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A comparison of ground-based methods for estimating canopy closure for use in phenology research

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ABSTRACT

Climate change is influencing tree phenology, causing earlier and more prolonged canopy closure in temperate forests. Canopy closure is closely associated with understorey light, so shifts in its timing have wide-reaching consequences for ecological processes in the understorey. Widespread monitoring of forest canopies through time is needed to understand changes in light availability during spring in particular. Canopy openness, derived from hemispherical photography, has frequently been used as a proxy for understorey light. However, hemispherical photography is relatively resource intensive, so we tested a range of inexpensive alternatives for monitoring variability in canopy closure (visual estimation, canopy scope, smartphone photography, smartphone photography with fisheye attachment; and image analysis with specialist hemispherical photography software or with simpler, open access image analysis software). Smartphone photography with an inexpensive fisheye lens attachment proved the most reliable estimator of canopy closure. We found no significant difference in canopy estimations from three widely-owned smartphone models with differing resolutions and fields of view, and no significant effect of camera operator on the results. ImageJ, a free image analysis software, detected canopy variability in a similar way to HemiView specialist hemispherical photography software. We recommend a combination of smartphone photography with fisheye attachment and analysis with ImageJ for identifying changes in the timing of canopy closure (but not for estimating absolute canopy closure). We discuss how large-scale citizen science using this approach could generate meaningful and comparative data on the timings of canopy closure in different forests, year-to-year.

1. Introduction

Climate change is affecting forest ecosystems around the globe, with changes in tree phenology widely documented for temperate forests (Richardson et al., 2013; Roberts et al., 2015; Vitasse et al., 2011). Growing season extensions have been observed for many European tree species, most notably due to canopies coming into leaf earlier (Menzel and Fabian, 1999; Menzel et al., 2006; Thompson and Clark, 2008). The phenology of dominant canopy trees exerts strong influence on the understorey environment, as canopy openness is highly related to available photosynthetically active radiation (PAR) (Brusa and Bunker, 2014; Gonsamo et al., 2013; Promis et al., 2012), influencing microclimate, soil respiration (Giasson et al., 2013; Yuste et al., 2004) and understorey plant dynamics (Van Couwenberghe et al., 2011). Therefore, earlier canopy closure and later senescence is likely to have wide-ranging impacts on the phenology and life processes of understorey plants and wider forest biodiversity. Studies have indicated threats to spring ephemeral herbs that utilise the period before canopy closure for completing their life cycle (Kim et al., 2015). Many tree saplings depend on spring sunlight prior to canopy closure for their growth and survival (Augspurger, 2008). Understorey species that are shade tolerant or those with greater phenological plasticity are likely to gain competitive advantage (De Frenne et al., 2011), and invasive species could become more prevalent (Engelhardt and Anderson, 2011; Willis et al., 2010). As canopy openness is a key determinant of ecological processes in the understorey, effective methods for monitoring intra and inter-annual changes in the timing of canopy closure/openness would be very useful, especially if they allowed data to be collected across a variety of spatial scales, and with plenty of replication.

Canopy phenology has been extensively studied in recent years. Satellite remote sensing has enabled data collection of forest leaf phenology at large spatial scales (Boyd et al., 2011; Wang et al., 2016; White et al., 2009; Wu and Liu, 2013; Zhang et al., 2005). These methods focus on deriving estimates of canopy green-up dates from Normalised Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) data, for the purpose of tracking photosynthetic

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activity to assess forest productivity, gas exchange and phenological feedbacks to the climate system (Richardson et al., 2013). While remote sensing data is useful for identifying large-scale phenological trends, the coarse resolution means that local variations between forest stands are often masked (Fisher et al., 2006; White et al., 2014). Furthermore, loss of temporal resolution due to atmospheric conditions (Cleland et al., 2007; White et al., 2014), and difficulties separating greening of the understorey from canopy greening (Hamunyela et al., 2013), can compromise the use of this data for identifying shifts in canopy closure timing.

A range of ground-based methods have been used to assess canopy structure and understorey light environments at the forest-level. Direct measures of understorey light are highly affected by sky conditions and accurate determination requires continuous measurement over several days (Engelbrecht and Herz, 2001; Gendron et al., 1998). This makes direct measurements inappropriate for phenology studies where the objective is to assess variation through time. As an alternative, hemispherical photography and Plant Canopy Analysers (PCAs) such as the LAI-2200, are commonly used to assess structural attributes of forest canopies (Frazer et al., 1997; Gonsamo et al., 2013; Hale and Edwards, 2002; Rich, 1990). Both instruments incorporate an extreme wide angle view to measure gap fraction – defined as the proportion of unobstructed sky in a given region of the projected image plane (Frazer et al., 1997) – at multiple zenith angles. For estimating understorey light levels, particularly during spring, wide viewing angles are an advantage as sunlight largely penetrates the canopy below the zenith. Using gap fraction measurements, Leaf Area Index (LAI) and canopy openness can be determined.

