observing light penetration through canopies over the century, one challenging task that remained is to monitor multi-layer canopy phenomenology separately and automatically.

Two most widely used variables for monitoring vegetation phenomenology are NDVI and LAI. NDVI reflects vegetation activity, whereas LAI is a key canopy structural variable that controls land–atmosphere interactions (Norman & Jarvis, 1974; Ryu et al., 2011). Although both metrics are related to canopy phenomenology, their utility for monitoring multi-layer canopy phenomenology is less well known. A series of studies measured NDVI in the field above the canopy, not inside the canopy (Fensholt & Sandholt, 2005; Ryu et al., 2010; Soudani et al., 2012). LAI is typically estimated by measuring the gap fraction (GF) (Miller, 1967; Monsi & Saeki, 1953; Welles & Norman, 1991), which requires measuring light intensity at two different heights. Several studies measured overstory and understory LAI separately using quantum sensors, but monitoring was manual (Baldocchi et al., 1984; Barr et al., 2004; Nasahara, Murakoa, Nagai, & Mikami, 2008). The emergence of inexpensive but reliable spectral sensors that measure both PAR and NIR regions separately (Garrity, Vierling, & Bickford, 2010; Ryu, Baldocchi, et al., 2010) has made it possible to monitor NDVI and LAI concurrently at multiple canopy depths.

Multi-layer canopy phenomenon monitoring data are needed to better interpret and evaluate satellite-derived phenomenology metrics. During a green-up period, satellite-derived phenomenological metrics are influenced by both over- and understory canopies and the forest floor (Ahl et al., 2006; Eriksson, Eklundh, Kuusk, & Nilson, 2006; Nagai et al., 2010; Suzuki, Kobayashi, Delbart, Asanuma, & Hiyama, 2011). Ahl et al. (2006) evaluated a series of phenomenological metrics derived from MODIS Land products and concluded that the over- and understory canopies should be monitored separately in the field. Furthermore, the coarse temporal revisit frequency of satellites and temporal composites in satellite imagery are additional sources of uncertainty when quantifying phenomenological metrics (Morisette et al., 2009). Continuous observation of over- and understory canopy phenomenologies might aid in the interpretation of satellite remote sensing phenomenology products.

In this study, we report how we used LED-sensors (Ryu, Baldocchi, et al., 2010) to monitor the multi-layer canopy phenomenology of a temperate deciduous broadleaf forest and an evergreen needleleaf forest in Korea during the spring of 2013. We installed LED-sensors, which measure spectral irradiance of red, blue, green, and near-infrared bands, at four different canopy depths to measure NDVI and LAI concurrently for each canopy layer at both sites. To evaluate the efficacy of LED-sensors at detecting phenomenological events, we integrated in-situ observations, upward-pointing digital camera data, and Plant Canopy Analyzer, LAI-2200 (LI-COR Biosciences, Lincoln, NE) data. We then evaluated MODIS NDVI-derived phenomenology metrics by scaling up in-situ phenomenological records through LED-NDVI and Landsat NDVI. Our goal in this study was to characterize phenomenological changes of multi-layer canopies for two different forest types, deciduous broadleaf forest and evergreen needleleaf forest. The scientific questions that we addressed are as follows: 1) Are phenomenological metrics in multiple canopy layers consistent between sensors and indices (NDVI and LAI)? 2) How do vertical profiles of NDVI and LAI differ before and after leaf expansion in deciduous and evergreen forests? 3) What does MODIS NDVI see during a green-up period?

2. Materials and methods

2.1. Site description

Study sites were a deciduous broadleaf forest (DBF) and an evergreen needleleaf forest (ENF) in Gwangneung Experimental Forest, which is part of the Korea Flux Network (Kim et al., 2006) (Fig. 1). Gwangneung Experimental Forest is located in the mid-western part of the Korean Peninsula, and has a typical cool-temperate climate. Annual maximum, minimum, and mean temperatures are 35, −15, and 10 °C, respectively. Annual mean precipitation is 1365 mm (Lim, Shin, Jin, Chun, & Oh, 2003). The DBF site is located on the upslope of the western part of the experimental forest (latitude: 37.748171N, longitude: 127.148176E, elevation: 260 m, slope: 10–20°). Overystory canopy consists of Quercus acutissima, Quercus serrata, and Carpinus laxiflora. Dominant understory species include Euonymus oxyphyllus and Cornus kousa. Both overystory and understory species are deciduous. Overystory tree height is 18 m (Ryu, Kang, Moon, & Kim, 2008). The ENF site is 1.2 km east of the DBF site (latitude: 37.74843N, longitude: 127.162593E, elevation: 128 m, slope: <3°). Dominant overystory and understory species are Abies holophylla and Cornus controversa, respectively. Overystory tree height is 27 m. Overystory and understory species are evergreen and deciduous, respectively.

