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Development of an app for estimating leaf area index using a smartphone. Trueness and precision determination and comparison with other indirect methods

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A B S T R A C T

Leaf area index (LAI) is a crucial variable in agronomic and environmental studies, because of its importance for estimating the amount of radiation intercepted by the canopy and the crop water requirements. Direct methods for LAI estimation are destructive, labor and time consuming, and hardly applicable in case of forest ecosystems. This led to the development of different indirect methods, based on models for light transmission into the canopy and implemented into dedicated commercial instruments (e.g., LAI-2000 and different models of ceptometers). However, these instruments are usually expensive and characterized by a low portability, and could require long and expensive maintenance services in case of damages.

In this study, we present an app for smartphone implementing two methods for LAI estimation, based on the use of sensors and processing power normally present in most of the modern mobile phones. The first method (App-L) is based on the estimation of the gap fraction at 57.5° (to acquire values that are almost independent of leaf inclination) from luminance estimated above and below the canopy. The second method (App-G) estimates the gap fraction via automatic processing of images acquired below the canopy. The performances of the two methods implemented in the app were evaluated using data collected in a scatter-seeded rice field in northern Italy, and compared with those of the LAI-2000 and AccuPAR ceptometer, by determining the methods' accuracy (trueness and precision, the latter represented by repeatability and reproducibility) and linearity. The performances of App-G (mean repeatability limit = 0.80 $m^2 m^{-2}$; mean reproducibility limit = 0.82 $m^2 m^{-2}$; RMSE = 1.04 $m^2 m^{-2}$) were similar to those shown by LAI-2000 and AccuPAR, whereas App-L achieved the best trueness value (RMSE = 0.37 $m^2 m^{-2}$), although it resulted the less precise, requiring a large number of replicates to provide reliable estimations. Despite the satisfactory performances, the app proposed should be considered just as an alternative to the available commercial instruments, useful in contexts characterized by low economic resources or when the highest portability is needed.

1. Introduction

Leaf area index (LAI) is a key variable for analyzing the interactions between plants and atmosphere, crucial for estimating the amount of radiation intercepted by vegetation and plant water requirements at different spatial scales, for studying the relationships between plants and environmental pollutants and for evaluating the photosynthetic activity (CO_2 sequestration).

Different methods were proposed for direct LAI measure, based on the collection of the leaves and on the subsequent measurements of their area by using dedicated instruments (e.g., Li-3100 C; Li-Cor, Lincoln, NE, USA) or by acquiring and processing leaf images. These methods are destructive and time consuming and, especially for species with small leaves or leaves subject to rapid withering and curling, they could be affected by a non-negligible

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level of uncertainty. In addition, being extremely labor and time consuming, subsamples are generally used to upscale to the total harvested sample and subsequently to unit area. Thus, direct methods are generally estimated to have an accuracy of about 10% or less (Daughtry and Hollinger, 1984). Moreover, they are practically inapplicable to tree species and forest ecosystems. For these reasons, different indirect methods have been developed, most of them based on simplified models of light transmission into the canopy. A variety of approaches for estimating LAI using direct and indirect methods were effectively reviewed by Bréda (2003), Jonckheere et al. (2004) and Weiss et al. (2004).

Several indirect methods estimate LAI from measurements of the gap fraction, defined as the fraction of sky seen from below the canopy (or fraction of soil seen from above) (Bréda, 2003; Jonckheere et al., 2004; Weiss et al., 2004; Garrigues et al., 2008). In many cases, these methods have been implemented into dedicated commercial instruments. These include systems using direct sunlight such as TRAC (Chen et al., 1997) and DEMON (Lang, 1986), ceptometers measuring the transmitted light fraction from incident diffuse and/or the direct illumination such as the SUNSCAN (Delta-T, Cambridge UK) or the AccuPAR (Decagon, Pullman, WA, USA), or sensors such as the LAI-2000 or LAI-2200 Plant Canopy Analyzers (Li-Cor, Lincoln, NE, USA), which measure the gap fraction from five different angles simultaneously. In other cases, indirect methods are applied by means of less specific devices, such as cameras with hemispherical (fish-eye) lenses, but although they demonstrated greater effectiveness and flexibility as compared to other approaches (Jonckheere et al., 2004), they are characterized by a lower level of automation, perhaps with the exception of the CI-100 plant canopy analyzer (CID Bio-Science, Camas, WA, USA), generally requiring a careful post-processing phase to provide LAI estimates.

