Agricultural and Forest Meteorology 218–219 (2016) 204–208

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Short communication

Measuring leaf angle distribution in broadleaf canopies using UAVs

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ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form 1 December 2015
Accepted 16 December 2015

Keywords:
Leaf inclination angle
Digital photography
Unmanned aerial vehicle

ABSTRACT

Leaf angle distribution (LAD) is an important parameter affecting the biophysical interaction of sunlight and forest canopies. But, difficulty in measuring LAD has limited exploration of its species-specific phenology and variation across environmental gradients. To evaluate whether digital photographs from unpersoned aerial vehicles (UAVs) could be used to measure LAD, we directly compared UAV-based measurements of leaf angle against those made from conventional leveled digital photographs taken from towers, ladders, buildings, or poles. We used two different UAV and camera systems, and found that both systems provided statistically similar results to the conventional measurements of LAD on five common broadleaf tree species of Europe and North America. In addition to overcoming challenges of UAV airspace regulation and piloting UAVs within complex forest canopies, we recommend potential users of this method should identify, minimize, and correct for any image distortion effects created by their UAV and camera system. With these considerations in mind, our results indicate that UAVs can be used to measure LAD in virtually any broadleaf forest environment, which opens the new possibility for obtaining accurate, species-specific information on the variability of LAD through time and along broad environmental gradients.

1. Introduction

The leaf angle distribution (LAD) is a key parameter in models useful for understanding the forest canopy processes of photosynthesis, evapotranspiration, radiation transmission, and spectral reflectance (Warren Wilson, 1959; Lemeur and Blad, 1974; Myneni et al., 1989; Asner, 1998). Yet, despite the strong sensitivity of many of these models to variability in LAD, the difficulty in measuring LAD often causes it to be one of the most poorly constrained model parameters (see e.g. Ollinger, 2011). Improving methodologies for measuring LAD is thus essential for advancing ecological understanding of its role within the biophysical interaction of sunlight and the forest canopy.

Recently, Ryu et al. (2010) introduced a robust and affordable method that allows reproducible measurements of leaf inclination angles based on digital photography. The method has shown potential to overcome many of the shortcomings of other LAD measurement techniques (Pisek et al., 2011; Zou et al., 2014). However, since only a small fraction of the ecological variability in forests can be measured from towers, poles, ladders, and other conventional platforms, the remaining challenge is how to collect these photographic leaf angle measurements for the remaining tall, or remote forest canopies.

Recent technological innovations have led to an upsurge in the availability of unpersoned aerial vehicles (UAVs) – aircraft remotely operated from the ground – and there are now many lightweight UAVs available at reasonable costs. Specifically for small, multi-rotor UAVs, recent innovations in power systems, self-leveling gimbal designs, stabilized flight, and lightweight cameras now allow for the study of individual organisms and their spatiotemporal dynamics at close range (Anderson and Gaston, 2013). Crucially for forest canopy research, these small multi-rotor UAVs could serve as portable canopy research towers; they are potentially small and nimble enough to pilot throughout a complex three-dimensional forest canopy environment, all while taking high-resolution, and level photographs of individual tree crowns.

In this short communication, we seek to test the potential of small multi-rotor UAVs to serve as a platform for measuring leaf angles using the leveled digital photography method. Specifically, we use two different UAV and camera systems to measure leaf angles, as well as estimate the LAD and G-functions of five broadleaf tree species common to Europe and North America. After discussing some important considerations for minimizing errors caused by

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http://dx.doi.org/10.1016/j.agrformet.2015.12.058
0168-1923/

factors such as the image distortion present on many UAV and camera systems, we directly validate our UAV-based LAD measurements against measurements made using conventional leveled digital photography platforms (e.g. towers, ladders, poles).

2. Methods and materials

2.1. Study sites and tree species

We made leaf angle measurements on broadleaf tree species at two sites: Tartu Observatory, Tõravere, Estonia (58.27°N; 26.46°E; 70 m elevation), and the Olson Observation Tower of the Monongahela National Forest, located in the Central Appalachian Mountains of West Virginia, USA (39.11°N; 79.60°W; 1139 m elevation). At Tõravere, we measured leaf angles of gray alder (*Alnus incana*; mean tree height (*H*) = 16 m) growing in a plantation, as well as silver birch (*Betula pendula* Roth; *H* = 23 m) and horse-chestnut (*Aesculus hippocastanum*; *H* = 20 m) trees growing in unmanaged forest stands. At the Olson tower site, we measured red maple (*Acer rubrum*; *H* = 20 m) and red oak (*Quercus rubra; H* = 25 m) trees within the unmanaged forest areas immediately surrounding the observation tower. We collected all measurements at Tõravere on 30 June 2015 and at Olson tower on 13 August 2015.