2.2. LED-sensors

LEDs are widely used as light sources, but in reverse mode, they can measure spectrally selective radiation (Mims, 1992; Ryu, Baldocchi, et al., 2010). LED-sensors were fully described and tested in a previous study (Ryu, Baldocchi, et al., 2010), thus we provide only a brief explanation of the LED-sensors here. In this study, we deployed 4-band LED-sensors, which monitor blue, green, red, and NIR spectral bands (Table 1). LEDs in the sensor head were housed beneath Teflon (Teflon®, DuPont, Wilmington, DE, USA) to diffuse the incoming light. Thus, the field of view of the LED-sensors was approximately 180°.
One sensor head was directed to the zenith and the other toward the nadir direction, which enabled us to monitor bi-hemispheric reflectance. We cross-calibrated each spectral band between the upward and downward LED-sensors in the lab by exposing all LED-sensors to a range of solar radiation. We installed LED-sensors on horizontal booms with a length of 2 m, and installed these booms at heights of 3, 13, 17, and 22 m in the tower at the DBF site and heights of 2, 9, 24, and 40 m in the tower at the ENF site (Fig. 1b and c). Data loggers (CR1000 for DBF site, CR5000 for ENF site, Campbell Sci., Inc., CSI, Logan Utah) sampled irradiance from each spectral channel every 1 s (ENF site) or 30 s (DBF site) and stored half-hour mean values.

Table 1
LED-sensor specifications.

<table>
<thead>
<tr>
<th>Spectral band</th>
<th>Peak sensitivity</th>
<th>Full width half maximum</th>
<th>Field of view</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>440 nm</td>
<td>65 nm</td>
<td>30°</td>
<td>BFB45CO0, Westech Opto-electronic Science and Technology Co., LTD, China</td>
</tr>
<tr>
<td>Green</td>
<td>525 nm</td>
<td>80 nm</td>
<td>30°</td>
<td>SGCHT10, Westech Opto-electronic Science and Technology Co., LTD, China</td>
</tr>
<tr>
<td>Red</td>
<td>646 nm</td>
<td>56 nm</td>
<td>120°</td>
<td>SMF-HM12520RD-599, Lumex, Inc., Palatine, IL, US</td>
</tr>
<tr>
<td>Near-infrared</td>
<td>843 nm</td>
<td>72 nm</td>
<td>80°</td>
<td>QED223, Fairchild Semiconductor Corporation, San Jose, CA</td>
</tr>
</tbody>
</table>
To quantify LAI of the different canopy layers, we measured light attenuation (i.e. gap fraction) using incoming irradiance collected in the blue band of the LED-sensor at two canopy depths as follows:

\[
LAI = -\ln \left[ \frac{G(\theta)}{k(\theta)\Omega_k} \right] \gamma_k
\]  

where \( G(\theta) \) is the extinction coefficient \( (G(\theta)/\cos(\theta)) \) where \( G \) is the leaf projection function (Warren Wilson, 1960) (see Appendix B), \( \gamma_k \) is the needle-to-shoot ratio area, which was 1.97 \( \pm \) 0.09 (mean \( \pm \) 95% CI) for needleleaf species and 1 for deciduous species (see Appendix B), \( k(\theta) \) is the view zenith angle, \( \Omega_k \) is an element clumping index which accounts for foliar clumping effects at larger-than-shoot level (Chen, Rich, Gower, Norman, & Plummer, 1997) (see Appendix A), and the overbar indicates the average of data over the day. We averaged over GF rather than averaging over the logarithm (i.e. \( \ln(G(\theta)) \)) to avoid overcorrection of clumping effects (Ryu et al., 2010). We used blue band LED readings to minimize scattering effects, as LAI–2200 uses a blue band quantum sensor (Welles & Norman, 1991). We measured scattering coefficients (i.e. sum of reflectance and transmittance) in the blue band for two dominant overstory species (Q. serrata, C. laxifolia) at the DBF site on DOY 171 using an ASD FieldSpec4 Wide-Res spectroradiometer (Analytical Spectral Devices Inc., CO, USA), and we found that the scattering coefficient was 0.038 \( \pm \) 0.003 (mean \( \pm \) 95% CI, \( n \) = 6).

For both sites, we defined overstory LAI of that as the upper two canopy layers and understory LAI as that of the bottom layer. To reduce noise in daily LAI time series, we took two different light conditions into consideration. First was diffuse sky conditions, because strong beam radiation and sunflakes enhance heterogeneity in forest light environments. Second was moderate irradiance conditions, because too low irradiance could cause erroneous GF estimates. To account for these conditions, we introduced a sky clearness index, which is the ratio of incoming irradiance measured by the LED blue band at the top of tower to the extraterrestrial solar irradiance quantified using the solar zenith angle and day of year (Liu & Jordan, 1960). Then we determined the upper 70% and 30% threshold values in the sorted daytime half-hourly sky clearness index data between DOY 100 to 180. We defined a “clear sky” as a sky clearness index greater than the upper 70% threshold and defined a “gray sky” when the index was between the two thresholds. We assumed that the gray sky conditions met the aforementioned two criteria. For each day, we computed LAI using half-hourly data for gray sky conditions using Eq. (1). For the case of the understory of the ENF forest, the forest floor was frequently dark, thus the use of gray sky conditions data produced noisy daily LAI data. We therefore used clear sky data to determine the understory LAI at the ENF site. Thus \( k(\theta) \) for the understory at the ENF site was determined for beam radiation conditions (Fig. A1), whereas \( k \) for the overstory at the ENF site and over- and understories at the DBF site was defined based on diffuse sky conditions (see Appendix A). Although the thresholds defined above are somewhat subjective, we found that they were needed to generate realistic, less noisy time series for over- and understory LAI calculations.

