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Measurement and estimation of leaf area index (LAI) using commercial instruments and smartphone-based systems

Raffaele Casa^a, Deepak Upreti^b, Federico Pelosi^c

Department of Agriculture and Forestry Sciences, University of Tuscia, Viterbo, Italy.

^arcasa@unitus.it, ^bdupreti@unitus.it, ^cfederico.pelosi.84@gmail.com

Abstract. The experimentation carried out within this project aimed at comparing various methods used to estimate leaf area index (LAI), which is a key variable to describe the vigour and productive potential of a crop. The direct or "destructive" method requires the removal of the biomass of the sample and is a very laborious and burdensome technique. The indirect estimates consist in the acquisition of a series of readings taken directly in the field with specific instruments, mainly based on the measurement of the quantity of light intercepted by the foliage and on the use of complex mathematical models. Indirect methods allow for a quick estimation of the LAI and there is a strong interest in developing economic and user-friendly tools. The tools compared in the present study included two state-of-the-art, rather expensive, commercial instruments, i.e. the Sunscan ceptometer (Delta-T, UK) and the LAI-2000 (Li-Cor, USA). These were compared to inexpensive alternatives offered by hemispheric photography from a smartphone equipped with a fish-eye lens and from a smartphone app called "Pocket LAI". All the methods tested showed the ability to provide an effective estimate of the LAI even if sometimes with an underestimation of the value measured by the direct method.

1. Introduction

Leaf area index (LAI) is a key biophysical variable for both crop monitoring and modelling applications, defined as the total one sided leaf area in relation to the ground [1]. It has been widely used in different agricultural applications [2] and remote sensing studies [3–5] including precision agriculture [6]. It is used also as key state variable in many crop growth models [7].

There are two approaches for measuring LAI in the field : direct and indirect methods [8, 9]. The direct or destructive method involves the removal of the biomass of the sample that is intended to be measured and is a very laborious and costly method. The indirect estimation consists in the acquisition of a series of readings carried out directly in the field with specific instruments, mainly based on the measure of the quantity of light intercepted by the foliage and the use of complex mathematical models. These commercial instruments estimate LAI from the gap fractions [10] measured from different angles, which is the fraction of sky seen from below the canopy (upward photography) or the fraction of soil seen from above the canopy (downward photography) [11].

There are different commercial instruments available for the indirect estimation of the LAI, and have good potential to estimate LAI as compared to direct destructive methods in many experimental conditions [12]. Sensors like LAI-2000 Plant Canopy Analyzers (LI-COR, Inc., Nebraska, USA) and DHP are some of the most widely used classical optical instruments for indirect LAI estimation [10, 13–15]. The downside of these instruments is that they are quite expensive, both in the terms of purchase and maintenance. An alternative to these instruments is the use of digital hemispherical photographs



acquired with a camera by attaching a fish eye lens to it. This method requires generally professional (and expensive) cameras and lenses and large processing time for image classification after acquiring images to obtain a good LAI of the representative sample. This limits the use of these instruments in real time [11].

As an alternative, exploiting the features available in the smartphones, a mobile application called PocketLAI was developed [16] to estimate LAI. This app was tested on paddy rice against commercial instruments LAI-2000 and Decagon Accupar ceptometer. LAI estimation is based on the segmentation of images acquired at 57°, below the canopy to estimate gap fractions [13]. It proved its reliability in terms of both trueness and precision.

Since all the methods for indirect estimation of LAI depend on the models for light transmittance into the canopy and these models are strongly affected by canopy architectures [9, 17], testing these methods on canopies with different structures is mandatory. The aim of this study was to compare LAI estimation from smartphone app, PocketLAI, DHP, LAI-2000 and Sunscan Ceptometer. The reasons behind this study were the encouraging results obtained from [16] and the need to test them on other crops as well.

