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Short communication

Estimation of leaf area index in understory deciduous trees using digital photography

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ABSTRACT

Fast and accurate estimates of understory leaf area are essential to a wide range of ecological applications. Indirect methods have mainly been used to estimate leaf area of overstory but their application in understory remains largely unexplored. In this study we described a combination of digital photographic methods to obtain rapid, reliable and non-destructive estimate of leaf area index of understory deciduous trees. Nadir photography was used to estimate foliage cover, vertical gap fraction and foliage clumping index. Leveled photography was used to characterize the leaf angle distribution of the examined tree species. Leaf area index estimates obtained combining the two photographic methods were compared with direct measurements obtained from harvesting (L).

We applied these methods in *Quercus cerris*, *Carpinus betulus* and *Fagus sylvatica* stands. Foliage cover estimates derived from two nadir image classification methods were significantly correlated with leaf area index measurements obtained from harvesting. The leveled digital photographic method, previously tested in tall trees and field crops, provided reliable leaf angle measurements in understory tree species. Digital photography provided good indirect estimates of L. We conclude that digital photography is suitable for routine estimate and monitoring of understory leaf area, on account of its fast and cost-effective procedure.

1. Introduction

Accurate estimates of leaf area index (L) are essential to the ecological characterization of forest ecosystems (Chen et al., 1997) and for modeling stand structure and dynamics (Xue et al., 2011). Because direct measurements of L in forests are destructive, time-consuming and often impractical, indirect optical methods have been widely used to indirectly estimate L from measurements of radiation transmittance through the canopy (for a review, see Bréda, 2003; Jonckheere et al., 2004; Welles and Norman, 1991). Beer–Lambert's law has often been used to model canopy transmittance (Eq. (1), based on Nilson, 1971):

$$P(\theta) = \exp\left(\frac{-G(\theta) \times \Omega(\theta) \times L_t}{\cos\theta}\right) \quad (1)$$

where $P(\theta)$ is the canopy gap fraction, $G(\theta)$ is the foliage projection coefficient and $\Omega(\theta)$ is the foliage clumping index at zenith angle θ. L_t is the plant area index, including foliar and woody materials. Over the last few decades, several comparisons have been made between direct and indirect methods to estimate the overstory leaf area index in forest ecosystems, as demonstrated in the previously cited reviews. However, very few attempts have been made to estimate the leaf area index of forest understory. Some studies showed that the understory leaf area may exceed that of the overstory (Law et al., 2001; Macfarlane et al., 2010). Accurate estimates of the understory leaf area index are also required for processed-based canopy photosynthesis models (Beaudet et al., 2002; Jolly et al., 2004), for designing silvicultural systems aimed at promoting natural tree regeneration (Caccia and Ballaré, 1998) and for understanding energy and mass exchange processes (Xue et al., 2011). As a consequence, rapid, non-destructive and reliable methods are strongly needed to estimate the understory leaf area index.

Thanks to recent technological development, digital cameras with high spatial and radiometric resolutions are becoming increasingly affordable and promote the use of digital photographic methods to indirectly estimate canopy structural variables such as gap fraction, foliage cover, leaf angle distribution and leaf area index. In addition, the digital image format is well suited to process photographs taken from above the canopy looking downward. For example, the use of vegetation indices has long been explored in crops and weed plants for indirectly estimating L from

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downward-looking cameras (e.g., Liu et al., 2013; Meyer and Neto, 2008). Basically, vegetation indices involve the transformation of the digital number (DN) of image pixels from each channel to generate features that are able to separate green vegetation (foreground) from non-vegetation elements (background). The use of vegetation indices derived from downward-looking photography has rarely been explored in forest ecosystems (e.g., Graham et al., 2009). Recently, Macfarlane and Ogden (2012) tested nadir photography in forest stands and proposed robust and affordable image classification methods to estimate the understory foliage cover (i.e., the portion of the ground area covered by the vertical projection of the foliage; Walker and Tunstall, 1981). Unfortunately, the authors did not test the accuracy of their photographic methods to estimate L because they had no estimates of the foliage projection coefficient or foliage clumping available to invert leaf area from the foliage cover at the time. In addition, they had no direct measurements available to verify the performance of their method. This calls for a validation of their method using direct reference measurements.

To infer leaf area from foliage cover f_f and its complement, vertical gap fraction $P(0)$, information of the foliage leaf angle distribution $f(\theta_L)$, which is related to the foliage projection coefficient $G(\theta)$, is required. These estimates can be obtained from digital photography using a leveled camera approach, a method recently proposed by Ryu et al. (2010) that has also been validated with direct leaf angle measurements in tall trees by Pisek et al. (2011). The method is potentially suitable for estimating the leaf angle distribution in understory owing to the accessible height of leaves in short canopies. For example, Zou et al. (2014) tested and validated this method in field crops.