At each canopy depth, the upward- and downward directions of the LED-sensors were used to calculate NDVI as follows (Tucker, 1979):

\[
\text{NDVI} = \frac{P_{\text{blue}} - P_{\text{red}}}{P_{\text{blue}} + P_{\text{red}}} \tag{2}
\]

where \( \rho \) is spectral reflectance (Table 1) and the overbar indicates the average of the clear sky data over a day. Computation of LAI relied on downward direction blue band radiation data; in contrast, both downward and upward direction spectral radiation data in the red and NIR bands were used to calculate NDVI. Because upward (i.e. reflected) radiation decreases with increasing canopy depth, which could reduce signal-to-noise in deeper canopy on cloudy days, we used clear sky conditions data to compute daily NDVI values.

2.3. Digital camera

To monitor LAI continuously on a plot scale, we used upward-pointing digital cameras. We provided a full description of camera settings and analysis of images from upward-pointing digital cameras in a previous study (Ryu et al., 2012). Briefly, in this study, three digital cameras (PowerShot A3000IS, Canon) were installed 1 m above the ground at the DBF site. Cameras were approximately 10 m apart from each other around the tower. All cameras pointed toward the zenith (Fig. 1b). Using the Canon Hack Development Kit (CHDK) (CHDK Project, http://chdk.wikia.com), we controlled the digital cameras to take photos three times per day — 1.5, 1, and 0.5 h before sunset to obtain photos under diffuse sky conditions. For all cameras, the focal length was set to 6 mm, the aperture to f/2.7, and exposure was automatic (Ryu et al., 2012). These settings yielded a view zenith angle from 0 to 32° diagonally. All images were saved in JPG format with the highest resolution [3648 \times 2736 pixels].

Digital photos at plot scale were also taken manually at a height of 1 m toward the zenith on DOY 105, 120, 126, 133, 140, and 155 using a DSLR camera (EOS 600D, Canon, Japan). The plot size was 400 m², and the tower was located near the center of the plot. Within the plot, a rope was arranged randomly and we took photos along the rope at intervals of 5 m. On average, 35 photos were taken per day. The DSLR camera’s settings were as follows: automatic exposure with aperture priority mode, aperture of f/18, and focal length of 55 mm. These settings produced a view zenith angle from 0 to 13° diagonally. Although the fields of view between the two different camera types differed (0 to 32° vs. 0 to 13°), extinction coefficients varied only slightly between 0 and 32° (see Fig. A1). Therefore, we used whole images without clipping to compute LAI.

We classified pixels as sky or vegetation using blue channel information extracted from each JPG image. Integrating the corner-detection method and dual binary threshold method (Macfarlane, 2011) in the blue channel histogram analysis enabled us to calculate the fraction of crown cover (CC), crown porosity (CP), and finally LAI (Ryu et al., 2012):

\[
LAI = \frac{-CC \times \log(\text{CP})}{k} \tag{3}
\]

Over the range of 0 to 32° in view zenith angles, \( k \) varied from 0.78 to 0.8 for the understory canopy and 0.6 to 0.62 for the overstory canopy at the DBF site (see Appendix A). We set \( k \) to 0.67 by computing the weighted average of \( k \) between over- and understory canopies where the overstory LAI was roughly twice the understory LAI based on the LED-sensors and LAI–2200 data (Fig. 2).

2.4. LAI–2200

To quantify seasonal changes in vertical variation of LAI at the DBF site, we used LAI–2200 at different canopy heights where LED-sensors were installed (Fig. 1b). One exception was the lowest part, where the LAI–2200 and LED-sensors were located at 1 m and 3 m, respectively. We measured the reference incoming irradiance at the top of the tower and collected nine readings (three readings each for east, south and west directions) at each canopy depth using a 90-degree view cap. Data were collected between 900 hh and 1200 hh (local time) through the green-up period on DOY 105, 116, 126, 131, 138, 154, and 170 in 2013. A recent paper proposed using LAI–2200 under any sky conditions by correcting for scattering effects caused by leaves in the beam and diffuse components of blue band radiation (Kobayashi, Ryu, Baldocchi, Welles, & Norman, 2013). We used the proposed algorithm,
which is incorporated in Fv2200 software (version 2.0a), to compute LAI.

2.5. In-situ observation of leaf-out dates

We visited the two sites every one to two weeks during phenological transition periods. Based on visual observation and image analysis within a 20 m radius centered on the towers, we identified leaf-out and full-leaf dates for over- and understory canopies at the DBF site and the understory canopy for the ENF site. Leaf-out date was defined as the date when 50% of new leaves were over 1 cm-long. Full-leaf date was defined as the dates when 70% of the leaves approached full-leaf size. We quantified uncertainty in leaf-out and full-leaf dates by taking account of the field visit interval.

2.6. Satellite remote sensing data

To assess satellite-derived phenology metrics, we used the daily interval at the 250 m resolution of the MODIS Surface Reflectance product, MOD09GQ and MYD09GQ (Vermote, El Saleous, & Justice, 2002). Because of spatial heterogeneity in the ENF site, where half of single MODIS pixels were deciduous broadleaf forest, we only tested MODIS NDVI at the DBF site. To consider geolocation uncertainty in MODIS, we selected four MODIS pixels whose centers were close to the DBF tower location (see Fig. 1(a)). We used only data classified as (a) ideal quality — “MODLAND QA bits” (00) in the MO(Y)D09GQ QA descriptions, (b) no clouds — “cloud state” (00) and “pixel is adjacent to cloud” (0), (c) low or average of aerosol quantity — “aerosol quantity” (01 or 10) in the 1 km State QA of MO(Y)D09GA products (Samanta et al., 2011). If all four pixels passed the quality check, we computed NDVI using red and NIR reflectance for that date. The proportion of deciduous broadleaf forest within the four pixels was 93.75%.