Gap fraction can be easily transformed into effective LAI values, i.e., the LAI value that would correspond to the assumptions made in the models applied. These include in most cases a random distribution of the leaves within the canopy, which can be rather unrealistic especially for row crops or heterogeneous canopies, in which a high degree of leaf clumping occurs. Methods allowing multidirectional gap fraction measurements, such as hemispherical photography or the LAI-2000, allow accounting implicitly or explicitly for the leaf angle distribution (LAD), whereas other methods require additional assumptions on LAD. Each method has its own requirements in terms of measurement conditions, with some methods providing accurate results only under diffuse illumination conditions, which are sometimes difficult to comply with.

The availability of a variety of commercial products for indirect LAI estimations have prompted a number of studies aimed at the evaluation of indirect methods, both testing single instruments (e.g., Stroppiana et al., 2006; Baret et al., 2010) or comparing the performances of different approaches (e.g., Peper and McPherson, 1998; Keane et al., 2005; Garrigues et al., 2008). As demonstrated by different studies (e.g., Welles and Cohen, 1996; Peper and McPherson, 2003), the performances of the different methods are influenced by the type of vegetation investigated and by the conditions of application, but also by the sampling protocol. In facts, these studies are usually performed without following standard validation protocols so that in many cases the results are difficult to compare and the interpretation of results is difficult because of the lack of standard information on the method used, e.g., repeatability and trueness. The accuracy of a method is given both by its trueness and by its precision. Trueness represents the closeness of agreement between the average value obtained from a large series of measurement replicates and an accepted reference value, whereas precision represents the closeness of agreement between independent test results obtained under stipulated conditions (ISO, 1994). Precision can in turns be represented by repeatability (just coming from measurements repeated by the same person under the same conditions) and reproducibility (laboratory effect, obtained with inter-laboratory studies).

In general, many commercial instruments for indirect LAI estimation proved to be a good alternative to destructive methods in many experimental conditions, allowing researchers to save time while maintaining a reasonable level of reliability in the estimations. The other side of the coin is that these instruments are usually expensive (from about 4 to about 10 thousand Euros) and their level of portability may not be so high (from about 2 to more than 10 kg), although they are also used for extensive campaigns in forests or mountain areas (e.g., Kovacs et al., 2004; Yilmaz et al., 2008; Thimonier et al., 2010). Another disadvantage of these instruments is related to the time needed for repairing them in case of damage, due to the need of sending the instrument, getting a diagnosis and waiting for the repair. Although this could appear as a minor drawback, these activities lead in many cases to cancel the field campaign in case of damages to the instrument.

Smartphones, mobile phones with advanced computing capability and connectivity, are becoming ubiquitous, their price is falling and their capabilities rapidly increasing. The availability of camera, accelerometer, GPS and increasing memory and processing power makes them suitable for a number of purposes, including methods for indirect LAI estimation. Software packages designed to run on smartphones, in short “apps”, are expanding fast, and already include scientific applications (see, e.g., D’Elia and Paciello, 2012; Weng et al., 2012).

The objectives of this paper are:

- to present an app (PocketLAI) developed for estimating leaf area index using a smartphone and
- to compare its performances with those of LAI-2000 and AccuPAR ceptometer by adapting the ISO 5725 validation protocol (ISO, 1994) to *in vivo* field methods.

2. Materials and methods

2.1. Description of the app for estimating leaf area index using a smartphone

2.1.1. Theoretical background

The application we developed for estimating LAI using a smartphone (PocketLAI hereafter) is an implementation of a simplified model of light transmittance based on the assumption of a random spatial distribution of infinitely small leaves. In this case, the gap fraction P_0 (θ_v, φ_v) in direction of the zenith angle θ_v and azimuth angle φ_v is:

$$P_0(\theta_v, \varphi_v) = \exp[-G(\theta_v, \varphi_v)\frac{LAI}{\cos(\theta_v)}]$$

where $G(\theta_v, \varphi_v)$ is the projection function, i.e., the mean projection of a unit foliage area in the direction (θ_v, φ_v), which depends on the leaf angle distribution of the canopy. As discussed by Weiss et al. (2004), it has been shown (Warren-Wilson, 1963) that for a view angle of 57.5° the G-function can be considered as almost independent of leaf inclination (G ≅ 0.5) so that, by inversion of the model of Eq. (1) we can obtain LAI from the gap fraction measured at 57.5°:

$$LAI = -\left(\frac{\cos(57.5^\circ)}{0.5}\right)\log(P_0(57.5^\circ))$$

It has been shown both theoretically and experimentally (Baret et al., 2010) that this particular directional configuration makes the information acquired independent from leaf angle distribution and minimizes leaf clumping effect in case of row crops.

