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Preliminary study on integrated wireless smart terminals for leaf area index measurement

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ABSTRACT

The last few decades have seen the emergence of many new methods for measuring leaf area index (LAI). One attractive method is to measure LAI by using a readily available simple instrument, such as a smartphone, as an alternative to traditional complicated and thus costly commercial instruments. We designed a novel integrated LAI measurement system, LAISmart, which is implemented by using two smart terminals communicating through a wireless connection in an integrated support infrastructure. The LAI is calculated by using the Beer gap fraction model on the assumption of spherical leaf angle distribution that takes the G value (the projection of unit foliage area on the plane perpendicular to the view direction θ) as constant at 0.5. The gap fraction is calculated by segmenting the image pixel into canopy and background. For the selection of image segment features, LAISmart provides two options, greenness index and blue band, which may be suited to different vegetation types. The proposed LAISmart was validated by measurements on four types of vegetation, i.e., Evergreen Needleleaf Forest (ENF), Deciduous Broadleaf Forest (DBF), Deciduous Needleleaf Forest (DNF), and broadleaf crop, on which 114 LAI values were calculated in the eight datasets. A pairwise comparison between LAISmart and LAI-2000 showed that the LAI values derived from LAISmart correlated strongly with those of the LAI-2000, with an R^2 value of 0.97, and had high accuracy in total, with a root–mean–square error (RMSE) of 0.45 m^2/m^2. The validation results revealed that the overestimation on LAI caused by underestimation of the *G* value might complement the bias caused by misclassification. Moreover, although there is no limitation on the shooting angle of LAISmart, it is recommended that LAISmart be used at the low zenith angle mode, e.g., upward- or downward-looking mode, rather than at the large zenith angle. Further validation will focus on other vegetation types such as grass and shrubs in order to improve the performance of LAISmart for different vegetation types.

1. Introduction

Vegetation constitutes an important component in land surface ecosystems, and leaves are vital organs of vegetation that interact with the outside environment. Leaf area index (LAI), which is defined as half the vegetation canopy leaf area per unit of surface area (Chen and Black, 1992), is an important parameter for quantitative description of photosynthesis (Wit, 1965), respiration, and transpiration of vegetation leaves (Yamori, 2016). Accurate and fast measurement of LAI is of fundamental importance for quantitative analysis of many physical and biological processes related to vegetation dynamics and their effects on the global carbon cycle and climate (Chen et al., 2002). Ground LAI measurement techniques can be divided into direct and indirect methods, the advantages, weaknesses, and working conditions of which have been conducted in many comprehensive reviews (Bréda, 2003; Jonckheere et al., 2004; Weiss et al., 2004).

Among ground measurement methods, photographic imaging techniques constitute an important branch. The basic principle of the photographic method is to take photographs of a canopy at single (Liu and Pattey, 2010; Liu et al., 2013; Ryu et al., 2012) or multiple shooting angles (Demarez et al., 2008; Leblanc et al., 2005; Leblanc and Fournier, 2014). The captured images are then segmented into leaf and background, which is known as gap classification, to obtain the gap fraction of the canopy at single or multiple angles. The LAI can then be computed on the basis of a gap fraction model (Nilson, 1971). In the technical solutions to obtain LAI by

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photographic imaging, diverse types of available imaging devices are available such as professional single-lens reflex (SLR) cameras, common digital cameras, and pre-1970 film cameras. Therefore, photographic imaging is a flexible LAI ground measurement technique.

In addition to traditional imaging devices, new instrumentation has become available to measure LAI. For example, some researchers have used smartphones to obtain LAI. Confalonieri et al. launched a mobile application based on smartphones that can be run on Android and iOS operating systems (Confalonieri et al., 2013, 2014). Known as PocketLAI, their application computes LAI by obtaining the gap fraction of a canopy at a specific angle of 57.5°. They initially conducted tests on a scatter-seeded rice crop and then performed comparative tests on other vegetation types (Francone et al., 2014; Orlando et al., 2015). Their findings provided an excellent example of achieving professional LAI measurement based on easily accessible smartphones.

Although PocketLAI is based on a portable device compared with the heavier professional SLR cameral, there is still much room for improvement. First, in the PocketLAI framework, LAI is calculated by using the gap fraction at a shoot angle of 57.5°. In such an assumption, PocketLAI ignores the fact that most mobile cameras have a large field of view (FOV). Consequently, when the image is captured at 57.5°, most pixels have viewing zeniths up to 90°. Larger zenith means larger risk of capture space that does not belong to the vegetation. Second, it may be easy to take a photograph at the configuration of zenith 57.5° in a tall forest, where the user can hold the device while standing. However, we found this task to be quite difficult among short plants, where the user must crawl on the ground to aim the vegetation at zenith 57.5°. Moreover, a mobile phone screen cannot be easily monitored by the operator in such situations; therefore, capturing the photograph at such a specific angle is virtually impossible when working among short vegetation.