To take into account spatial heterogeneity within a single MODIS 250 m pixel, we used Landsat 7 ETM+ and Landsat 8 imagery (30 m resolution) for path 116/row 34. By visual inspection, we removed Landsat imagery that included >30% cloud or semi-transparent clouds. This screening process resulted in three images (DOY 107 for Landsat 7 ETM+, and DOY 131 and 179 for Landsat 8) for this study. We applied atmospheric correction using the dark object subtraction method (Song, Woodcock, Seto, Lenney, & Macomber, 2001) to remove path radiance effects, and computed red and NIR reflectance and finally NDVI. We computed the statistical properties of Landsat NDVI at three scales on DOY 131 which is between overstory leaf-out and full-leaf dates. The three scales include 1) 3 by 3 Landsat pixels centered on the DBF tower, 2) Landsat pixels within the MODIS 250 m pixel that included the DBF tower, and 3) Landsat pixels within the four MODIS 250 m pixels (four parallelograms in gray in Fig. 1a).

2.7. Statistical analyses

To determine leaf-out and full-leaf dates, we used the curvature change rate of a sigmoidal curve fitted to daily time series of LAI and NDVI (Eq. 4) (Zhang et al., 2003):

$$y = a + \frac{b}{1 + \exp(c - dx)}$$

where $a$, $b$, $c$, and $d$ are parameters, $x$ is day of year, and $y$ is LAI or NDVI.

To quantify uncertainty in the leaf-out and full-leaf dates, we conducted the following steps. First, we determined uncertainties in the four parameters using the nlparci function in MATLAB (MathWorks Inc., Natick, MA, version R2012b). Using the multivariate normal random number sampler based on the best parameter set with its covariance matrix (mvnrnd function in MATLAB), we randomly generated 20,000 parameter sets. We determined leaf-out and full-leaf dates for each parameter set over the 20,000 sets, and finally computed 95% CIs for leaf-out and full-leaf dates. We present all data as means ± 95% CI unless specified otherwise. If the 95% CIs of the calculated means did not overlap with each other, they were considered to be significantly different at $\alpha = 0.05$.

3. Results

3.1. Seasonal evolution of LAI at the DBF site

Three independent estimates of LAI derived from LED, LAI-2200, and upward-pointing digital cameras showed consistent seasonal patterns and magnitudes of LAI at the DBF site (Fig. 2). LED-sensors captured different seasonal evolutions of the over- and understory LAI, LED-sensor-derived leaf-out dates of the over- and understory were DOY 124 and 116, respectively, which were almost identical to those based
on in-situ observations (DOY 126 and 115) (Fig. 3). Understory LAI ranged from 0.5 to 1, whereas overstory LAI varied from 0.5 to 2.6, which resulted in a peak LAI of 3.6. There was good agreement between the overstory leaf-out date based on LAI-2200 (DOY 128) and the in-situ observation, but there was a 7-day delay in leaf-out date for the understory (DOY 122) based on the LAI-2200 data. Peak LAI values for the over- and understory were 2.6 and 1.4, respectively, which were similar to the values obtained from the LED-sensors. Upwards-pointing digital cameras offered total LAI that included both over- and understory canopies. Peak LAI was 4, which was comparable to the LED-sensor and LAI-2200 estimates. The leaf-out date was DOY 119, which was not statistically different from the leaf-out date based on in-situ observation of the understory canopy (p > 0.05), but was significantly earlier than the in-situ leaf-out date obtained for the overstory canopy (p < 0.05). Overall, both leaf-out and full-leaf dates determined by LAI-2200 and LED-sensors were not significantly different from the in-situ observations (p > 0.05) (Fig. 3). Ranges of uncertainty in leaf-out and full-leaf dates were largest for LAI-2200, followed by the LED-sensors and digital cameras.

3.2. Temporal and vertical variations of NDVI at the DBF site

NDVI estimates derived from LED-sensors at different canopy heights showed consistent seasonal patterns (Fig. 4a). Leaf-out dates determined from the four different heights were DOY 118, 116, 115, and 114 for heights of 22 m, 17 m, 13 m, and 3 m, respectively. Compared to in-situ observations of leaf-out dates, NDVI detected understory leaf-out accurately, whereas it did not capture leaf-out in the overstory canopy (Fig. 3). Full-leaf dates defined by NDVI were not significantly different from in-situ observations for either over- or understory canopies (p > 0.05). Peak NDVI values in the growing season ranged from 0.9 (top of tower) to 0.7 (forest floor). Uncertainty in leaf-out and full-leaf dates determined by NDVI was narrowest among all methods (Fig. 3).