2.1.2. Implementation and characteristics of the app

PocketLAI app adapts the approach described above to a smartphone (Figs. 1 and 2), using an inclinometer derived by the device's accelerometer and the camera to obtain an estimate of $P_0(57.5°)$. The gap fraction estimate is acquired automatically while rotating the device along its main axis starting with the display orientated downward and concluding with the display in vertical position (or *vice versa*).

More specifically, once the app is put in measuring-mode, the user has 5 s to place the device below the canopy; then – after the app triggers a vibration event – the orientation of the screen surface is continuously recomputed from the components of the *g* vector, provided in real time by the accelerometer sensor, by using plain vector algebra. When the angle between the vertical and the normal to the screen reaches 57.5°, a camera frame is captured and transferred to the processing algorithms while the app issues a second vibration event to inform the user of the occurred successful acquisition.

Two methods for the determination of P_0 from the data acquired were implemented in PocketLAI and tested in this study. The first (App-G hereafter) derives P_0 from processing images acquired below the canopy using the smartphone camera in live-preview mode. Data from this continuous stream (~25 FPS) is preferred to avoid the time-lag caused by invoking a full-frame image capture, as this would result in a deviation from the target angle.

Images are automatically processed using an algorithm we expressly developed to detect sky pixels, based on a segmentation strategy: pixels are classified according to their chromatic values. The algorithm uses two different segmentations for cloudy and clear sky conditions: the first (cloudy sky) is simply based on the pixels intensity and is based on the assumptions that leaves appear darker than the sky in images acquired below the canopy. The second segmentation strategy (clear sky, with high levels of direct radiation) is based on the analysis of pixels chromatic values in an HSB (Hue Saturation Brightness) color space and is able to detect sky and clouds even from the parts of vegetation that, directly invested by light beams, can appear lighter and brighter than the sky (Fig. 3). This is possible through the identification of the residual green chromatic component persisting even in the most reflective part of the plants.

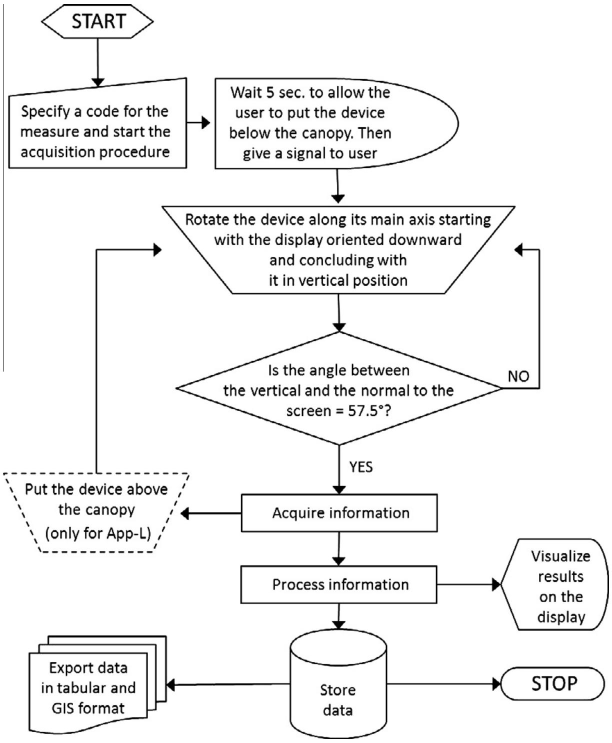

Fig. 1. Flowchart showing the functioning of the smart application for leaf area index estimates.

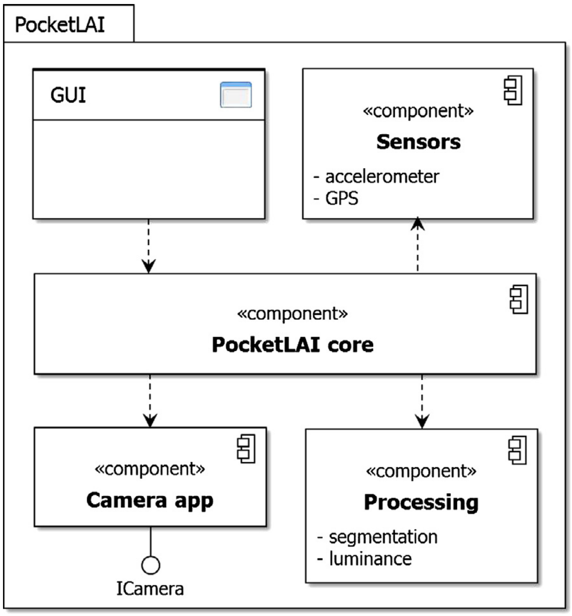

Fig. 2. UML Component diagram of PocketLAI.

