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# Automated computation of leaf area index from fruit trees using improved image processing algorithms applied to canopy cover digital photograpies

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ABSTRACT

Leaf area index (LAI) is a critical parameter in plant physiology for models related to growth, photosynthetic activity and evapotranspiration. It is also important for farm management purposes, since it can be used to assess the vigor of trees within a season with implications in water and fertilizer management. Among the diverse methodologies to estimate LAI, those based on cover photography are of great interest, since they are non-destructive, easy to implement, cost effective and have been demonstrated to be accurate for a range of tree species. However, these methods could have an important source of error in the LAI estimation due to the inclusion within the analysis of non-leaf material, such as trunks, shoots and fruits depending on the complexity of canopy architectures. This paper proposes a modified cover photography method based on specific image segmentation algorithms to exclude contributions from non-leaf materials in the analysis. Results from the implementation of this new image analysis method for cherry tree canopies showed a significant improvement in the estimation of LAI compared to ground truth data using allometric methods and previously available cover photography methods. The proposed methodological improvement is very simple to implement, with numerical relevance in species with complex 3D canopies where the woody elements greatly influence the total leaf area.

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## 1. Introduction

Leaf area index (LAI) is a dimensionless parameter that relates the total area of leaves in the canopy (one sided) with a specific area of soil (Jonckheere et al., 2004). This index is of high importance in plant physiology and plant modeling to up-scale other physiological parameters that are usually measured at the leaf scale. Therefore, an accurate LAI estimation will allow more precise values of physiological information at the whole-plant or whole-tree level. This index is also useful to quantify the level of plant vigor, canopy architecture and water demands at the whole-plant or tree level.

Direct or indirect methods can be used to quantify and estimate LAI (Bréda, 2003). The direct, or allometric, methods consider a partial or complete defoliation of the canopy to assess total leaf area of the plants or trees, which can be associated to a specific area of soil. The latter method offers an accurate measure of real leaf area (LA) and can be used to calibrate other indirect methods. The destructive nature of the direct methods does not allow resampling the same trees; therefore it is impossible to assess growing patterns within a season and between seasons. An alternative to destructive methods are the indirect methods based on mathematical algorithms that describe the transmission of light through the canopy to estimate total LA which is based on Beer's Law (Bréda, 2003; Jonckheere et al., 2004; Vose et al., 1995; Weiss et al., 2004). These methods require estimates of the canopy light extinction coefficient ($k$) and corrections of leaf overlaps by assuming that foliage is randomly distributed in the canopy (Garrigues et al., 2008; Vose et al., 1995). However, instrumentation based on the latter principle could be cost prohibitive and requires high level of know-how to acquire and analyze the data. Examples of this instrumentation are Ceptometers (AccuPAR LP-80, Decagon Devices Inc., Pullman, WA, USA) and LI-Cor 2000 and 2200 (Licor

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Inc., Lincoln, Nebraska. USA). Furthermore, errors associated to this type of instrumentation are on the order of 10–40% underestimations (Bréda, 2003) compared to observed data, which could be associated to the scattering of blue light (Macfarlane et al., 2007). Due to the latter, it is recommended to use these instruments in cloudy conditions or close to dawn or dusk, which involves a practical complication for these methods (LI-Cor 2000-2200 Manual. Licor Inc., Lincoln, Nebraska. USA).

Other indirect methods are based on digital photography, such as digital hemispherical photography (DHP) or fish-eye and cover photography, which estimates LAI by analyzing the size of gaps within canopies and associating these with the level of light transmission through them (Duveiller and Defourny, 2010; Macfarlane et al., 2007; Martens et al., 1993). The fish-eye photographic method requires specific hardware (fish-eye lens) and makes use of non-automated image analysis software (Fuentes et al., 2008). Furthermore, results from fish-eye photography are similar to those found with cover photography for forests (Macfarlane et al., 2007), which does not require any extra hardware besides a common digital camera with medium pixel resolution (5 Megapixels) (Pekin and Macfarlane, 2009). Pekin and Macfarlane (2009) indicated the advantages of this method in comparison to the fish-eye method, arguing that digital images can be routinely obtained during normal working hours because sky luminance is more even, facilitating pixel classification. Additionally, common digital images are rectangular shaped providing higher resolution than DHP methods. Common digital images are less sensitive to photographic exposure providing more accurate measurements of the gap fraction at the zenith. Recently, Fuentes et al. (2008) developed an semi-automated method to analyze cover photography, in order to estimate LAI and other canopy architecture parameters. This method has been based on the cover photography method developed by Macfarlane et al. (2007) adding the automation by batch analyzing images to identify the big gaps within canopies. The application of this semi-automated method proposed resulted in good estimations of LAI for Australian forests compared to indirect methods and satellite methods (Fuentes et al., 2008), for apple trees compared to allometry and using a variable light extinction coefficient (Poblete-Echeverria et al., 2015) and for grapevines compared to allometry, high resolution satellite information and indirect methods (Fuentes et al., 2014).