2.2. Leveled digital photography measurements

For all measurements of leaf angle, we followed the leveled digital camera approach originally described by Ryu et al. (2010). Taking care to collect the control and UAV-based images during calm conditions to prevent wind effects on leaves (Tadrist et al., 2014), we took level photographs at several heights on the crowns of at least three trees of each study species. For each photo, we set the camera zoom or proximity of the UAV to the tree so that individual leaves could be clearly resolved and several full branches were visible within the image extent. To capture this image extent, the UAV was necessarily positioned far enough from the tree crown so that any wind disturbance from the small rotors would have no effect on leaf angle measurements. After capturing images in the field, we inspected the photographs for the presence of leaves oriented approximately perpendicular to the viewing direction of the camera. Finally, we used the angle measurement tool of an image processing software (e.g. Adobe Photoshop; www.adobe.com, or ImageJ; http://rsbweb.nih.gov/ij/) to measure the leaf angle between the zenith and leaf normal. Generally, species do not tend to exhibit any characteristic leaf azimuth orientation (Falster and Westoby, 2003; but see also e.g. Kimes, 1984), so we assumed a uniform distribution of leaf azimuth orientations.

For the UAV-based measurements at Tõravere, we collected the digital photos by manually piloting a DJI Phantom 3 Professional Quadcopter (Shenzhen, Guangdong province, China) with an integrated gimbal-mounted 4 K camera. The camera featured a 94° angle-of-view lens with an f/2.8 aperture comprised of 9 elements, including an aspherical element. The camera gimbal uses information from the UAV's onboard accelerometer in an attempt to keep the camera level with the horizon, even as the aircraft banks. After downloading the images in the non-proprietary DNG RAW format, we applied the DJI Lens Correction filter in Adobe Photoshop to remove the partial "fish-eye" lens distortion in the original images. Prior to analysis for leaf angle, we exported the distortion-corrected images to a JPEG format.

For the UAV-based measurements at the Olson Observation Tower site, we manually piloted a 3DRobotics Y6 hexacopter (3DR, Berkeley, California) outfitted with a gimbal-mounted Canon Powershot S110 compact camera. Similar to the UAV used at Tõravere, this gimbal also communicates with the UAV's onboard accelerometer in attempt to maintain the camera level with the horizon. We used a Canon Hacker Development Kit (CHDK) script to alter the camera firmware so that it would collect a full resolution, 12 MP JPEG image every 4 s during the UAV flight. Images from the Canon Powershot S110 camera had negligible distortion, so we did not perform any distortion correction prior to leaf angle analysis.

For purposes of direct and image-to-image, comparison with the UAV-based measurements, we used poles, ladders, windows of nearby tall buildings, and observational towers to collect a control series of leveled digital images at the same heights, and at the same positions in the tree crowns as the photos collected from the UAVs. In Tõravere, we used a leveled Canon PowerShot A610 compact camera with a 5 MP resolution and 4.5–80 mm telephoto lens. At the Olson Observation Tower site, we used a leveled Canon EOS Rebel T3i Digital SLR camera with an 18 MP resolution and 18–200 mm telephoto lens.

2.3. LAD and G-function

The probability of the transmission of a beam of light through the canopy (***P***) with a completely random dispersion of the infinitesimal size of the leaves has been commonly described by a 'Beer-Lambert law' function (Monsi and Saeki, 1953, 2005; Ross and Nilson, 1965):

$$P\left(\theta\right) = \exp\left[\frac{-G\left(\theta\right)\mathrm{L}}{\cos\theta}\right] \tag{1}$$

where L denotes the downward cumulative leaf area index, θ is the view zenith angle, and ***G*** is the 'G-function' which quantifies the projection coefficient of unit foliage area on a plane perpendicular to the view direction (Ross, 1981). The quantification of G-function requires knowledge of the leaf angle distribution.

For describing the LAD, we assumed a uniform distribution of leaf azimuth angles as well as an independence of leaf angle from leaf size. We fit the measured leaf angles with the two-parameter Beta distribution (Goel and Strebel, 1984), which has been shown to be the best suited for describing the probability density of θ_L (Goel and Strebel, 1984; Wang et al., 2007):

$$f\left(t\right) = \frac{1}{B\left(\mu,\nu\right)}\left(1-t\right)^{\mu-1}t^{\nu-1} \tag{2}$$

where $t = 2\theta_L/\pi$. The Beta-distribution function $B(\mu, \nu)$ is defined as

$$B(\mu,\nu) = \int_0^1 (1-x)^{\mu-1}x^{\nu-1}\mathrm{d}x = \frac{\Gamma(\mu)\Gamma(\upsilon)}{\Gamma(\mu+\nu)} \tag{3}$$

where Γ is the Gamma function and μ and ν are two parameters calculated as

$$\mu = \left(1-\bar{t}\right)\left(\frac{\sigma_0^2}{\sigma_t^2}-1\right) \tag{4}$$

$$\nu = \bar{t}\left(\frac{\sigma_0^2}{\sigma_t^2}-1\right) \tag{5}$$

where σ_0^2 is the maximum standard deviation with expected mean $\bar{t}$ ($\sigma_0^2 = \bar{t}(1-\bar{t})$) and σ_t^2 is variance of t (Wang et al., 2007).

Assuming an azimuthally symmetric canopy, we can write

$$G\left(\theta\right) = \int_0^{\pi/2} A\left(\theta,\theta_L\right) f\left(\theta_L\right)\mathrm{d}\theta_L \tag{6}$$