The second method for P_0 determination (App-L) requires image acquisition both below and above the canopy (Fig. 1), and it is based on the estimation of luminance from the information provided by the device camera:

$$L = \frac{N^2 \cdot k}{t \cdot S}$$

where L (candela m^{-2}) is the luminance, N (is the f-number or focal ratio), t (seconds) is the exposure time, S is the ISO sensitivity, and k is the reflected-light meter calibration constant.

In this case, P_0 is then derived by using the following equation:

$$P_0 = \frac{L_b}{L_a} \cdot \beta$$

where L_b and L_a are the luminance below and above the canopy, respectively; β is a calibration parameter, used to correct the L_b estimation for the amount of radiation scattered by the canopy. The value for β (1.61) was derived in this study from the slope of the linear regression ($R^2 = 0.99$) calculated on direct and indirect measurements collected in a dedicated calibration plot in three moments during the crop cycle. The value of β determined in this study can be assumed as valid for rice and other species presenting similar canopy characteristics, although further tests should be carried out for the latters.

The application is provided with an integrated tool for optimal sample size determination (i.e., the number of LAI estimates to be averaged) based on the visual jackknife method (Confalonieri et al., 2009), free from any statistical assumption and particularly suitable for agro-environmental applications. This allows the collection of measurements representative of the specific canopy analyzed.

The development of App-G was carried on using Eclipse IDE 3.7.2 32bit for MS Windows and choosing Android SDK rev. 8 (Froyo) as the target platform to ensure the highest backward compatibility. For App-L, MS Visual Studio 2010 Express for Windows

Fig. 3. Capability of the algorithm for the automatic image processing of correctly detecting sky pixels even when parts of vegetation, directly invested by light beams, appear clearer and brighter than the sky.

Phone (C#) was used. For App-G, the application memory footprint (heap size) was kept below the 24 MB limit imposed by the platform by designing proper reuse of UI elements and ensuring no memory leak was introduced in application lifecycle. The simpler algorithm implemented in App-L (no image processing is needed) allowed keeping the runtime memory occupation value below 15 MB. App-G was tested using an entry level ARMv7 800 MHz power handheld; App-L was tested using a Qualcomm Snapdragon 1400 MHz. Both the devices were equipped with a 5 megapixel focus free camera, with a complementary metal oxide semiconductor (CMOS) image sensor (≅360–740 nm; e.g., Igoe et al., 2013).

2.2. Accuracy (trueness and precision) determination

Data for the comparison of the performance of PocketLAI against LAI-2000 and AccuPAR, were collected in Gaggiano (Northern Italy, 45.24°N, 9.02°E, 117 m a.s.l.) during 2012. Rice (*Oryza sativa* L., cv Volano, Japonica type) was scatter seeded on April 30, and grown under continuous flooding conditions. Rice received 120 kg N ha^{-1}, as urea, split in two events. Field management allowed prevention of water and nutrient stresses and kept the field weed and pest free.

Plant density was set to 200 and 140 plants m^{-2} in two 16 m^2 square plots (D1 and D2 hereafter). The small size of the plots was due to the need of maximizing the within-plot homogeneity.

In order to adapt the ISO 5725 validation protocol to *in vivo* field methods, the inter-laboratory effect was simulated by dividing operators in three independent groups (laboratories hereafter, according to the ISO 5725 terminology), that were provided with instruments and their user's manuals and that performed measurements in different moments within the day. This allowed to simulate the effect of slight differences in the interpretation of the methods which in the ISO protocol can derive from the presence of different laboratories, whereas the different measurement moments within the day allowed to reproduce the effect of performing measurements under different conditions (temperature and irradiance level in our case).

The ISO 5725 effect of different levels for the property being measured was reproduced by carrying out the measurements in three dates during the crop cycle, corresponding to the third-leaf stage (June 11; code 13 of the BBCH scale for rice; Lancashire et al., 1991), to the mid-tillering stage (July 9; BBCH code 23), and to the booting stage (July 30; BBCH code 49, flag leaf sheet open). This allowed to cover a wide range of LAI values.

