Agricultural and Forest Meteorology 246 (2017) 15–21

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Digital photography for tracking the phenology of an evergreen conifer stand

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ARTICLE INFO

Keywords:
Phenology
Hemispherical photography
LinearRatio
RAMI pine stand

ABSTRACT

Gap fraction measurements with digital a hemispherical camera were carried out in 2007–2016 in a Scots pine (*Pinus sylvestris* L.) stand growing on transitional *Sphagnum* bog in Järvselja, Estonia. The measurements were done at the time when (1) the pines had maximum foliage, or (2) after autumn needle fall or before bud burst. Data for gap fraction calculation were extracted from camera raw files. For data recording, the sensor output signal maximum was kept according to the image brightness histogram within the interquartile range of the sensor dynamic range. A linear conversion method (LinearRatio) was used for image processing. The relative needle loss in autumn (20–30%) increased gap fraction by 0.02–0.05 at view zenith angles from 10° to 60° and decreased the mean plant area index from 1.86 to 1.68 after autumn litter fall. The measurement results were in good agreement with a theoretical gap fraction model simulation and with gap fraction estimates made from cover photos. The measurement and data processing protocol is appropriate for long-term monitoring in permanent sample plots.

1. Introduction

Measurements of transmitted radiation through the plant canopy can be linked back to canopy properties (Reifsnyder et al., 19711972; Baldocchi et al., 1984; Kuusk et al., 2002; Schwalbe et al., 2009) and are useful for interpreting plant phenology observations from satellites (Zhang et al., 2003; Rautiainen et al., 2012; Lukasová et al., 2014) and photosynthesis (Tooming, 1977). Atkins et al. (1937) measured irradiance I_b below a forest canopy and irradiance I_a in a nearby opening at the same time to describe the forest understorey light climate and defined daylight factor $t = I_b/I_a$. Hemispherical photos have been used to interpret radiation measurements (Evans and Coombe, 1959) and for characterization of plant canopies and estimating the daylight factor (Anderson, 1964). Quantum sensors are used in plant canopy analyzers to measure incident radiation in the blue spectral region where foliage is almost opaque and non-reflecting for estimation of canopy gap fraction $t(\theta) = I_{b,\theta}/I_{a,\theta}$ at view zenith angle θ (Welles and Norman, 1991). A hemispherical photograph provides a permanent record of canopy structure compared to non-imaging devices (Rich, 1990; Jonckheere et al., 2004) and the images can be used for long-term monitoring of plant canopies.

For image acquisition with photographic cameras, appropriate exposure has to be determined. Welles (1990) suggests that in the case of sufficient contrast between sky and plant elements in hemispherical images the image processing could be automated. A wide range of relative exposure values (EV) (-5 to $+3$) has been recommended to achieve the sufficient contrast (Chen et al., 1991; van Gardingen et al., 1999; Macfarlane et al., 2000; Zhang et al., 2005).

Image construction for human vision from digital CCD or CMOS sensor readings in consumer digital cameras involves colour information interpolation, white balance adjustment, gamma correction and histogram stretching to create 8-bit ready-for-viewing instant images (Lebourgeois et al., 2008). Inoue et al. (2004) found that there was a clear influence of the used file type (JPEG, TIFF) and camera properties on canopy openness estimates. Leblanc et al. (2005) used raw data (unprocessed readings from sensor) and Leblanc (2008) recommended to operate cameras in manual mode and to check image brightness histograms directly after taking the image to avoid overexposure. Semi-automatic image capture modes can result in apparent local over-exposures (blooming effects) in images (Leblanc et al., 2005; Pueschel et al., 2012; Chianucci et al., 2014), however, Woodgate et al. (2015) found a good agreement between canopy indices from LAI-2000 and instant image-based estimates when the images were taken with fixed aperture and automatic shutter speed in A-mode with -2 EV

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http://dx.doi.org/10.1016/j.agrformet.2017.05.021
Received 11 June 2016; Received in revised form 6 March 2017; Accepted 29 May 2017

constraint.

Canopy gap fraction $t(\theta)$ can be estimated from hemispherical images by superimposing sampling grids over the photos (Evans and Coombe, 1959; Anderson, 1964). For digital images, separation of sky and canopy has been carried out by setting a certain threshold according to pixel brightness (Jonckheere et al., 2005; Glatthorn and Beckschäfer, 2014). Thresholding is prone to operator subjectivity and selection of algorithms if the images contain mixed pixels (Jonckheere et al., 2005). Song et al. (2014) proposed exposure corresponding (EC) thresholding for hemispherical images which, however, requires a reference camera in an open area for estimation of the optimal exposure. Two thresholds per image can be used to solve the so-called mixed pixel problem (Leblanc et al., 2005; Macfarlane et al., 2014), but thresholding applies better to cover photos which have substantially fewer mixed pixels than hemispherical photos (Macfarlane et al., 2007a). Local thresholds for image segments must be used to account for variations in the grey value of unobscured pixels caused by the differences in illumination and vignetting (Wagner, 2001). Thresholding or pixel classification approach is the main method in the special software for the processing of hemispherical images e.g. GLA (Frazer et al., 1999), CIMES-FISHEYE (Gonsamo et al., 2011), CAN-EYE (Weiss, 2013), Hemisfer (Schleppi et al., 2007) and DHP (Leblanc et al., 2005). Cescatti (2007) showed that two consumer grade digital cameras can be operated as a pair of plant canopy analysers and defined a thresholding free image processing method called LinearRatio. The LinearRatio is based on camera sensor raw readings which are linearly dependent on incident radiation (Zhang et al., 2005; Lebourgeois et al., 2008). It is possible to use the LinerRatio method with a single calibrated camera, since the above-canopy reference image can be constructed from non-obscured sky pixel samples from canopy gaps (Lang et al., 2010, 2013).