2. Materials and Methods

The measurements with the different methods was carried out in 2014 and 2015 on a total of 39 samples. The measures took place at the Maccarese SpA farm (17 samples) in the province of Rome (41.83° lat. N, 12.22° long. E, alt. 8 m a.s.l.). The surveys carried out for the other 22 samples took place at the experimental farm of the University of Tuscia, located in Viterbo (42.72° lat. N, 12.12° long. E, altitude 310 m). The measures were carried out on: spelt (*Triticum dicoccum* L.), durum wheat (*Triticum durum* Desf.), maize (*Zea mays* L.), alfalfa (*Medicago sativa* L.) and broad beans (*Vicia faba* ssp. *minor* L.).

2.1. Instruments Used

In this study direct, destructive LAI estimates have been considered as a reference LAI estimate and other indirect methods of LAI estimation are compared with this reference. Indirect methods of LAI estimation are – Sunscan Ceptometer (Delta-T, UK), LAI-2000 Plant Canopy Analyzer (LI-COR, USA), Hemispherical Photography from smartphone camera (equipped with fish eye lens), and smartphone app (PocketLAI).

2.2. Sampling Protocol

Many factors can influence the measurement technique used for a given coverage, such as height, size, sky conditions and sensor field of view [18]. For this reason, the measures were carried out with each instrument following a precise sampling protocol. The data of the same instruments were acquired in crop areas within frames placed on the ground of 0.9 by 1 m size.

The measurements were carried out in different plots of cultivated fields, choosing portions of the field in which the crop was homogeneously distributed and had an average height of about 30 cm. The frames were placed on the ground, thus separating the sample from the remaining crop. It was taken care in the choice of the exposure in the light of the selected surface unit, to ensure that the light conditions were such as to minimize the percentage of error in the readings.

2.2.1. Direct Methods

The LI-3100C (LI-COR, Lincoln, USA), area meter was used for the direct (or destructive) estimation of the LAI. The device is designed to be able to carry out a precise measurement of the foliar area, for leaves of any size. The leaves are collected from the total sample and placed one by one on a transparent conveyor belt that allows them to pass in front of a linear scanner.

The leaves travel under a light source so that the projected image is subsequently reflected by a three-mirror system on a scanning camera. The measurement of foliar area that derives from it is shown on the display, allowing reading and is expressed in cm². The roller, of which the instrument is fitted, is

used to crush the leaves on the conveyor belt to avoid an underestimate of the real value, due to the foliar flap crumple.

With regards to the protocol used for the direct method of the LAI estimation, it was necessary, first, to remove the sample biomass, inside the quadrat, cutting the plants at the base of the collar, taking care not to harvest plant litter that could cause LAI overestimates. The collected biomass was weighted to extract sub-samples equal to about one third of the sample weight. The sub-sample, built from whole plants, was subdivided dividing the leaves from the branches and weighted them separately. Then both the leaves and stems were passed through the meter area. The value estimate by the meter area is considered as the one closest to the real value and therefor plays a fundamental role in comparing different methods.

2.2.2. Indirect Methods

2.2.2.1. LAI-2000

The data acquired with the LAI-2000 instrument were collected by taking a reading above the canopy and six readings below the canopy for each quadrat. In order to carry out the six readings under the vegetation, inside the quadrat, the sampling scheme shown in Fig.1a was adopted. The spatial layout of the readings was conceived in order to carry out an estimate of the LAI as much as possible corresponding to the sample of the plant cover contained within the quadrat, subsequently collected for the destructive determination by the direct method. A limited field of view was adopted up to the fourth ring (for zenith angles 0° to 58°), and a cover to limit the circular acquisition sector to 90° . The area measured by the instrument, for each reading, was calculated using:

$$r = \tan(58) * H \quad (1)$$

$$A = \frac{\pi r^2}{4} \quad (2)$$

where H is the height of the vegetation. In order to correct for the error introduced because the measurements were not acquired under diffuse light conditions, a calibration of the instrument was carried out according the LAI-2200 manual (LI-COR, Lincoln, USA). A series of readings were acquired with the use of a diffuser cap: 1) with diffuser resting on the sensor in the shadow, 2) with diffuser resting on the sensor exposed to direct light, 3) with the sensor without the diffuser, in the shadow. Also, maximum attention was paid to ensure that the sensor was shaded, in order to avoid exposure of the sensor to direct sunlight.

