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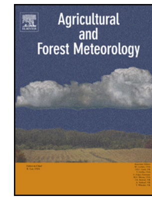

Correction for light scattering combined with sub-pixel classification improves estimation of gap fraction from digital cover photography

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ABSTRACT

Digital cover photography (DCP) has emerged as an indirect method to measure gap fraction of vegetation canopies. However, as with other photographic methods, determining camera relative exposure value (REV) and threshold for pixel classification, cause substantial uncertainties in gap fraction estimates. Here we propose a new method to improve the measurement of gap fraction under various solar zenith angles (SZAs), sky conditions, and canopy structures. This method computes gap fractions of ambiguous vegetation or sky pixels using an unsaturated raw image from DCP and a reconstructed sky image from the raw image, thus taking full advantage of the potential of raw image processing. This is combined with pre-classification of pixels that are unambiguously canopy and sky to greatly reduce light scattering effects that are likely to be present within the canopy. To test the sensitivity of the new method, we acquired images at one-hour intervals between 20 and 85° of SZAs under closed, half-closed, and open canopies with REV settings from 0 to −5. The new method showed little variation in gap fractions across the diverse SZAs in closed, half-closed, and open canopies. A perforated panel experiment, which was used to test the accuracy of the estimated gap fractions, confirmed that the new method accurately estimated gap fractions across a range of hole size, gap fractions and SZAs. We conclude that the new method opens new opportunities to estimate gap fractions accurately regardless of solar positions from open to closed canopies, and is a significant advance for accurate and precise monitoring of canopy cover and leaf area index (LAI), and for calibrating and evaluating satellite remote sensing LAI products.

1. Introduction

Digital cover photography (DCP) is an emerging indirect method to quantify canopy cover and leaf area index (Ryu et al., 2010, 2012, 2014; Macfarlane, 2011; Chianucci and Cutini, 2013; Kimm and Ryu, 2015; Poblete-Echeverría et al., 2015). DCP uses a narrow field of view (FOV: 0–30°), which provides higher image resolution than digital hemispherical photography (FOV: 0–90°) (Pekin and Macfarlane, 2009). DCP-derived gap fraction, the proportion of sky that is unobstructed by canopy in an particular viewing direction (Welles and Cohen, 1996) and leaf area index (LAI) have performed at least as well as other indirect methods in Eucalyptus forest (Macfarlane et al., 2007b), open woodland savanna ecosystem (Ryu et al., 2010; Piayda et al., 2015), and deciduous broadleaf forest (Ryu et al., 2014; Song and Ryu, 2015). However, estimation of the gap fraction of vegetation canopies is sensitive to many factors including solar zenith angles (SZAs), sky heterogeneity, and camera exposure settings (Jonckheere et al., 2005). Many protocols to measure gap fractions using a digital camera require capturing images under restrictive conditions (e.g., overcast sky, clear sky, SZAs >85) (Breda, 2003; Leblanc et al., 2005; Lang et al., 2010; Macfarlane, 2011; Chianucci et al., 2014; Ryu et al., 2014), and inconsistent protocols for determining the camera relative exposure value (REV) setting and thresholds for classifying pixels into sky and vegetation hamper the comparability of studies (Beckschäfer et al., 2013).

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To achieve accurate estimates of gap fractions under various sky conditions and vegetation structures, it is imperative to establish a standard protocol for camera REV settings, image processing and analysis.

The camera REV setting is determined by the combination of the camera's shutter speed and *f*-number, and is an important factor influencing the estimation of canopy gap fraction (Chen et al., 1991; Zhang et al., 2005). In over-exposed images (large REV), digital numbers (DNs) of sky pixels can be saturated and the boundaries between the sky and canopy can be overexposed, which leads to overestimated gap fraction. On the other hand, in under-exposed images (small negative REV), DNs of canopy pixels are saturated (DN = 0) and DNs of small gaps may be too similar to canopy pixels to be correctly classified (Rich, 1990; Schwalbe et al., 2006; Beckschäfer et al., 2013). As a general rule, to obtain a good contrast between canopy and sky pixels, the REV should be decreased as the canopy density increases (Chen et al., 1991; Macfarlane et al., 2000), but this may be insufficient on its own to allow correct classification of all pixels in an image, especially under conditions of varying SZA and heterogeneous sky conditions.

Raw digital image acquisition has clear benefits in quantifying canopy structures (Cescatti, 2007; Lang et al., 2010; Macfarlane et al., 2014) over the Joint Photographic Experts Group (JPEG) image, a standard of file formats and lossy compression technique for color images (Wallace, 1991). Raw DNs collected through the charge-coupled device (CCD) or the complementary metal oxide semiconductor (CMOS) sensor have a linear response to light intensity (Mullikin et al., 1994; Cescatti, 2007; Lang et al., 2010). In contrast, DNs in JPEG format have a non-linear relationship to light intensity that results from the application of automatic gamma corrections, as well as other in-camera processing (Cescatti, 2007). The raw format stores original information in higher bit-depth (10–32 bit) than the JPEG format (8-bit), which distorts the original DNs and reduces the original information content through a lossy compression algorithm (Wallace, 1991; Jonckheere et al., 2005; Verhoeven, 2010; Macfarlane et al., 2014).

