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COMPARING OPTICAL AND DIRECT METHODS FOR LEAF AREA INDEX DETERMINATION IN A MAIZE CROP

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1. Introduction

Leaf area index (LAI) is a dimensionless variable defined by Watson [1947] as the total one-sided area of photosynthetic tissue per unit ground surface. LAI is a crucial variable in the modelling of many hydrological processes, such as transpiration, evaporation and rainfall interception by vegetation.

Recent review papers [Jonckheere 2004; Weiss 2004; Hyer 2004; Kussner 2000; Gower 1999] provided a broad outlook on the aspects and problems associated with the determination of LAI. Basically the methods fall under two categories: direct and indirect. Although the former methods, based on a direct measure of leaf area, are the most accurate, they have the disadvantage of being highly time-consuming and therefore not practically compatible with the monitoring of the leaf area variation in time and space, especially over large areas [Jonckheere 2004].

To overcome some of the practical limitations which characterize direct methods, since the Sixties several indirect optical devices based on the measurement of radiation transmitted through the canopy have been developed. They are based on the Beer-Lambert law and assume that the radiation intercepted by a canopy is a function of incoming radiation, canopy structure and its optical properties [Jonckheere 2004; Monsi 1953]. Several devices are available on the market, each one with its own protocol for the execution of measurements, but the studies comparing some of these instruments under field conditions in agricultural canopies are still very few [rice crops: Stroppiana 2006; Sone 2009; soybean crops: Malone 2002; maize crops: Wilhelm 2000; bean crops: de Jesus 2001].

Among the more recent optical devices, the LI-COR LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, NE, USA) and the Decagon AccuPAR-80 ceptometer (Decagon Devices, Pullman, WA, USA) are widely used. Both are portable instruments providing immediate LAI estimates by measurements taken above and below the canopy. The LAI-2000 meter measures the incoming radiation by means of a fish-eye lens apparatus. The hemisphere is subdivided in five concentring zenithal sectors, rings or bands (respectively centred on zenithal angles θ = 7°, 23°, 38°, 53° and 68°), each one considering the complete range of azimuthal angles ϕ. The radiation collected by each zenithal sector is directed to a different photoelectric sensor. An optical filter is adopted to reject solar wavelengths out of the range 320-490 nm; in this interval leaves behave as black bodies. By measuring the radiation transmitted at different zenithal sectors, the leaf angle distribution can be retrieved and LAI can be obtained by the inversion of a Poisson model. The LAI-2000 should be used only under diffuse light conditions (uniformly overcast sky, dawn, dusk) to minimize light scattering of leaf surfaces which could bias the LAI retrieval and measurements should be carried out at a distance of about 3 times the plants height from the edge of the plot [Malone 2001; LI-COR 1992]. Many studies showed that the LAI-2000 provides estimates which are systematically lower than the destructive sampling when LAI ≥ 3-5 m^2m^{-2}, justifying this with the reaching of an asymptotic "saturation" level due the canopy closure at the higher LAI values [Sone 2009; Jonckheere 2004; Hyer 2004; Gower 1999]. Some authors [Sone 2009; Stroppiana 2006; Leblanc 2001; Wilhelm 2000; Grantz 1993] suggested that neglecting the 5th ring (average zenithal angle 68°, the larger one) in LAI computation may improve the estimation in vertical canopies or situations where the sensor field of view is less than 3 times the crop height. This point is nevertheless an open issue, since some authors found a decrease in estimated LAI with the elimination of the lowest ring [Chen 1996].