The downside of the photographic methods is that they incorporate non-leaf material within images, such as trunks (in the case of trees), branches and fruits (in the case of fruit trees), wires and structures from training systems (in the case of grapevines). For this reason, Bréda (2003) proposed that results from the image analysis of cover photography should be called Plant Area Index (PAI) rather than LAI. In the case of forests with closed canopies, Macfarlane et al. (2007) and Fuentes et al. (2008) found that the inclusion of trunks and branches are not significant for the accuracy of estimated LAI. However, this effect could be relevant for horticultural crops and perennial fruit trees, especially in early stages of growth within a season. The effect has been demonstrated for grapevines 'Merlot', which presented an overestimation of LAI of around 3% on average using the cover photography method compared to allometry from bud-burst until veraison. In the later stage, the canopy was big enough to cover branches and cordons, reducing significantly the estimation error (Fuentes et al., 2014). This error is seemingly non-significant for grapevines, which can be associated to the training system used (Vertical Shoot Positioning) and the architecture of canopies, which are highly managed (clumping index close to 1). However, for fruit trees with open canopies, such as apple, pear or cherry trees, the object segmentation method to isolate leaves from branches and stems has been not evaluated previously.

In the case of apple trees in Chile, the cover photography and analysis method proposed by Fuentes et al. (2014) obtained an error of 44.6% in the LAI estimation when using a common light extinction coefficient compared to allometric LAI. The LAI estimation improved, with an error of 17.5%, by using a $k$ obtained from a model based on canopy cover for the same images. A further improvement on the estimation was achieved by measuring incident and below canopy photosynthetic active radiation (PAR) to obtain a proxy of $k$ with an error of only 8.5% in comparison to allometric LAI (Poblete-Echeverria et al., 2015). The latter work makes evident that significant errors can be introduced in the estimation of LAI due to the complexity of fruit tree canopies and the sensitivity of the LAI algorithms to $k$. Reducing this error by incorporating further light interception measurements complicates measurements in field conditions.

Object segmentation is one of the most discussed problems in digital image processing. There are segmentation methods based on the application of simple operators such as the gradient (Gonzalez and Woods, 2008), iterative algorithms for automatically estimating thresholds (Otsu, 1979), and highly sophisticated methods such as Active Contours based on Variational Calculus (Chan and Vese, 2001). To address the trade-off between the precision level and economic and computational costs of the method implementation Occam's razor is applicable, according to which under the same conditions, the simpler explanation is usually preferable. Following the Law of Parsimony, to estimate the leaf area index, a 2-level thresholding method is proposed. This method addresses the segmentation problem with low complexity techniques, allowing the use of conventional devices to capture and process images.

Based on the original cover photography code developed by Fuentes et al. (2008), this paper aims to automate filtration of non-leaf material from digital images using specific segmentation algorithms based on the combination of RGB and CIE Lab color model (CIE, 1976). The proposed method also allows the revision of pre-obtained images to improve the estimation of LAI and other canopy architecture parameters.

## 2. Theoretical background of color models

A color model is a three-dimensional space (if the model has 3 channels), and the colors are points or vectors within that space. Color models provide a way to represent colors and such representation must be unique, *i.e.* a color must be associated to a single vector. In literature, three types of color models are described (Gonzalez and Woods, 2008). The first type corresponds to color representations depending on hardware requirements. Among these models are the RGB (for computer screens) and CMYK (for mixing inks in printers). The second type represents the color by its cognitive parameters, i.e. parameters that come from the way the brain interprets visual information. A representative example is the HSV model that considers the hue (H), saturation (S), and an indication of light intensity (V). These two types of color models are not designed for digital image processing because they are not perceptually correct, i.e. two different colors are not necessarily far from each other in the vector space. The Commission Internationale d'Eclairage (International Commission on Illumination, www.cie.co.at) has developed color models that are perceptually correct such as CIE Lab (CIE, 1976). These models allow to compare colors using Euclidean Distance. For this reason, the latter model is extensively used in industrial applications, particularly in various image processing problems that come from agriculture.

This research corresponds to a case of color object segmentation, *i.e.* the segmentation of leaves from the rest of the tree image. The use of the CIE Lab model allows to naturally address the needs

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