3.3. Temporal and vertical variations of NDVI at the ENF site

NDVI measured from LED-sensors showed different seasonal patterns between over- and understory canopies (Fig. 4b). NDVI measured from the top of the tower (40 m) was fairly constant until DOY 129 (NDVI ~ 0.73), then increased abruptly and reached a plateau (NDVI ~ 0.8) on DOY 139. In contrast, NDVI measured at a height of 9 m, where the sensors only saw understory deciduous species, increased by two-fold from 0.4 (DOY 118) to 0.8 (DOY 137). The understory leaf-out date determined based on NDVI agreed well with the in-situ observation (DOY 120). In contrast to the DBF site, NDVI measured at the top of the tower did not contain a clear green-up signal from the understory canopy. The fourth LED-sensor installed at the height of 2 m monitored only the NDVI of the forest floor, which was mostly covered by needle litter, and did not show any clear seasonal pattern. Both leaf-out and full-leaf dates determined by NDVI were not significantly different from in-situ observations for the understory canopy (p > 0.05) (Fig. 5). We did not have in-situ observations of leaf-out and full-leaf dates for the overstory canopy, but we had one photo taken on DOY 133 that revealed expansion of new, bright green needles. NDVI data identified leaf-out and full-leaf dates as DOY 129 and 139, respectively.
3.4. Seasonal variations in LAI at the ENF site

Continuous observations of LAI by LED-sensors yielded measurable seasonality in both over- and understory canopies (Fig. 6). LAI of the overstory canopy (*A. holophylla*) started to increase on DOY 126 (LAI 6.4) and full canopy development was achieved on DOY 140 (LAI 7.4). New leaves of the understory canopy were detected on DOY 120, in agreement with the *in-situ* observation (DOY 120) (Fig. 5). Leaf-out and full-leaf dates determined by LAI showed wider uncertainty than those determined based on NDVI for both over- and understory canopies. New needle expansion in the overstory canopy was 6 days later than the understory leaf-out date. Peak LAI in the understory was 0.9, which resulted in a peak LAI of all canopies of 8.3. An independent LAI estimate based on LAI-2200 of the forest floor was 8.6 ± 0.5 on DOY250.

3.5. Evaluation of MODIS NDVI at the DBF site

We evaluated MODIS NDVI against *in-situ* measured NDVI values, then tested phenological metrics of MODIS NDVI. To bridge scale mismatches between footprint of LED-sensors and MODIS pixels, we quantified statistical properties of Landsat NDVI at the three scales that include LED-sensor footprint, one MODIS pixel and four MODIS pixels on DOY 131 (Fig. 7). Mean NDVI values were almost identical for the

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Fig. 5. Leaf-out and full-leaf dates determined by *in-situ* observations, LED-NDVI, and LED-LAI for (a) the overstory canopy and (b) the understory canopy at the evergreen needleleaf forest site. Photo in the upper panel was taken on DOY 133, and shows new needle expansion. Error bars indicate 95% confidence intervals.

Fig. 6. Temporal variations in the leaf area index for the over- and understory canopies estimated from LED-sensors at the evergreen needleleaf forest site.

Fig. 7. Statistical properties of Landsat NDVI values at the DBF site on DOY 131. (a) 3 by 3 Landsat pixels centered on the DBF tower. (b) Landsat pixels within one 250 m MODIS pixel that included the DBF tower. (c) Landsat pixels within the four 250 m MODIS pixels (four parallelograms in gray in Fig. 1a). std is standard deviation.
three scales, ranging from 0.8 to 0.81. Relative standard deviation (ratio of standard deviation to mean) was less than 4% in all cases. Landsat NDVI values less than 0.77 appeared only within the boundary of four MODIS pixels (Fig. 7c), which indicate evergreen trees (see Fig. 1a). Consistent mean NDVI values with low variation across the three spatial scales enabled us to evaluate four MODIS NDVI pixels against LED-NDVI values and in-situ observations of phenological metrics.

Time series of the MODIS NDVI and Landsat NDVI agreed well with LED-NDVI (y = 0.98x, R² = 0.98, RMSE = 0.03 for Landsat NDVI, y = 0.99x, R² = 0.96, RMSE = 0.04 for MODIS NDVI) (Fig. 8a). MODIS NDVI values for leafless and full-leaf conditions were 0.4 and 0.9, respectively, consistent with the LED-NDVI values for these conditions. Leaf-out and full-leaf dates determined by MODIS NDVI using Eq. (4) were DOY 117 and 135, respectively (Fig. 8b). Leaf-out date based on MODIS NDVI was not significantly different from the understory leaf-out date based on in-situ observation (P > 0.05).

4. Discussion
4.1. Are phenological metrics in multiple canopy layers consistent between sensors and between indices?

There were notable discrepancies in phenological metrics across both sensors and indices. We start by discussing the upward-pointing digital camera results. Camera installed on the forest floor at the DBF site was only able to identify leaf-out and full-leaf dates for the understory canopy (Fig. 3). We speculate that the longer length of the path from the camera to the overstory canopy prohibited detection of the overstory phenology. To determine LAI from digital cameras, a total canopy extinction coefficient that takes into account both over- and understory canopies should be quantified (Eq. 3). However, extinction coefficients of the over- and understory in the zenith direction were 0.61 and 0.78, respectively (Fig. A1). In this study, we computed the total canopy extinction coefficient weighted by the over- and understory LAs. Because the cameras tended to fail to detect the overstory canopy phenology, the total canopy extinction coefficient we calculated is likely to be inaccurate. At the ENF site, we also installed three digital cameras (results not shown), which produced substantial noise in the LAI time series. These cameras did not capture the slight increase in overstory LAI around DOY 130 (Fig. 4b), probably due to a longer camera path length, as for the DBF site. To monitor multi-layer canopy phenology with digital cameras, installation of cameras at multiple canopy heights may be necessary.