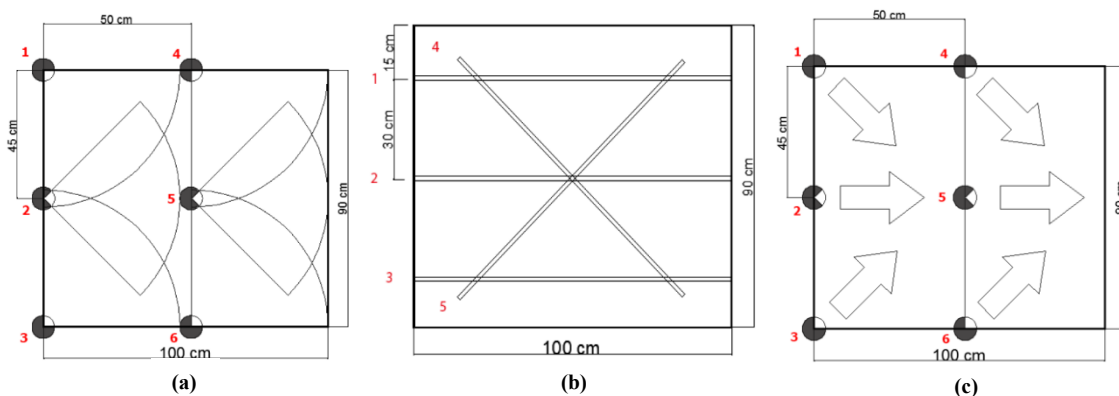


Fig1. Sampling Plan - a) LAI-2000 b) Sunscan Ceptometer c) PocketLAI

2.2.2.2. SunScan Ceptometer

The sampling protocol used for Sunscan ceptometer consisted of five readings carried out under the canopy cover and one above it [19]. The measurements were obtained, for the first three readings, by placing the rod on three points, equidistant from them, parallel to the greater side of the quadrat (Fig. 1b). The fourth and fifth readings were made by positioning the rod at 45° , with respect to the vertices of the quadrat, and the last reading was done above the crop to measure the incident radiation. Finally, an additional reading was carried out to measure the radiation reflected from the soil on a adjacent area where there was no vegetation.

2.2.2.3. Digital hemispherical photography

For the methodology based on hemispheric photography an iPhone-5 (Apple Inc, USA) equipped with a special cover was used. A fish eye lens suitable for the camera of the smartphone was employed. The readings consisted in the acquisition of a series of hemispherical images taken by placing the instruments on the ground with the lens of the camera oriented towards the sky. The camera has a field of view limited to 50° with respect to zenith and a cover was used that limited the acquisition to a circular sector of 90° to allow to mask the operator from the photo. After checking the contrast between the cover and the sky, the images were stored and subsequently processed by the CanEye software [19] up to the LAI estimation. The measurement protocol used for this method is the same that is used for LAI-2000 Fig1a.

2.2.2.4. PocketLAI – Smartphone App

A Samsung Galaxy Xcover GT-S7710 smartphone with an Android 4.1.2 operating system was used to test the PocketLAI app. Once, the app is started, the smartphone is in read mode and the operator has 5 seconds to position the device below the vegetation. Shortly, after positioning the smartphone, the application emits a first signal of vibration, the orientation of the screen is continuously recalculated using the accelerometer sensor. When the angle between the vertical and the normal reaches 57.5° , the image is captured and processed, using an algorithm described by [15]. Similarly, further readings are calculated, and a LAI value is estimated. The protocol used with PocketLAI application is shown in Fig1c.

3. Results and Discussions

Table 1 shows the comparison between the values of LAI obtained through the destructive sampling and those acquired by indirect methods. Comparisons include all data collected during the period from 10 March 2014 to 28 January 2015. The range of LAI values explored in this study is reasonably wide to the values reported in [19–21]. Fig. 2 presents scatterplots showing R^2 and RMSE values.