LAI is the most widely used metric of canopy structure (Jonckheere et al., 2005; Weiss et al., 2004), though it is also one of the most difficult to characterise accurately (Bréda, 2003). LAI is defined as one half the total green leaf area per unit ground surface area (Chen and Black, 1992). Hemispherical photography and PCAs assess the whole canopy as viewed from a single point, using gap fraction inversion principles and radiative transfer theory respectively (Chen et al., 1997; Macfarlane et al., 2007; Woodgate et al., 2015). As such, LAI derived from optical methods actually characterises ‘Plant Area Index’ (as trunks and branches are included as well as leaves), and is highly related to understorey light levels (Bréda, 2003; Jonckheere et al., 2004). However, both methods are costly, particularly PCAs, which in addition to high instrument costs, require simultaneous reference light readings outside the canopy. This is problematic in forests, as a wireless set up or remote data loggers are needed, adding additional resource implications and making the method impractical for large-scale use (Bréda, 2003). Furthermore, both methods for estimating LAI assume that canopy elements are randomly distributed. In reality, a degree of ‘clumping’ occurs both within and between plant canopies (Bréda, 2003; Chen et al., 1997; Ryu et al., 2010; Weiss et al., 2004). The degree of clumping varies depending on forest type and structure, and also shows strong seasonal variation according to the phenological stage (Ryu et al., 2010). Therefore accurate LAI estimation requires determination of a clumping index for a given canopy at a given time of year, and specialist equipment and/or software is required (Chianucci et al., 2015; Ryu et al., 2010).

Digital Cover Photography (DCP) using ordinary digital cameras can also be used to estimate LAI following the method proposed by Macfarlane et al. (2007). This method has a number of advantages as specialist equipment and software are not required, though a number of steps are involved in analysis to calculate effects of foliage clumping (Chianucci et al., 2014; Macfarlane et al., 2007). DCP has been successfully used to track canopy development in phenological studies concerned with photosynthesis and gas exchange (Ryu et al., 2012). However, the restricted viewing angle of DCP cover photography is less appropriate for tracking the progress of canopy closure, where the objective is to assess change in the relative timing of shading in the understorey. Although LAI is highly related to understorey light (particularly where it is based on gap fraction at multiple zenith angles) it is primarily used to quantify ecosphysiological attributes of forest canopies (photosynthetic and transpiration rates) to study climate-biosphere interactions (Bréda, 2003; Chen et al., 1997; Jonckheere et al., 2004; Macfarlane et al., 2007; Woodgate et al., 2015). Where the aim is to track changes in relative canopy closure to determine temporal variability in understorey light, canopy openness is a more appropriate and straightforward metric to use (Brusa and Bunker, 2014).

Canopy openness is the proportion of the entire sky hemisphere that is unobstructed by vegetation when viewed from a single point (Jennings et al., 1999), and is highly correlated with understorey light (Brusa and Bunker, 2014; Gonsamo et al., 2013; Pellikka, 2001; Promis et al., 2012; Roxburgh and Kelly, 1995; Whitmore et al., 1993). Hemispherical photography has been widely used to assess canopy openness, representing the sum of all gap fraction values, weighted according to zenith angle, and multiplied by 100 to give a percent visible sky value (Frazer et al., 1997). The advent of digital cameras and their increasing availability has made hemispherical photography more widely available for forest science (Brusa and Bunker, 2014; Frazer et al., 2001; Hale and Edwards, 2002; Inoue et al., 2004). However, cost and resource implications still preclude many forest managers from using it as a monitoring tool. While hemispherical photography does not require reference light readings to be made, images must be taken under specific weather conditions – on dry, still days, without direct sunlight, normally early or late in the day, or on a day with uniform overcast skies (Rich, 1990). This places considerable constraint on when data can be collected. Once images have been obtained, analysis can be time-consuming and expensive. Though free specialist software programmes now exist that provide comparable results to professional software (Promis et al., 2011), expertise is still required. Overall, the technique is prohibitively expensive, in terms of cost and time, for phenology studies that require high levels of replication.

A variety of cost-effective, rapid assessment alternatives to hemispherical photography have been used to assess canopy openness, including photography without a fisheye lens (Pellikka, 2001), the canopy scope (Brown et al., 2000), and simple visual estimations (Jennings et al., 1999). These methods differ in their view zenith angle; therefore canopy openness in this context is defined as the proportion of unobstructed sky within the total area viewed. While these methods are used to characterise coarse-level variation in canopy openness, their ability to detect fine-scale changes in canopies through time needs to be assessed. Another option has emerged in the last few years with the rise of smartphones that have high resolution cameras. Inexpensive fisheye lens attachments for smartphones have recently become available for less than US$10. Smartphone photography, if reliable, could provide an efficient means of collecting large quantities of data on the timing of canopy closure using citizen science.

The use of citizen science has proven highly successful in other areas of phenological research, including observational studies of plant budburst and leaf-out timing (Collinson and Sparks, 2008; Jeong et al., 2013; Mayer, 2010). The widespread and increasing ownership of smartphones means that many people now carry sophisticated cameras, making them ideal citizen science tools. However, a considerable range of makes and models exist. These vary in their camera specifications (e.g. resolution, focussing capability and angle of view), which could affect canopy openness estimations (Frazer et al., 2001; Inoue et al., 2004; Jennings et al., 1999). Therefore, for this method to be practical for large-scale use, different makes and models of smartphone need to give comparable estimations.

In this study, we compared canopy openness values (% visible sky) from hemispherical photography, with estimates derived from visual estimation techniques and from smartphone photography, with and without the use of a fisheye lens attachment. Data were collected in winter, spring, summer and autumn, at fixed points across four broadleaved woodlands in south-west England, to assess the extent that surrogate methods can estimate variation in canopy openness. We then