LAI-2200 was the only instrument that required manual operation. Although the leaf-out and full-leaf dates determined by LAI-2200 were not significantly different from the in-situ observations (Fig. 3), the range of uncertainty was greater than that of LAI estimates obtained from LED-sensor data and upward-pointing digital camera data. Coarse revisit frequency to the field site and noise in the data are likely the major contributors to the large uncertainty. This finding highlights the importance of quantifying uncertainty in phenological metrics. The four parameters in the sigmoidal model (Eq. 4) are loosely constrained with a few data points. Likewise, leaf-out and full-leaf dates based on MODIS NDVI (16-day interval) showed 10-fold larger uncertainty (~10 days) than those based on LED-NDVI (daily interval) at the DBF site (Figs. 8b and 3a). The length of growing season has been increasing by only 3–4 days per decade in the northern hemisphere (Peñuelas, Rutishauser, & Filella, 2009). It is therefore important to reduce uncertainty in phenological metrics through high-frequency observation to track vegetation seasonality under a changing climate.

Both functional (NDVI) and structural (LAI) variables were obtained from LED-sensor data, and phenological metrics based on LED-sensor data varied across sites and canopy heights. Overall, LED-LAI revealed less bias, but higher uncertainty ranges for phenological metrics than LED-NDVI (Figs. 3 and 5). The range of uncertainty in phenological metrics from LED-NDVI was only 1 and 4 days for the DBF and ENF sites, respectively, which is less than 40% of the range of uncertainties associated with LED-LAI and LAI-2200 (Figs. 3 and 5). However, LED-NDVI did not capture the overstory leaf-out at the DBF site because of the greening signal of the understory canopy. LED-NDVI showed a significantly earlier full-leaf date than LED-LAI for the overstory canopy at the DBF site (Fig. 3a), implying that NDVI might have been saturated before the canopy achieved full-leaf conditions (Huete et al., 2002). We believe synergistic use of LED-NDVI and LED-LAI could better constrain phenological metrics in multi-canopy layers.

We found that LAI estimates based on LED-sensors agreed well with independent optical estimates. Optical instruments were error-prone in estimating LAI because of foliar clumping effects (Stenberg, Linder, Smolander, & Flowerellis, 1994), light exposure for digital camera (Zhang, Chen, & Miller, 2005), and scattering effects for LAI-2200 (Kobayashi et al., 2013). LAI estimates from LED-sensor data were comparable with those obtained using the other instruments. Peak LED-LAI at the DBF site (~35) was 0.4 lower than the LAI-2200 and digital camera peak LAI values. The lowest LED-sensor was installed at a height of 3 m, whereas LAI-2200 and digital cameras were used at a height of 1 m. Thus, we speculate the missed LAI below the 3 m height might have resulted in slight underestimation of LED-LAI compared to the LAI obtained via the other instruments. Indeed,
understory LAI based on LAI-2200 was 1.3, which was 0.4 higher than LED-LAI. Adding 0.4 to the LED-LAI resulted in a good match with the peak LAI values from the other instruments. There was greater uncertainty in the LED-LAI estimates of phenological metrics for the understory canopy than the overstory canopy at both sites. Forest floor experiences heterogeneous light environments and low light levels (Rautiainen et al., 2011; Vezina, 1961), thus quantifying the gap fraction for the understory canopy is associated with higher uncertainty. Employing more LED-sensors at the forest floor will help to reduce uncertainty in phenological metrics of the understory canopy. We stress the importance of quantifying leaf inclination angles. Characterization of leaf inclination angle distributions for over- and understory canopies in both DBF and ENF sites using the leveled digital photography method allowed us to convert the gap fraction to LAI. One previous study monitored whole tree LAI daily using an upward-pointing digital camera (Ryu et al., 2012), but to our knowledge, no study has continuously monitored LAI in multi-canopy layers. This current study offers a new way to monitor LAI in different canopy layers using LED-sensors. The LAI values obtained using LED-sensors will aid in evaluating and improving multi-layer canopy representations adopted in land surface models, such as the Community Land Model (Bonan, Oleson, Fisher, Lasslop, & Reichstein, 2012).

4.2. How do vertical profiles of NDVI and LAI differ before- and after leaf expansion in deciduous and evergreen forests?

