IMPROVING METHODS FOR MODELLING LEAF AREA INDEX IN ISOLATED URBAN TREES

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Press release

In my short mission I discussed the problems of radiative transfer in vegetation and of use of optical canopy instruments for isolated plant analysis with the members of vegetation remote sensing group in Tartu Observatory. After thorough reviewing of indirect optical methods, I individuated digital photography as a potentially suitable method for application in urban settings. Several features available from digital photography (i.e., leaf inclination angle measurements from levelled camera approach; vegetation indices of greenness derived from Digital Number inversion) have been proposed for crop and forestry systems, but still not tested at the individual (urban) tree scale. By combining different digital camera approaches I proposed strategies for improving leaf area index retrieval in urban settings, an important step for understanding ecosystem processes related to leaf area in urban systems.

Keywords: leaf area index, isolated trees, optical canopy instruments, digital photography, scaling

Problem definition

Green infrastructures are key components in the planning of sustainable cities. The fields of landscape ecology and urban ecology have emerged from research to become the primary advocates of ecological design in cities (Ong, 2003). Interest in determining the role urban forests have in removing air pollutants, mitigating heat island effects, cooling buildings and sequestering carbon dioxide has increased with the continued urban expansion (Peper and McPherson, 2003). The influence urban forests and individual tree species have on chemical emission and the formation of greenhouse gasses represents an active research topic.

The ability to estimate leaf area index (LAI) is essential to accurately modelling these physiological and functional processes. The amount of leaf area is directly related to the pollutant interception and emission rates of individual tree species (Nowak, 1994). LAI also influences rainfall storage capacity and its effect on reducing water runoff (Xiao et al., 2000). LAI is also used as main input variable in building energy balance simulations (Sailor, 2008)

Despite its importance, the majority of studies focused on LAI estimation were performed in vegetation ecosystems, i.e., forests, orchards and row crops. Use of different available methods to estimate LAI in urban settings has rarely been explored (Peper and McPherson, 2003). In addition, such methods are ideally applicable at stand scale and are therefore poorly suitable in urban settings, where trees are typically sparse and isolated. Accurate measurements in urban settings are also hindered by proximity of trees to infrastructure elements, which can strongly affect the accuracy of tree canopy analysis.

The objectives of the STSM are the followings:

i) Reviewing the theory and methodology available related to leaf area index estimation.

ii) Outlining advantages and disadvantages of the various methods related to isolated urban trees measurements.

iii) Individuating at least one methodology for estimating LAI which could be potentially suitable in urban settings. Evaluating sampling procedures to alleviate the drawbacks of applying the selected methodology to isolated urban tree level.

The following points were discussed with the members of vegetation remote sensing group in Tartu Observatory and described in the following sections.

Reviews of existing methods for estimating LAI

Basically, there are two main categories to estimate LAI, direct and indirect methods (Breda, 2003; Jonckheere et al., 2004). Direct methods measure LAI in a direct (or semi-direct, see Dufrêne and Breda 1995) way, They are the most accurate, but they have the disadvantage of being time-consuming and as a consequence making broad scale application not feasible (Jonckheere et al. 2004). Accordingly, these methods are not suitable for routine measure and monitoring of LAI. However, the need for validation of indirect and remotely sensed methods remains, so direct methods can be considered important as cross-calibration tools (Cutini et al. 1998). Direct methods include destructive sampling and leaf litter collection (Brèda, 2003). For the sake of conciseness, we did not describe direct methods in details, since their application in urban settings is unpractical.

Indirect optical methods infer leaf area index from measurements of the transmission of radiation through the canopy and making use of the radiative transfer theory (Nilson, 1971; Norman and Campbell, 1989; Ross, 1981). These non-destructive methods are based on a statistical and probabilistic approach to foliar element (or its complement, gap fraction), distribution and arrangement within the canopy (Bréda 2003). LAI is calculated by inversion of the Beer-Lambert law, which computes canopy gap fraction (Equation 1, after Nilson, 1971):

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

where $P(\theta)$ is the gap fraction, $G(\theta)$ is the G-function and correspond to the fraction of foliage projected on the plane normal to the zenith direction, $\Omega(\theta)$ is the foliage clumping index at a given zenith angle (θ) and L is the leaf area index. The product of L and $\Omega(\theta)$ is often defined as effective leaf area index, which assumes no foliage clumping given the gap fraction relating the probability of beam penetration through the canopies.