Another variable needed for the indirect estimation of L is foliage clumping; by knowing the foliage cover, the vertical clumping index $\Omega(0)$ can be estimated from the vertical gap fraction using theoretical gap fraction formulas.

In this paper, we tested whether digital photography can be used to estimate the leaf area index in understory deciduous trees. Different photographic methods were combined for this purpose. Nadir photography was used to estimate foliage cover and its complementary vertical gap fraction. Leveled digital photographs were used for estimating leaf angle and the foliage projection coefficient $G(0)$. Finally, we estimated the foliage clumping index $\Omega(0)$ from a gap size distribution approach (Chen and Cihlar, 1995; Leblanc, 2002). Leaf area index derived from digital photography was compared with destructive L measurements obtained from harvesting.

2. Materials and methods

2.1. Study site and experimental design

The study was performed in May 2014 at the Forestry Research Centre, Arezzo, Italy (43.48°N; 11.88°E), in understory plots established within a 0.25 ha, 30-year old, 15-m tall Turkey oak (*Quercus cerris* L.) forest. Three deciduous forest understory species were examined: hornbeam (*Carpinus betulus* L.), Turkey oak and beech (*Fagus sylvatica* L.). For each species, a rectangular 60 × 40 cm understory plot was established in which 40 three-year old saplings that were about 0.5 m tall were planted with regular spacing. The plot size and the field of view of nadir photographs were chosen to make direct harvesting measurements feasible. Because our study focused on pure methodological differences, we did not apply a probabilistic sampling scheme as it would be recommended for e.g., estimating understory leaf area at site level.

Nadir and leveled photographs were first acquired for each plot (method described below); subsequently, four saplings were removed nine times until four saplings were retained in each plot to sample a realistic range of foliage cover in natural forest understory. Nadir photographs were acquired after each harvest. All saplings were then removed for direct measurements of L and biomass.

2.2. Direct measurements of L from harvesting

Direct measurements of leaf area (L) were obtained with the harvesting method. Each sapling was removed and completely defoliated after each image collection session. The leaf area of all leaves was immediately measured after removal using the Li-COR 3000 area meter (Li-COR, Lincoln, NE, USA); L values were then calculated prior to any harvesting and after each removal by dividing the measured leaf area to the actual plot area.

2.3. Nadir photography

All nadir images were collected with a Nikon D90 DSLR camera equipped with AF Nikkor 50 mm f/1.8D lens (Sendai Nikon Corp., Otawara, Tochigi, Japan). The aperture was set to F 8.0, automatic exposure, ISO 400, automatic white balance, maximum resolution and FINE quality JPEG. These settings provided a zenith angle range of approximately 0–15°, which is very similar to that of the cover photography method, an upward-looking photographic method previously tested in forest overstory (Chianucci and Cutini, 2013; Macfarlane et al., 2007; Ryu et al., 2010). The camera was attached to the top of an extendable 2–10 m pole via an angled steel bracket such that the camera would point downward when the pole was held at arm's length with the base of the pole between the operator's feet. Depending on the pole's extension, images were taken from a height of 3–4 m above the ground. A bubble level at breast height ensured the camera lens was vertically oriented during the image acquisition. The shutter was operated by an infrared remote control with a 2-second delay.

We captured photographs close to sunrise under uniform and calm conditions to prevent wind effects on the leaves. The images were then cropped to fit the actual plot's extent before image classification.

Foliage cover (f_f) and its complementary vertical gap fraction were estimated using two classification methods developed by Macfarlane and Ogden (2012), namely, "LAB2" and Rosin's (2001) corner detection method. The authors previously observed that LAB2 was the best classification method for nadir images of understory with cover > 0.1, while the corner detection method was the best classification method for nadir images with cover < 0.1. We used routines coded in MATLAB (Macfarlane and Ogden, 2012).

First, four groups of pixels used as training sets were automatically detected for each image using logical tests based on the DNs of the original RGB image (Table 1). To perform the LAB2 classification method, the DNs of each RGB image were transformed using the green leaf algorithm (GLA) as follows (Eq. (2), Booth et al., 2005):

$$\mathrm{GLA} = \frac{(2\mathrm{G} - \mathrm{R} - \mathrm{B})}{(2\mathrm{G} + \mathrm{R} + \mathrm{B})} \tag{2}$$

where G, R and B are the green, red and blue channel of the image, respectively. Eq. (2) yields values ranging from −1 to 1. Values ≤0 were classified as definite background (Group 1, Table 1) and the GLA was rescaled to values between 0 and 1. The RGB images were

Table 1
Identification of training sets for foliage cover classification (for meaning of R, G, B, GLA, see Section 2.3).

Group ID	Note	Logical test
1	Non vegetation materials (background)	R + B ≥ 2G = GLA ≤ 0
2	Green vegetation (foreground)	G > R & G > B & G > 25
3	Dark pixels, non vegetation materials	G ≤ 25
4	Residuals from previous classifications	–