Two plant functional types had different vertical NDVI and LAI profiles during the green-up period. At the DBF site, understory canopy unfolded leaves 11 days earlier than the overstory canopy, as reported for other temperate deciduous forests (Richardson & O’Keeffe, 2009; Seiwa, 1998). Understory canopy achieved a full-leaf canopy 7 days earlier than the overstory canopy. Four NDVI sensors installed across the DBF tower did not detect the difference in phenology between the two canopy layers (Fig. 3a). When the understory canopy unfolded new leaves, all four sensors focused on the understory canopy because the overstory canopy was leafless. LED-LAI measured at the top of the tower identified the leaf-out date as DOY 118, which was significantly different from the in-situ observation of the overstory leaf-out date of DOY 126 ($P < 0.05$), and was not significantly different from the understory leaf-out date determined by in-situ observation ($P > 0.05$). LED-NDVI at a height of 13 m correctly identified both leaf-out and full-leaf dates, because it monitored the understory canopy phenology exclusively (Fig. 3b). In contrast to LED-NDVI, LED-LAI captured both leaf-out and full-leaf dates for both over- and understory canopies (Fig. 3a). Importantly, LAI was computed using light attenuation through each canopy layer. Thus the LAI estimate for each canopy layer was independent from that of the other canopy layers. This finding highlights that observing light attenuation through canopy layers is a better way to monitor multi-layer canopy phenology in temperate deciduous forests where the understory unfolds leaves when the overstory canopy is leafless.

At the ENF site, the overstory canopy comprised very dense evergreen foliage (LAI ~ 7). In spring, the understory deciduous species unfolded leaves around DOY 120, while the overstory canopy expanded new needles around DOY 129. In contrast to the DBF site, LED-NDVI detected the difference in phenology between the two canopy layers. Because of the dense overstory evergreen canopy, the LED-sensors installed at the top of the tower reported a consistent NDVI value (~0.7) before new needle expansion, while the NDVI value of the understory increased from 0.4 to 0.7 (Fig. 4b). Thus the top LED-sensor monitored the overstory canopy exclusively to the exclusion of the other sensors. It is notable that LED-NDVI detected a slight but measurable increase in new needle expansion around DOY 129. To our knowledge, this is the first report of detection of evergreen needleleaf forest phenology using NDVI. We speculate that near-surface observations at a high temporal frequency, which is not possible with satellite or airborne remote sensing, enabled us to track phenological changes in the evergreen needleleaf trees. Interestingly, LED-LAI derived from light attenuation observations started to increase around DOY 126, which supports the new needle expansion detected by LED-NDVI. Similar to the DBF site, LED-NDVI identified leaf-out and full-leaf dates for the understory canopy with high accuracy (95% CI < 3 days). Thus at the ENF site, both NDVI and LAI captured phenological metrics well for both over- and understory canopies, although LED-NDVI showed much narrower uncertainty than LED-LAI.

4.3. Implications for remote sensing of forest phenology

Satellite remote sensing of NDVI has revealed advancement in green-up signals across the northern hemisphere in recent decades (Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; Piao et al., 2003), but the factors that contribute to these signals are complex, such as snow melt (Dye & Tucker, 2003) and the presence of the understory canopy (Ahl et al., 2006). To better understand satellite NDVI data, it is essential to measure over- and understory canopy phenology separately (Ahl et al., 2006). At the DBF site, we confirmed that MODIS NDVI showed realistic performance compared to LED-NDVI at the top of the tower and Landsat imagery (Fig. 8a). We found that the MODIS NDVI leaf-out date estimate was almost identical to that of the understory canopy (Fig. 8b), and was 9 days earlier than the overstory leaf-out date. This finding is consistent with LED-NDVI measured from the top of tower (Fig. 3). Understory NDVI increased two-fold from 0.35 to 0.8 during the spring (Fig. 4a), while the understory LAI approached a value of 1 (Fig. 2). Thus the slight increase in the understory LAI when the overstory canopy is leafless may have substantial impacts on satellite-derived NDVI. MODIS predicted an earlier leaf-out date than that based on in-situ observations for the overstory canopy in a temperate deciduous forest where the understory canopy tends to unfold leaves earlier than the overstory canopy (Ganguly et al., 2010). Therefore, use of phenological metrics for both over- and understory canopies is essential to evaluate satellite phenology products.

Webcam-based phenology monitoring networks have advanced in recent years (Richardson et al., 2007; Sonnentag et al., 2012). Most webcams are mounted on towers, resulting in oblique or horizontal views to include maximum canopy coverage in the images (Sonnentag et al., 2012). This setting has merits when monitoring landscape-scale canopy phenology. However, images collected from a horizontal or oblique view are unlikely to detect the understory canopy phenology, even in the overstory leafless period, due to the presence of stems and longer path lengths. One study that compared phenology metrics between webcam and MODIS in four deciduous broadleaf forests reported that leaf-out dates were 4–17 days earlier based on MODIS data than based on webcam data (Hufkens et al., 2012). We suspect that earlier leaf-out in the understory canopy may not have been detected well by the webcam, whereas MODIS saw the green-up signal of the understory canopy as found in the current study. Horizontal view webcam images collected in a flux tower tracked overstory pepper weed phenology, but were not able to detect grass layer phenology beneath the pepper weed canopy (Sonnentag et al., 2011). We advocate monitoring over- and understory canopy phenology separately to better interpret remote sensing of phenological metrics.