The solution of Eq. 1 requires three values to be measured: the gap fraction at a given zenith angle $P(\theta)$, its related clumping indices $\Omega(\theta)$, and the foliage projection function $G(\theta)$. $P(\theta)$ is directly measured by optical instruments, while the other two variables are usually estimated by applying some gap fraction models (Miller, 1967; Norman and Campbell, 1989).

A useful distinction should be drawn between methods which measure gap fraction at multiple zenith angles and methods that measure gap fraction at a single zenith angle. Methods based on multiple gap fraction measurements were frequently employed, because they enable measuring largest footprint view of a canopy in one single point measurement (Leblanc and Fournier, 2014). In addition, such methods have the reputed advantages of providing *L* from gap fraction measurements without requiring *a-priori* knowledge of the foliage leaf angle distribution (Leblanc et al., 2005). The Miller's theorem (1967) is a widely used algorithm in optical methods based on multiple gap fraction measurements (Nilson, 1971; Leblanc et al., 2005; Norman and Campbell, 1989; Ryu et al., 2010). Hemispherical photography and LAI-2000 Plant Canopy Analyzer are the most commonly used methods based on multiple gap fraction measurements.

A second group comprises methods based on single gap fraction measurement. Generally, these methods require and additional parameter to solve the Beer-Lambert law for *L*, that is the foliage leaf angle distribution, which is related to $G(\theta)$, with the exception of methods based on gap fraction measurements at inclined 57.3 zenith degree. Use of 57.3° (≈ 1 radian) is desirable because at that zenith angle the G- projection function is almost independents from leaf inclination angle (G~ 0.5; Warren and Wilson 1960); Bonhomme et al. (1974) used 57.3° view angle of hemispherical images to estimate LAI in young crops. Restricted (inclined, upward or downward looking) view photography, ceptometer and TRAC (Tracing Radiation and Architecture of Canopies) are the most commonly used methods based on single gap fraction measurement.

All indirect optical methods share the following assumptions:

- Leaves are randomly distributed within the canopy;

- Leaves are small compared to the total field of view of the sensors and compared with the canopy;
- Foliage is black, namely leaves do not transmit light.

Under these assumptions, gap fraction and transmittance are equivalent (Bréda 2003).

Advantages and disadvantages of the various methods for isolated urban trees application

Typically, urban trees are sparse and isolated, and thus methods based on multiple gap fraction measurements might require some adjustments, in such situations. For example, the LAI-2000 PCA manual provides some suggestions for measuring LAI in isolated trees. Restricting view caps could be fitted to reduce the field of view of the sensor at the appropriate spatial scaling required for isolated tree measurements (Li-COR, 2009). Reducing the zenith range might also be required to avoid bias caused by surrounding infrastructure elements and also to avoid including neighbouring trees in the measurements. Although theoretically feasible, such adjustments can strongly affect estimates of LAI from PCA instruments. Large branches in the crown can dominate the sensor's view when reducing the field of view of the sensor. Also, reducing the zenith range is claimed to introduce negative bias in the standard LAI-2000 PCA algorithm (Leblanc and Chen, 2001). One could also argue that these limitations can hardly be controlled in urban settings, because the operator is unable to visually inspect and determine what actually the sensor "sees". For this reason, digital photography can be preferred because it provides a permanent record that can be visually inspected for determining position, size, density and distribution of gap fraction and surrounding elements (Jonckheere et al., 2004). However, the limitation of downscaling estimates to isolated tree level from multiple gap fraction measurements remains. For this reason, use of methods based on single gap fraction measurement appeared mostly suitable for estimating LAI in isolated trees. The 'other side of the coin' was that an additional parameter related to foliage angle distribution is required to estimate LAI from single gap fraction measurement. Single measurement obtained at the 'magic' 57.3° angle has not this requirement, and allows estimating LAI directly from gap fraction measurement obtained at that inclined angle. However, at such inclined view sometimes sensor could see no foliage, resulting in LAI estimates of zero below a tree. The influence of woody vegetation at this angle might also have a strong impact on gap fraction measurement (Kucharick et al., 1998).

A major constraint in estimating LAI in urban settings is that surrounding infrastructure elements can strongly affect the accuracy of gap fraction estimates. For these reason, some procedures are required to objectively separate vegetation from non-vegetation elements prior to perform gap fraction measurements. Among the optical methods, digital photography holds great potential to overcome this limit. For example, vegetation indices have long been explored in crops and weed plants for estimating LAI from downward looking cameras (e.g., Liu and Pattei, 2010; Meyer and Neto, 2008). Basically, vegetation indices involve transformation of digital number of image pixels from each channel to generate features to separate green vegetation from surrounding background. The various algorithms proposed were meant to exploit the contrast between the reflected light intensity of leaves in green waveband, and the other elements captured by photograph. This procedure can therefore be potentially able to separate leaves from infrastructure elements; however, its application has not been tested in urban settings.