Digital hemispherical photographs captured by Iphone with fish eye lens attached provides the best estimates of LAI for alfalfa (RMSE = $0.33 \text{ m}^2/\text{m}^2$) followed by PocketLAI (RMSE = $0.40 \text{ m}^2/\text{m}^2$) (Table 1).

Table1. RMSE values of LAI estimates for different crops and instruments

	RMSE (m^2/m^2)			
	Sunscan Ceptometer	LAI-2000	DHP Processed	PocketLAI
Alfalfa	0.88	0.60	0.33	0.40
Broad bean	0.30	0.48	0.30	0.65
Durum wheat	1.17	0.83	0.87	1.05
Emmer	1.54	1.16	0.31	1.77
Maize	0.87	0.89	0.58	0.77
Wheat	1.36	1.05	0.68	1.46

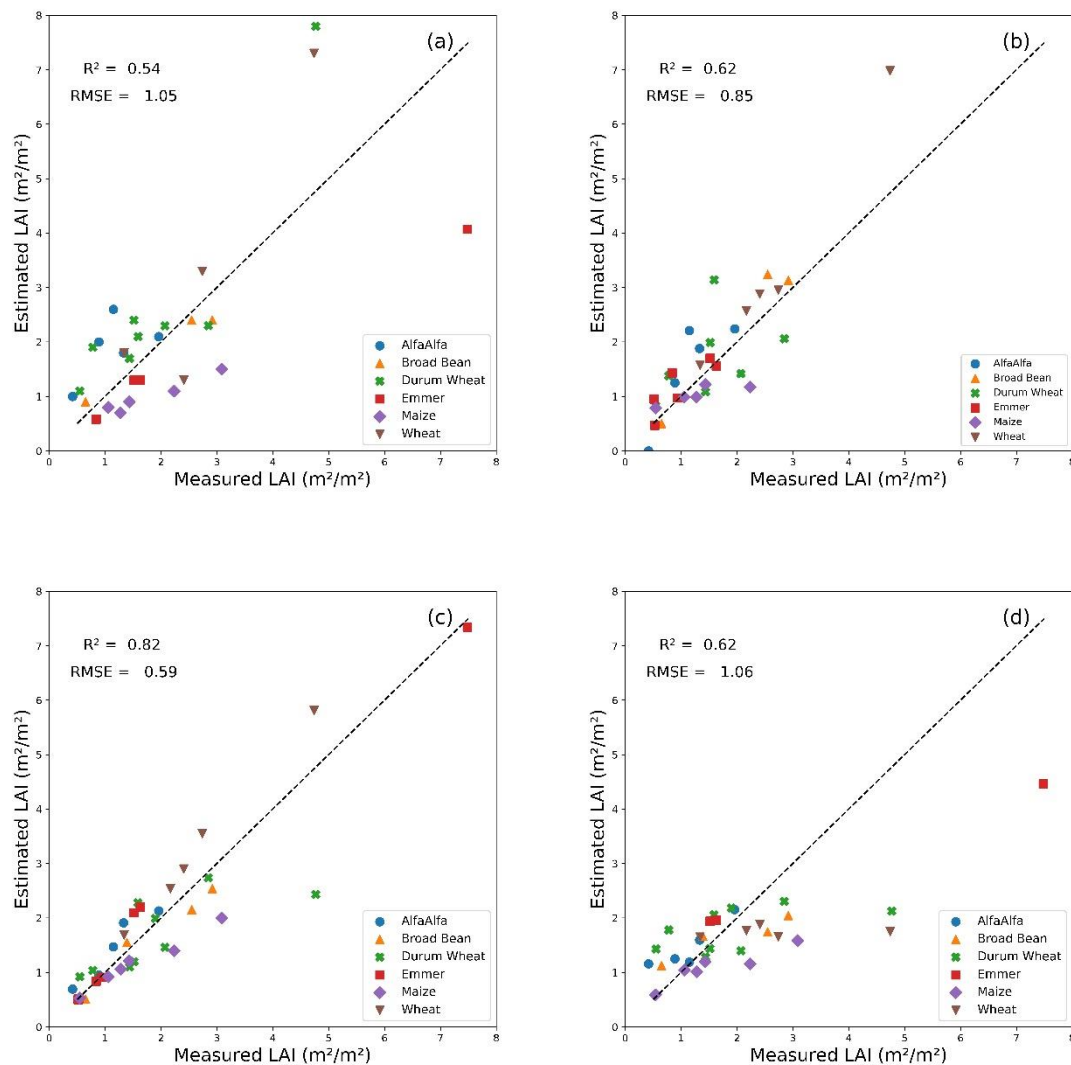


Fig 2. R^2 and RMSE for a) Sunscan Ceptometer, b) LAI-2000, c) DHP d) PocketLAI Application

For broad bean, LAI lowest error was estimated by Sunscan Ceptometer (RMSE = 0.30 m²/m²) and DHP (RMSE = 0.30 m²/m²). In case of durum wheat LAI values estimated were best achieved using LAI-2000 (RMSE = 0.83 m²/m²) and DHP (RMSE = 0.87 m²/m²), higher values of LAI showed some over estimation for wheat with SunScan Ceptometer. DHP images resulted in the lowest error in emmer (RMSE = 0.31 m²/m²), maize (RMSE = 0.58 m²/m²) and wheat (RMSE = 0.68 m²/m²). PocketLAI mobile application although have satisfactory performance, it showed some under estimation and saturation effect for LAI values higher than 2.

In this study, DHP processed with the CanEye image processing software obtained the best overall results in terms of RMSE. The downside of this method is the time taken for processing the images after acquisition. It is impractical for real time deployment. Commercially available instruments LAI-2000 and Sunscan Ceptometer are although widely used for the indirect estimation of LAI and accepted globally as a reliable source to estimate LAI, these instruments are expensive in terms of cost and maintenance. PocketLAI application for LAI estimation was found satisfactory in terms of goodness of

fit and error estimates, it is an economic and feasible alternative for large and frequent field campaigns. As, the PocketLAI application used in this work calculates gap fraction in only one incident direction ($\sim 57.5^\circ$), some modifications of the calculation of gap fraction, by for example considering gap fractions from multiple directions and taking an average of them, may lead to better and improved estimation of LAI.

4. Conclusions