5. Summary and conclusions

To monitor multi-layer canopy phenology separately, we employed LED-sensors at four different canopy heights in a deciduous broadleaf forest and an evergreen needleleaf forest. LED-sensor enabled us to monitor NDVI and LAI concurrently at different canopy heights. Key findings are as follows: 1) LED-sensors identified leaf-out and full-leaf
dates for over- and understory canopies at both sites; understory canopies unfolded their leaves 8–11 days earlier than the overstory canopies; 2) LED-LAI showed less bias in phenomenological metrics than LED-NDVI, but LED-NDVI had a narrower 95% CI for phenomenological metrics than LED-LAI; 3) LED-NDVI did not capture the overstory leaf-out date in the deciduous forest because it was influenced by the greening understory canopy; 4) both LED-NDVI and LED-LAI detected new needle expansion of the overstory canopy at the evergreen forest site; and 5) LED-LAI values agreed well with those obtained from other instruments such as LAI-2200 and upward-pointing digital cameras. We evaluated what MODIS NDVI sees during the spring, and found that leaf-out date detected by MODIS NDVI corresponded with the understory leaf-out date at the deciduous broadleaf forest. Continuous, separate observations of multi-layer canopy phenology will be instrumental in better interpreting satellite phenology products and evaluating and improving land surface models that adopt multi-layer canopy representation.

Appendix A. Extinction coefficient

Extinction coefficient, \( k \), depends on the leaf inclination angle distribution and view zenith angle. We measured leaf inclination angles, the angle between the leaf surface normal and zenith, for dominant species at both sites using the leveled digital camera photography method on DOY 206, 2013 (Pisek, Ryu, & Alikas, 2011; Ryu, Sonnentag, et al., 2010). In the DBF tower, we took photos of the surrounding trees to determine leaf inclination angles (Ryu, Sonnentag, et al., 2010). We manually quantified clumping effects at the shoot level for the overstory canopy. To quantify clumping effects at the shoot level for the overstory canopy, we estimated extinction coefficient (\( k(\theta) = G(\theta)/\cos(\theta) \)) (Ryu, Sonnentag, et al., 2010) (Fig. A1). Numbers of sampled leaves were 251, 476, 203, and 219 for the overstory of the DBF, understory of the DBF, overstory of the ENF, and understory of the ENF, respectively.

To compute LAI using LED-sensors, we needed to estimate extinction coefficients under diffuse sky condition. Extinction coefficient under isotropic diffuse sky radiation was calculated as follows (Goudriaan, 1977):

\[
k_\theta = -\ln\left(\frac{\pi/2}{2 \int_0^{\pi/2} \exp(-G(\theta)\Omega(\theta)\text{LAI}/\cos\theta) \sin\theta \cos\theta d\theta}\right) / \text{LAI} \times \Omega \tag{A1}
\]

Clumping index, \( \Omega(\theta) \), was determined as the ratio of \( \ln[G(\theta)] \) to \( \ln[G(\theta)]_\text{hi} \) (Lang & Xiang, 1986; Ryu, Nilson, et al., 2010). Under a clear sky day in summer, paired samples of GF for the same view zenith angles at 5 degree intervals from 15 to 85° were obtained from morning and afternoon data. Then, a different averaging method was applied to GF(\( \theta \)) and \( \Omega(\theta) \) was quantified. To compute \( k_\theta \) in Eq. (A1), LAI was used as the input data. As we did not know LAI a priori, we used a reasonable range of LAI values to obtain the range of \( k_\theta \). For the DBF site, we used the peak LAI range of 2 to 4 for the overstory and 0.5 to 2 for the understory. Corresponding \( k_\theta \) values were 0.75 ± 0.02 (mean ± 1 SD) and 0.86 ± 0.01 for the overstory and understory, respectively. For the ENF site, we used a peak LAI range of 4 to 8 for the overstory canopy, which corresponded to a \( k_\theta \) of 0.76 ± 0.02.

Appendix B. Needle-to-shoot area ratio

To quantify clumping effects at the shoot level for the overstory canopy (\textit{Abies holophylla}) at the ENF site, we estimated the needle-to-shoot area ratio \( y_{\theta\phi} \) in Eq. (2) (Chen et al., 1997). We quantified one half of the total shoot area \( A_s \) using the projected shoot area \( A_{ps} \) taken from 19 different angles in the zenith (\( \theta \)) and azimuth (\( \phi \)) directions (\( \theta = 0°, 30°, 60°, 88°, \phi = 0°, 60°, 120°, 180°, 240°, 300° \)):

\[
A_s = 2 \times \left\{ \frac{2\pi}{2} \int_0^{\pi/2} A_{ps}(\theta, \phi) \cos\theta d\theta d\phi \right\} \left\{ \frac{2\pi}{2} \int_0^{\pi/2} \cos\theta d\theta d\phi \right\} \tag{B1}
\]
Images were analyzed with Photoshop (Photoshop CS6, Adobe, Country). We repeated the same procedure with three different shots. To quantify the hemi-surface area of all needles (\(A_n\)), we detached all the needles from twigs in a shoot and measured the lengths and perimeters of cross sections of the needles. Needle lengths were measured with Vernier calipers (CD-15CX, Mitutoyo, Japan). Photos of the cross section of needles were taken using a digital camera (40 mm of 35 mm equivalent focal length, F/10, DMC-G3, Panasonic, Japan), and perimeters of the cross sections were measured with computer-aided design software (AutoCAD, AutoDesk, Inc, USA). We multiplied mean needle length, mean semi-perimeter of cross section in needles, and number of total needles to determine \(A_n\). Finally, we calculated needle-to-shoot area ratio as the ratio of \(A_n\) to \(A_s\). We determined that the needle-to-shoot area ratio (\(\gamma\)) was 1.97 ± 0.09 (mean ± 95% CI).

References


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