For all the indirect methods, i.e., App-L, App-G, LAI-2000 (in both 4- and 5- ring configurations) and AccuPAR, four measurement replicates were carried out by dividing each plot in 4 m^2 quadrants and by performing measurements with the operators on the border of the plot. For all the instruments, each replicate included five below-canopy readings (Stroppiana et al., 2006) randomly performed within each quadrant. This design, i.e., distribution of replicates in homogeneous quadrants, allowed to take the four replicates on homogeneous areas of the plot and to preserve the canopy from possible trampling effects due to the high number of measurements performed during the campaign (four methods, three laboratories, four replicates, three dates).

According to the ISO 5725, the Cochran's test for homoscedasticity (Cochran, 1941) was applied to identify possible outliers among the laboratories for what concerns the variances calculated on the four replicates, for each plant density, for each date and for each method. In the same way, Grubbs' test (Grubbs, 1969) was applied to identify possible outliers among the laboratory means. For both the tests, values were considered as stragglers and outliers based on the comparison of the tests results with their 5% and 1% critical values. According to ISO (1994), straggler values were included in successive statistical analyses, whereas outliers were excluded (Bocchi et al., 2008).

After discarding outliers, standard deviations of repeatability (s_r) and reproducibility (s_R) were calculated. Since s_R is given by $\sqrt{s_r^2 + s_L^2}$ in which s_L^2 represents the variance among laboratories, s_R^2 was expected to be greater or equal to s_r^2. When s_r was greater than s_R, s_r was corrected by setting s_r equal to s_R (Horwitz, 1995; Scaglia et al., 2011). Finally, repeatability (r) and reproducibility (R) limits were calculated by multiplying, respectively, s_r and s_R by $\sqrt{2}t$, with t being the critical value of the Student t distribution (2 tails) at the 95% confidence level for $n - 1$ freedom degrees. All the data were processed using the software AMPE (Acutis et al., 2007).

The need for reference measurements to get the trueness of the methods was reproduced by the comparison of the values provided by indirect methods with those coming from planimetric destructive measurements, performed on 20 plants randomly collected for each plot and date (Confalonieri et al., 2009). LAI was then derived multiplying the average plant area by the number of plants per square meter. Photographs of flattened out leaves taken against a calibrated background grid were acquired in the field and processed subsequently in order to reduce area meter errors due to leaf curling. Trueness was quantified by calculating the root mean square error (RMSE; 0 to $+\infty$, optimum 0) (Fox, 1981), modelling efficiency (EF; $-\infty$ to +1; optimum +1; if negative indicates that the average of reference values is a better predictor than the indirect estimations) (Loague and Green, 1991), and coefficient of residual mass (CRM; $-\infty$ to $+\infty$, optimum 0; if positive indicates underestimation and *vice versa*) (Loague and Green, 1991).

Table 1
Precision (repeatability and reproducibility) of the methods implemented in the app, of the AccuPAR LP-80 ceptometer, and of LAI-2000 in both 5- and 4-ring configurations. Italicized areas indicate the best performances.

Date	Plot	Method	Mean LAI ($m^2\ m^{-2}$)		Repeatability		Reproducibility	
			Destructive	Estimated	*r*[a]	RSD_r[b]	*R*[c]	RSD_R[d]
11/6/2012	D1	App-G	0.49	0.20	*0.16*	*28.33*	*0.18*	*31.04*
		App-L		0.51	1.04	72.03	1.09	75.52
		AccuPAR		0.24	0.48[f]	70.03[f]	0.48	70.03
		5R		0.60[e]	1.04[f]	63.30[f]	1.04	63.30
		4R		0.54	0.88	54.79	0.91	56.99
	D2	App-G	0.25	0.09	*0.15*	*57.76*	*0.15*	*57.94*
		App-L		0.33	0.66[f]	71.90[f]	0.66	71.90
		AccuPAR		0.13	0.28[f]	75.00[f]	0.28	75.00
		5R		0.47	0.89[f]	68.14[f]	0.89	68.14
		4R		0.39	1.04[f]	95.60[f]	1.04	95.60
9/7/2012	D1	App-G	3.11	4.13	1.45[f]	12.50[f]	1.45	12.50
		App-L		3.22	2.58[f]	28.67[f]	2.58	28.67
		AccuPAR		3.37	1.16	12.30	1.19	12.56
		5R		3.16	*0.83*[f]	*9.43*[f]	*0.83*	*9.43*
		4R		3.56	0.98[f]	9.85[f]	0.98	9.85
	D2	App-G	2.02	2.55	1.11[f]	*15.54*[f]	1.11	*15.54*
		App-L		1.86	1.37	26.27	1.93	37.11
		AccuPAR		1.84	*0.84*[f]	16.36[f]	*0.84*	16.36
		5R		2.11	1.42[f]	24.04[f]	1.42	24.04
		4R		2.32	1.67[f]	25.70[f]	1.67	25.70
30/7/2012	D1	App-G	6.10	4.03	0.97	8.56	1.03	9.12
		App-L		5.40	1.94	12.82	4.04	26.70
		AccuPAR		4.37	*0.79*	*6.43*	*0.95*	*7.74*
		5R		3.51	1.51[f]	15.39[f]	1.51	15.39
		4R		3.98	1.78[f]	16.01[f]	1.78	16.01
	D2	App-G	2.92	3.80	0.96	*9.03*	*1.02*	*9.58*
		App-L		3.48	1.51	15.48	1.58	16.27
		AccuPAR		2.84	*0.84*	10.62	1.17	14.74
		5R		2.69	1.58	20.93	1.70	22.59
		4R		3.02	1.86	22.05	2.01	23.79

