



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 ($R^2 = 0.96$, 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.

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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, Grimmer, Cropley, 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

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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 phenology of a coniferous forest well, although the same technique captured the canopy phenology 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 phenology. One century ago, Salisbury (1916) observed that changing light environments at the forest floor are related to phenology. 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 phenology (Baldocchi, Hutchison, Matt, & McMillen, 1984, 1985; Chason, Baldocchi, & Huston, 1991; Hutchison 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 infrastructure such as rails, motors, cables, masts and radiometers, which hampers continuous observation of multi-layer phenology 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 together, 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 phenology separately and automatically.

Two most widely used variables for monitoring vegetation phenology 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 phenology, their utility for monitoring multi-layer canopy phenology 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, Muraoka, 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 phenology monitoring data are needed to better interpret and evaluate satellite-derived phenology metrics. During a green-up period, satellite-derived phenological 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 phenological 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 phenological metrics (Morissette et al., 2009). Continuous observation of over- and understory canopy phenologies might aid in the interpretation of satellite remote sensing phenology products.

In this study, we report how we used LED-sensors (Ryu, Baldocchi, et al., 2010) to monitor the multi-layer canopy phenology 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 phenological 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 phenology metrics by scaling up *in-situ* phenological records through LED-NDVI and Landsat NDVI. Our goal in this study was to characterize phenological 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 phenological 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: 37.748717N, longitude: 127.148176E, elevation: 260 m, slope: 10–20°). Overstory canopy consists of *Quercus acutissima*, *Quercus serrata*, and *Carpinus laxiflora*. Dominant understory species include *Euonymus oxyphyllus* and *Cornus kousa*. Both overstory and understory species are deciduous. Overstory 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 overstory and understory species are *Abies holophylla* and *Cornus controversa*, respectively. Overstory tree height is 27 m. Overstory 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°.

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