Raw image acquisition and processing methods to quantify gap fraction have emerged recently. Lang et al. (2010) described a method involving the reconstruction of a sky image from a single hemispherical raw image taken from the forest floor by combining interpolation with a sky radiance model. The gap fraction of each pixel was computed as the ratio of the mean of DNs in the canopy image to the mean of DNs in the reconstructed sky image, which Cescatti (2007) termed 'linear conversion' based on the linear light response of the camera's light sensor. Unfortunately, the sky image reconstruction method required manual detection of sky pixels, which limits its application to large numbers of images. The 'linear conversion' method was not tested for different REV settings, and will likely be sensitive to light scattering effects by leaves (Kobayashi et al., 2013). For example, the DNs of canopy pixels in digital images are generally greater than zero (black) owing to a combination of lighting conditions and scattering effects, thus taking the ratio of canopy pixel DNs seems likely to overestimate the gap fraction. Although complex methods have been proposed to correct for light scattering in indirect estimates of gap fraction and LAI (Kobayashi et al., 2013), in this study we test a simple method of correcting for scattering (and the fact that leaves are not completely black) when applying the 'linear conversion' method by simply identifying pixels that are 'unambiguously' canopy (i.e. not sky and not 'mixed' pixels) and assigning these pixels a gap fraction of zero.

In a later study, Macfarlane et al. (2014) recommended acquiring raw images with one stop of under-exposure (REV = −1), applying a contrast stretch to the blue channel of the red-green-blue combined color digital image, and saving as JPEG format for image analysis. To quantify the gap fraction in the blue channel, a binary pixel classification was used to classify pixels as canopy or sky. The procedure used by Macfarlane et al. (2014) did not fully utilize the raw image information because it only used the raw data as a preprocessing step to reduce sensitivity of results from JPEG images to photographic exposure. In that study it was also observed that the gap fraction in images with small gaps was underestimated compared to images with large gaps despite adjusting for photographic exposure. We hypothesize that applying the 'linear conversion' method to small gaps will reduce the bias in estimated gap fraction that is caused by gap size. It is also unclear whether a small negative REV setting (REV = −1) is valid for a range of canopy structures and sky conditions.

We propose a protocol for image acquisition and processing that combines the strengths of previous approaches and fully exploits the potential of raw digital images. We tested the method across various SZAs, REV settings and gap fractions, under both forest canopies and in a controlled experiment with perforated panels. We compared the new method to three previous methods (an adaptation of Lang et al. (2010); Macfarlane (2011); Macfarlane et al. (2014)) to evaluate whether this new method can out-perform those methods. We hypothesize that combining:

- acquisition of unsaturated raw images
- raw image processing to obtain DNs that are linearly related to light intensity
- classification of unambiguous regions of canopy and sky
- automatic reconstruction of a sky image
- the 'linear conversion' method for sub-pixel gap fraction estimation of mixed pixels

will yield a robust method that largely eliminates biases resulting from photographic exposure, within canopy light scattering and sky heterogeneity.

2. Methods and materials

2.1. Method 1 (sub-pixel raw with scattering correction)

Our proposed protocol for image acquisition and processing, which we henceforth refer to as 'Method 1' (Fig. 1), involves the following steps:

a) acquire an unsaturated raw image to ensure all DNs in the image respond linearly to light intensity.
b) process the raw image by (1) extracting the blue channel, (2) analyzing the histogram to detect unambiguous sky and vegetation pixels, (3) reconstructing a sky image from the unambiguous sky pixels and (4) removing scattering effects in vegetation by forcing the DN of the unambiguous vegetation pixels to zero.
c) compute the sub-pixel gap fraction of the ambiguous pixels (i.e. the mixed pixels) as the ratio of mean in DNs of the scattering corrected canopy image and the mean in DNs of the reconstructed sky image.

A detailed explanation of each step of the method follows.

2.1.1. Acquisition of raw image

The key objective of raw image acquisition is to obtain unsaturated DNs that have a linear response to light intensity (Beckschäfer et al., 2013). Our protocol to achieve this is to capture image under the canopy with a REV of 0 in aperture priority mode then check the histogram in camera display mode to ensure DNs of the blue channel are not saturated. We reduced the REV by adjusting the *f*-number until there was no evidence of saturation. The first unsaturated image was chosen the best-exposed image as it covers wider