The validation of data capturing and image processing methods for estimation of plant canopy indices can be based on artificial targets or model canopies (Welles and Norman, 1991; Song et al., 2014; Macfarlane et al., 2014) or simulated images (Leblanc and Fournier, 2014). Validation data can be obtained also by litter fall collection (Chason et al., 1991; Stenberg et al., 1994; Dufrêne and Bréda, 1995; Ryu et al., 2010), by using allometric regression models (Chen and Black, 1991; Smith et al., 1991), by destructive sampling (van Gardingen et al., 1999) or by destructive modification (Smolander and Stenberg, 1996; Stenberg et al., 2003; Macfarlane et al., 2007b) of the real canopies. However, allometric regression foliage mass models may yield biased estimates (Gower et al., 1999; Lang et al., 2007) and the models are insensitive to phenophases. The phenological events causing small changes in the canopy structure can be used for non-destructive assessment of the performance of the indirect optical methods (Stenberg et al., 1994; Deblonde et al., 1994).

In this study we seek to evaluate the suitability of digital photography for long-term tracking of phenology in an evergreen coniferous stand. Specifically, we use a series of digital hemispherical photographs and multi-date cover photographs from a pure Scots pine (*Pinus sylvestris* L.) stand located in Järvselja, Estonia, and described by Kuusk et al. (2013), for gap fraction measurements. The hemispherical photos were taken since the year 2007 at fixed places in two phenological phases 1) when trees in the forest have the maximum amount of needles and 2) after the autumn needle fall. The hemispherical photographs were processed by using the LinearRatio method (Cescatti, 2007) adopted for a single camera (Lang et al., 2010) and cover images were processed by an automatic thresholding algorithm. Forest structure data from the test site and a theoretical gap fraction model (Nilson, 1999; Nilson and Kuusk, 2004) were used to interpret the changes in the measured gap fraction.

2. Material and methods

2.1. Test site

The test site (58°18′41″ N 27°17′49″ E) is located in Järvselja, Estonia, in Kanajalasoo transitional bog in a pure Scots pine forest. The pine stand served as a test site in the fourth phase of the RAdiative transfer Model Intercomparison exercise (RAMI) (Widlowski et al., 2015), therefore it will further be referred to in the text as the “RAMI pine stand”.

The RAMI pine stand was 124 years old in 2007. Regardless of the long-lasting drainage with ditches around the bog since 1922 (Krigul, 1962), the soil consists of a 1-m thick *Sphagnum* moss peat layer over the nutrient-poor fine-texture sand, which limits the growth of trees. The stand density was 1115 trees per hectare and the mean height of the trees was 15.9 m. A subset of sample trees was remeasured in 2016 and the stand mean height and height to live crown base have increased by 1.1 m since 2007. During past decades no substantial stand structure altering disturbances have occurred. Forests in Kanajalasoo bog have naturally developed (Sisask, 2013) and we have not found stumps that would indicate thinning cuttings. There are 9 marked sample points L1–L9 positioned in a rectangular grid at a 30 m distance from each other (Kuusk et al., 2013). There is almost no forest understorey vegetation taller than 0.5 m except birch tree with a height of about 3 m visible from L1. No measurements of needle phenology were carried out in the RAMI pine stand. The litterfall estimate for relative reference was obtained from a near-by pine stand where the annual litter flux was measured. This pine stand grows on a drained transitional (mesotrophic) bog according to Lõhmus (2004). The stand is younger (55 years old in 2014), stand density is 940 trees per hectare and the mean tree height and stem diameter are 17.0 m and 18.4 cm, respectively. Needle litter was sampled with six randomly placed litter traps (collecting area 0.533 m^2 each) according to the intensity of litter fall. The total annual flux of needle litter was 2.4 $Mg\ ha^{-1}\ year^{-1}$ and the estimated maximum foliage mass in summer was 4.05 $Mg\ ha^{-1}$. The maximum annual litter fall (roughly 50%) occurred in autumn from September to November. During other months the needle litter fall was quite modest. The intensive needle fall in autumn is in accordance with literature data, however, Kollist (1967) pointed out also a possible second period of intensive needle litter fall in pine stands in late spring or early summer. Drainage and site fertility are essential factors which affect the amount of the annual litter flux and needle longevity (Kollist, 1967; Niinemets and Lukjanova, 2003). The soil in the RAMI pine stand is less fertile compared to the litter collection stand and on the mass basis the relative autumn litter fall of needles in the RAMI pine stand can be estimated as 20–30% compared to the maximum needle mass in summer.

2.2. Hemispherical photographs

All the hemispherical photos (DHP) were taken with the calibrated Canon EOS 5D camera and Sigma 8mm 1:3.5 EX DG lens described by Lang et al. (2010). The camera was fixed to a tripod using a ball head mount which provided a convenient single rotating knob for fixing the camera position. The camera viewfinder was covered with a piece of opaque tape to prevent unwanted light entering and illuminating pixels near the sensor centre. A two-axis bubble level was attached to the camera flash socket. Light metering was set to central point mode. Exposure compensation of -0.5 EV was always used. The optics was focused to infinity and autofocus was switched off. If no assumptions could be made about suitable settings for the optimal exposure, then before each series the camera was pointed upward and initiated by setting the exposure mode to aperture priority, aperture to $f/8.0$ and ISO to 100. Then an approximate shutter speed was estimated from the camera display without taking a real photo. The camera was then switched to manual mode and exposure settings were selected so that