This paper proposes an LAI measurement system known as LAISmart, which is based on integrated smart terminals such as smartphones. In the designing of LAISmart, we provided flexible options on the shoot angle and the algorithm of image processing. Another improvement of the LAISmart is that it separates the function of PocketLAI into a sensing component and a monitoring component by using an additional smartphone employed as the user operating terminal; these two components are then connected via a wireless network. Such improvement facilitates the operation on different vegetation types.

The primary aim of this paper is to present the design of LAISmart from the aspects of its hardware and its algorithm on calculating the gap fraction and LAI parameter. An additional aim is to validate the assumption on the leaf angle distribution when calculating LAI without the knowledge of leaf angle. The validation work was supported by eight datasets collected on four types of vegetation from different shooting directions.

2. Materials and methods

2.1. Composition of the LAISmart system

LAISmart is composed of two smartphones connected by a support system and communicating by a wireless network. The frontend terminal serves as a data collection terminal, and the backend terminal serves as a user operation console (Fig. 1).

Currently, both the backend and frontend smart terminals are run on the Android operation system, and their hardware configuration must include a Global Positioning System (GPS) sensor, a gyro sensor, an imaging sensor, and a Wireless Fidelity (WIFI) sensor. The smart terminals of LAISmart are configured by two mobile phones with a resolution of 13 megapixels and a maximum FOV of 70°.

When operating LAISmart, the user can adjust the shooting angle of the frontend terminal by adjusting the direction of support system. In addition, the frontend angle value together with its GPS location and the preview image can be displayed at the backend screen through the wireless network, which is established by the hotspot used for the backend terminal. Before the measurement begins, the operator can set the photographing direction of the imaging sensor according to the vegetation height. For tall trees or short but continuous crops, the imaging sensor is recommended to be shot upward. In such situations, only vegetation and sky are in the FOV, whereas for short but discrete canopy, the operator can shoot downward with the sensor above the canopy. In such situations, the vegetation and soil are in the FOV.

2.2. Calculation of canopy gap fraction

Extraction of the gap fraction from the images is actually achieved by automatic segmentation of vegetation and non-vegetation in the digital photographs. In LAISmart, the Otsu algorithm (Otsu, 1979) is used to extract the gap fraction of the image automatically. The principle of the Otsu algorithm is to search for a segmentation threshold that maximizes the between-class variance of the segmented binary images.

However, owing to the effects of shooting conditions (e.g., direction of imaging sensor and ratio of sky light), the choice of the image segmentation feature for the foreground (vegetation) and background (sky or soil) varies in actual measuring situations. In fact, it is impractical to maintain one feature that can automatically segment images in a variety of conditions. Therefore, based on the original RGB image, the LAISmart system provides two candidate features the first is greenness index (GI) (Booth et al., 2005),

$$GI = \frac{2 * G - R - B}{2 * G + R + B}, \quad (1)$$

where R, G, B is the red, green, and blue band intensity in a color image, respectively. The second option is to use the blue band intensity value (B) directly (Welles, 1990).

GI is effective for distinguishing vegetation from soil in downward photography or upward if the leaf vegetation has good transmittance, whereas the B feature can effectively distinguish vegetation and sky in upward photography with strong scattered light. The OpenCV library (http://opencv.org) was used in LAISmart to implement the Otsu algorithm.

2.3. Retrieval of LAI from gap fraction

On the condition that the leaves are randomly distributed and their sizes are significantly smaller than that of the canopy, the relationship between canopy gap fraction and LAI can be expressed as the Beer gap fraction model (Nilson, 1971):

$$P(\theta) = e^{-G(\theta)LAI/\cos\theta}. \quad (2)$$

Then, LAI can be obtained as

$$LAI = -\ln P(\theta)\cos(\theta)/G(\theta), \quad (3)$$

where $P(\theta)$ represents the canopy gap fraction at the view zenith of θ, and $G(\theta)$ is the projection of the unit foliage area on the plane perpendicular to the view angle.

According to Eq. (3), knowledge of $G(\theta)$ is needed for retrieving LAI. Research results from Goudriaan (1988) indicate that the distribution function of the leaf angle could be approximated by a spherical distribution and in such situations, the average projected area ratio of leaves $G(\theta)$ is 0.5 independent of the viewing angle of the sensor. Although arguments have been presented on this