[a] Repeatability limit.
[b] Relative standard deviation of repeatability.
[c] Reproducibility limit.
[d] Relative standard deviation of reproducibility.
[e] Laboratory 3 is an outlier according to the Cochran test.
[f] Corrected value (s_r set equal to s_R in case $s_r > s_R$; Horwitz, 1995; Scaglia et al., 2011).

3. Results

Table 1 shows the results of the precision determination for the evaluated methods. The Cochran's test identified laboratory 2 as straggler for the App-L method applied to the highest plant density (D1) in the first date; laboratory 3 resulted straggler for LAI-2000 4-rings in the same plot and date; laboratory 1 was identified as straggler for both the LAI-2000 configurations for the second date and plant density D2. However, the corresponding values were considered for precision determination according to ISO (1994). On the contrary, laboratory 3 was identified as an outlier by Cochran's test for LAI-2000 5-rings measurements collected in the first date for plant density D1. These data were excluded by the procedures for precision determination.

AccuPAR and App-G (segmentation for cloudy conditions in the first date, for clear sky conditions in the others; see Section 2.1.2) resulted the methods with the best performances in terms of precision, achieving, in general, the lowest values for the repeatability and reproducibility limits, with App-G resulting slightly less affected by the effect of different operators. AccuPAR resulted the most precise method in the second part of the crop cycle, thus for higher LAI values, whereas App-G showed the best repeatability and reproducibility for the first date, with LAI values (destructive method) lower than 0.5 $m^2\ m^{-2}$ (Table 1). App-L was the method that presented the worst reproducibility, resulting markedly affected by an operator-effect.

Fig. 4 shows the relationships between repeatability (*r*) and reproducibility (*R*) limits and LAI values measured with the destructive method. For all the methods but App-L, both *r* and *R* were lower for the first sampling date, whereas no relevant changes were observed for the other two dates, suggesting a relatively constant precision for LAI values higher than about 2 $m^2\ m^{-2}$. On the contrary, App-L showed a significant linear relationship between LAI and *R* ($R = 0.543\ LAI + 0.632$, $R^2 = 0.92$, $p < 0.01$). Although App-L resulted the less precise among the methods evaluated, the significance of this relationship could support users while interpreting their results because of the possibility of calculating reproducibility limits for whatever LAI value. For all the other methods and for practical purposes, *r* and *R* can be assumed to increase from 0 to 2 $m^2\ m^{-2}$ and to remain constant for values higher than 2 $m^2\ m^{-2}$ (Fig. 2).

Table 2 and Fig. 5 show the agreement between (i) the LAI values measured with the destructive method for the three dates and the two plant densities, and (ii) the averages of the corresponding values estimated by each indirect method. App-L presented the best values of RMSE and EF, and achieved the best value for CRM together with App-G. All the method are characterized by an underestimating behavior (positive CRM), although this tendency is less relevant for the two methods implemented in PocketLAI. For all the methods but App-L, this is the result of a marked underestimation – more pronounced for LAI-2000 5-rings – in the third date for the highest plant density (Fig. 5), when the destructive method provided the highest LAI value (6.10 $m^2\ m^{-2}$).