Attempts to individuate a methodology for estimating LAI in isolated urban tree

Based on the previous considerations, the following priority items were individuated for designing a field protocol for estimating LAI in isolated urban tree:

- Spatial scaling: the sensor's field of view should be proportional to the spatial arrangement of individual tree canopy.
- Leaf angle measurements should be available from field measurements if single or restricted view measurements are used.
- A procedure should be available to separate vegetation and non-vegetation elements prior to gap fraction measurements.
- Rapid, cost-effective and measurement-accessible protocol. Destructive methods are unpractical, but also tall isolated trees should require some adjustments in the field protocol.

An ideal device was individuated consisting of an optical digital camera fitted with focal length lenses providing a restricted angle of view. Camera should be oriented upward from below the isolated tree. An example of a method using a similar setup was digital cover photography, which was developed by Macfarlane et al., (2007). The method used a 70 mm equivalent lens format to obtain a view zenith angle of approximately 30°. This method have been tested in various forest stands (Chianucci and Cutini, 2013; Macfarlane et al., 2007; Ryu et al., 2012) but it has never been applied at isolated tree level. Nonetheless, the method appeared suitable to fit the spatial scaling required for individual tree sampling. Digital photography has the advantage of being able to vary the size of sampling using different focal length lenses, thus providing a flexible tool to achieve a compromise between adequate distance from the sensor coverage and adequate spatial representation. As preliminary observation, users should test which focal length should be used to better fit the spatial scaling requirements, which are mainly dependent from the angle of view of the lens and the height of the target tree.

As restricted view angles require further measurements of leaf inclination distribution to invert LAI from gap fraction measurements, users should be able to measure leaf inclination angle of the target trees. It is worth nothing that leaf angle distributions have rarely been measured in most vegetation studies, while a spherical distribution of leaf normal is often assumed at the purpose (Chianucci and Cutini, 2013; Macfarlane et al., 2007). However, Pisek et al., (2013) demonstrated that the spherical distribution is often not a valid assumption for temperate and boreal tree species. The authors used a leveled-digital camera approach firstly proposed by Ryu et al., (2010b) to collect fast non-destructive leaf angle measurements of individual trees from photographs. Therefore, this method should be highly suitable in urban trees. A series of photographs from tree crowns can be acquired along a vertical profile, in agreement with the field protocol proposed by the leveled-digital camera approach (Pisek et al., 2013; Ryu et al., 2010b). Use of ladders or extendible poles might allow measurements in tall trees.

Finally, the digital image format is also well suited for the quantitative and qualitative analysis of isolated trees, particularly regarding the needs to separate vegetation from non-vegetation (infrastructure) elements, which appeared the greatest obstacle to applying indirect methods in urban settings. Spatially, each digital image is represented by a matrix of cells (pixels). Radiometrically, each pixel is characterized by a numerical value (Digital Number, DN), which express the amount of radiation reflected from an object, represented in a specific band of the light spectrum. Optical digital cameras standard describe the colour characteristics of the visible range using three monochromatic components, namely Red, Green and Blue, sorted in three separate channels (RGB), so each pixel of a digital image standard will have a different numeric value depending on the amount of radiation reflected in the separate RGB channels. The different and specific capacity of the elements to reflect the radiation allows discriminating different entities according to their specific reflectance. For example, the high reflectivity of leaves in the green wavelength interval allows operating simple transformations to enhance the contrast between green leaves and surrounding background. Uses of so-called vegetation indices have long been reported in agriculture literature but their application in urban settings remains still to be tested. To date, the greatest obstacle to an objective and rapid method appeared to be the detection of a threshold value that separates vegetation and non-vegetation pixels in image.

Conclusions

The STSM allowed outlining a potential protocol for estimating LAI in isolated trees growing in urban settings. Digital photography holds great potential to overcome the major limits of applying indirect methods in urban environments. The method is fast, cost-effective, and allows widespread use of the method, which could be ideally suitable for monitoring and research programs. Digital images provide a permanent record that can be re-analyzed with improved method as they become available, and the quality control can be checked by observers who might not be available in the field. The methodology proposed have never been tested in actual field measurements, so further tests are needed to verify the reliability of the proposed photographic approach.

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