All the methods showed the ability to provide an estimate of the LAI that is closer to the estimation of the measurement with the area meter, that is the direct reference measure, the more the canopy meets the assumptions based on a random distribution of the leaves. In general, with regard to the accuracy of the instrument, the performance of the app was very similar to that of LAI-2000. A better performance of the LAI-2000 was found as compared to Ceptometer. As has already been observed by many authors, all methods adopted for the estimation of LAI generally lead to an underestimation of the measured value to the direct method [7, 8]. In this study some over estimation was observed with digital hemispherical photographs, LAI-2000 and Sunscan Ceptometer (Fig. 2). The main problem encountered with LAI-2000 was an underestimation due to a saturation phenomenon, which was also found in Sunscan Ceptometer, which occurs under very high crop density conditions. Removing the external ring readings slightly more reliable. Regarding the PocketLAI app, a underestimation for LAI values greater than 2 was found. However, this method has undisputed advantages over all other instruments, especially as regards the greater practicality of use and the economic aspect: a few euros in case the users are already in possession of a smartphone, compared to approximately 10 thousand euros planned for the purchase of tools like LAI-2000 or Sunscan. An additional advantage of the app is the elimination of the costs of repair and maintenance, thus excluding the risk of a possible interruption of the measurement campaign in case of damage of the device. However, the problems shown by the app cannot be attributed exclusively to the calculation processes it works to estimate the value of the foliar area index because they derive it mostly from the field vision (58°) of the camera used for the measurement. The performance of the hemispherical photography-based method was the best in terms of accuracy among the methods used. Also, in this case it has been shown that it is possible to use low cost equipment, consisting of a smartphone and a fish eye lens purchased online for a few euros. However, this method requires a later phase of processing the images on computers, using specific software such as CanEye, not allowing an instantaneous calculation of the LAI and requiring a specialist competence in the data processing phase.

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