App-L ($R^2 = 0.97$, $p < 0.01$) and AccuPAR ($R^2 = 0.92$, $p < 0.01$) showed the highest linearity, with the other methods presenting

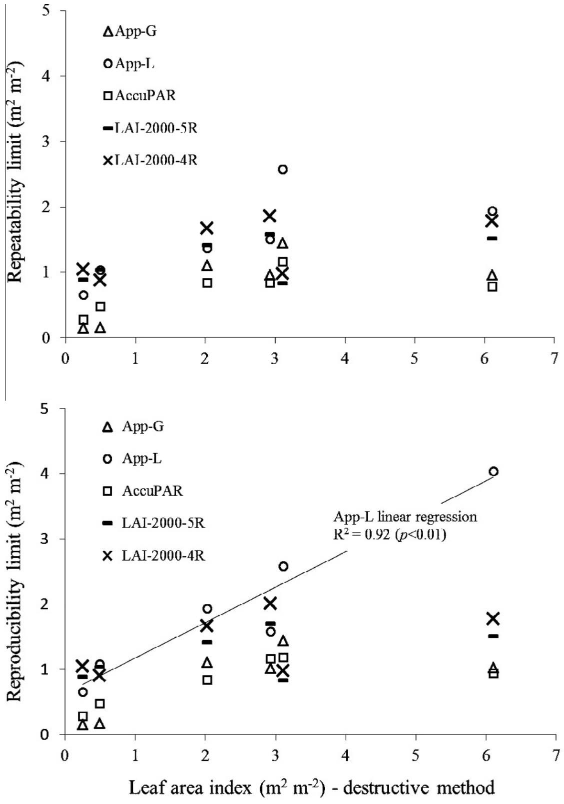

Fig. 4. Relationships between repeatability and reproducibility limits and leaf area index values measured with the destructive (planimetric) method.

Table 2
Trueness of the two methods implemented in the app, of the AccuPAR LP-80 ceptometer, and of LAI-2000 in both 5- and 4-ring configurations. Grayed areas indicate the best performances.

Method	Root mean square error (RMSE)	Modelling efficiency	Coefficient of residual mass
App-G	1.04	0.72	*0.01*
App-L	*0.37*	*0.96*	*0.01*
AccuPAR	0.73	0.86	0.14
5R	1.07	0.70	0.16
4R	0.90	0.79	0.07

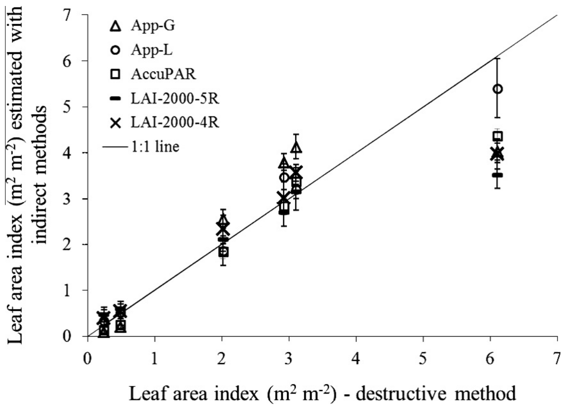

Fig. 5. Comparison between leaf area index values estimated with the indirect methods and those measured with the destructive (planimetric) method.

R^2 ranging from 0.72 (App-G, $p < 0.05$) to 0.84 (LAI-2000 5-rings, $p < 0.05$).

4. Discussion

All the methods tested have the capability to provide an estimate of an "effective LAI", which is as close to the destructive LAI as much as the canopy is close to the assumptions made of randomly distributed small leaves. Scatter seeded rice provided a canopy without a row structure, in which stronger clumping effects must be taken into account (Baret et al., 2010). In addition, all the methods provide an estimate of the plant area index rather than of LAI, since they do not distinguish between leaves and stems.

In general, the performance of App-G were similar to those shown by AccuPAR, and both the methods showed slightly better metrics with respect to LAI-2000, especially for precision (repeatability and reproducibility). A higher capability of AccuPAR to reproduce destructive LAI compared to LAI-2000 was already noticed by Facchi et al. (2010) for herbaceous species, whereas other authors underlined a better LAI-2000 behavior for grassland (He et al., 2007), trees (e.g., Peper and McPherson, 1998) and bushes (Brenner et al., 1995). In our case, the main problem with LAI-2000 was an underestimation of the LAI values for the third date (booting stage) and the highest plant density. This saturation effect was already noticed for LAI-2000 – and less for AccuPAR – by Facchi et al. (2010) for a maize crop. This, together with the ceptometer capability to be used also in direct light conditions, might make AccuPAR a more versatile tool for LAI estimation than LAI-2000. We took care of performing LAI-2000 measurements in cloudy conditions or casting a large shadow on the sensor and the canopy by means a large sheet held by canes, but residual errors due to non perfectly diffuse light conditions might have occurred. The 4-ring configuration of LAI-2000 resulted more accurate than the standard 5-rings one, as already observed in previous studies carried out on rice (e.g., Stroppiana et al., 2006) and maize (Wilhelm et al., 2000) crops.

Among the methods compared, App-L was characterized by the lowest precision and by the highest trueness. This makes this method suitable only in case of the possibility of performing a large number of replicates.

By discussing performance results also in light of other features (Table 3), the methods implemented in PocketLAI (App-G and App-L) present advantages compared to both AccuPAR and LAI-2000 especially for their costs (i.e., few euros in case of already having the use of a smartphone compared to different thousand euros) and for their portability. The latter, although being considered a secondary issue in many cases, could become crucial in case of extensive campaigns, like those carried out on mountain grassland, forests, etc. The low cost of the app could represent a relevant advantage too in research contexts characterized by low resources or when different instruments would be simultaneously needed during the same campaign. Another advantage of PocketLAI is the elimination of maintenance and repair costs, and to the elimination of the risk of interrupting the campaign in case of damages to the single instrument available in a research group.

Like the hemispherical camera and other instruments not tested here (e.g., CI-100 plant canopy analyzer, CID BioScience, Camas, WA, USA), the App-G method allows to get LAI estimates with just the below-canopy reading. This could make it suitable in case of forests, vineyards or tall herbaceous canopies like those characterizing, e.g., maize and sugarcane.

5. Conclusions

Recent advances in the technology available in mobile devices like smartphones is opening new opportunities for using their hardware architectures and sensors for purposes different from

Table 3
Considerations on the methods used for indirect leaf area index estimation (see Peper and McPherson, 2003).

Instrument	App (both methods)	AccuPAR	LAI-2000
Cost (approx.)		4600 €	10,000 € for current model (i.e., LAI-2200)[a]
Size		9.5 × 3.3 × 102 cm Case: 11.8 × 24 × 109 cm	Acquisition unit: 63.8 × 4.4 × 5.1 cm Control unit: 20.9 × 9.8 × 3.5 cm Case: 65 × 14 × 43 cm
Weight		0.55 kg (4.15 kg with case)	1.3 kg (6.5 kg with case)
Conditions	Clear or cloudy	Clear or cloudy	Cloudy sky, or sun at or below horizon (diffuse light)
Setup	Below (and above for luminance-based method) canopy leveling through an integrated digital inclinometer	Above and below canopy leveling required (bubble level)	Above and below canopy leveling required (bubble level)
Reference readings	Above canopy readings for luminance-based method; none for image processing-based one	Above canopy readings	Above canopy readings

[a] Second optical sensor for tall canopies not included.

those these commercial devices were built for. In fact – and at least for the applications discussed in this study – neither the quality of sensors nor the computational power of processors limited the functionality of the algorithms used to estimate biophysical variables using mobile devices. For what concerns the quality of sensors, this is probably due to the magnitude of other sources of uncertainty related to the variable investigated – related to, e.g., the variability among plants, or deviations (when real plants are considered) from the assumptions behind the models for light transmission into the canopy – that likely hides possible problems deriving from the low cost of the hardware used.

The two methods for LAI estimation proposed in this study (implemented in the smartphone PocketLAI) showed similar performances compared to instruments already available on the market, i.e., AccuPAR and LAI-2000. App-G (based on the gap fraction) was comparable to these instruments for both trueness and precision, whereas App-L (based on luminance estimates above and below the canopy) resulted more correlated with destructive LAI measurements although markedly less repeatable and reproducible. None of the compared methods got validation metrics decidedly better than the others. So, what we propose (PocketLAI) could just be an alternative that could be useful in certain operational contexts, characterized by low economic resources or when portability is important.

Further tests – on different species and canopy structures and under different agroclimatic conditions – are needed to confirm the reliability of the methods implemented in the app. However, the experience of using standard validation protocols, i.e., an adaptation of ISO 5725, was found very useful, assuring objectivity to the whole validation procedure.

Future developments of the app will involve different technical aspects, like the implementation of options for the use of information acquired at different angles (like for LAI-2000) and options for explicitly accounting for the clumping effect.

The App-G method is currently available for the Android platform, which does not have at the moment the possibility of implementing the luminance-based method (App-L), which is currently available for Windows Phone. Next steps will be the development of the iPhone version of the app (running also on some iPod models), that will include both the App-G and App-L methods.

Software availability

Name of software: PocketLAI
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