The Decagon AccuPar-80 ceptometer is composed of an integrated controller and a 80 cm probe contain-

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ing 80 quantum sensors positioned at 1 cm distance over it; photosensors measure the radiation in the photosynthetically active radiation (PAR) spectral range: 400-700 nm. Differently from the LAI-2000, measurements taken by the ceptometer do not provide information about the canopy structural characteristics, since the incoming radiation is not acquired as a function of the zenithal angle. The model for retrieval of LAI from the measurements of canopy transmission is a simplified version of that proposed by Norman and Jarvis [1975] and it is reported in the instrument's manual [Decagon Devices 2001]. The leaf angle distribution parameter x [Campbell 1986] must be set by the user depending on the crop, while the leaf absorbivity a is set by the instrument to 0.9 for all the canopies (i.e. leaves do not behave as black bodies in the PAR range). The scarce literature dealing with LAI measurements in agricultural crops shows that, once selected the appropriate x value (a list of x values for the main crops is provided in the manual), the ceptometer can provide sufficiently reliable estimates even in absence of a site-specific calibration [Wilhelm 2000]. Advantages with such a device are the ease of use and the possibility to take measurements under any light condition.

Since the Eighties many attempts have been made to estimate LAI values from photographs taken by cameras equipped with fish-eye lens located above or under the canopy (with lens oriented respectively upward or downward). Hemispherical photographs, capturing the light attenuation and the contrast among the objects (i.e. canopy vs. sky/soil) could represent a valid source of information to retrieve canopy architecture parameters and leaf area. Hemispherical photographs provide an extreme view angle (generally 180°), the resulting circular image shows a complete view of all sky directions, with the zenith in the centre and the horizons at the edges [Jonckheere 2004]. The advent of high resolution digital cameras, along with the advancement of image processing techniques and the availability of larger computing power have increased the possibility to utilize hemispherical photographs for the retrieval of LAI, commonly from the inversion of a Poisson model. One of the main problems cited in literature related to the use of hemispherical photography for LAI determination is the selection of the optimal brightness threshold to distinguish leaves from the background (i.e. sky or soil) for the production of a binary image. However, with high resolution RGB cameras this problem is less critical, since the frequency of mixed pixels is reduced [Jonckheere 2004]. Different packages are nowadays available for the hemispherical images processing, among others: Hemiview (Delta-T Devices), SCANOPY (Reagent Instruments) and CAN-EYE [Weiss 2002].

Canopy non-randomness (i.e. clumping at the plant and canopy scales) is a problem for all optical devices. Comparing LAI obtained by those instruments with destructive sampling leads to an underestimation in the case of aggregated canopies and to an overestimation for regular foliage [Fassnacht 2009]. This issue was investigated particularly in the case of forest canopies, but the few published studies dealing with agricultural crops showed that for many crops the clumping index is different from unity and varies as a function of the development stage and plant density. In particular, for maize, values in the 0.65-0.9 interval were found for average plant density conditions, the higher values usually corresponding to initial development stages [López-Lozano 2007; Demarez 2008].

This paper presents the results of an experimental campaign conducted in full field conditions, aimed at the comparison of LAI values estimated by three optical instruments (AccuPAR-80 ceptometer, LAI-2000 LI-COR meter and a digital camera with a fish-eye lens) with those measured by destructive sampling. The experiment was carried out in August 2006 in a maize field of about 10 ha located in the Lombardy Plain (Northern Italy), in a phenological phase just antecedent to the flowering (LAI-max). Six plots were delimited in an homogeneous portion of the field and measurements with the four methods were conducted before and after the execution of successive thinnings of plant populations in the plots. Measurements were carried out in three plots (replicates) for each thinning level. The paper illustrates the experimental design, the measurement protocols for the different methods and the results of the statistical analyses performed on the collected data.

2. Materials and methods

2.1 *Experimental site*

The experimental campaign was conducted in the period 02-06 August 2006 in an irrigated maize field of about 10 ha located in the farm A. Menozzi (Landriano, Pavia; UTM coords: 1520840 E, 5018605 N) belonging to the State University of Milan. The soil is an Oxyaquic Eutrudept, loamy skeletal (USDA-2003 classification), developed from sandy and gravelly fluvial sediments. In 2006 *Zea Mais* (class 600) was sown after *Lolium Multiflorum* in the field, to produce forage for livestock. After manure application and soil operations, maize was sown on 30 May (inter-row distance 70 cm, seeding distance 19 cm); emergence was on 6 June. Crop was irrigated as needed to avoid water stress. The date of harvest was on 10 October (unitary production 44 t ha^{-1} of fresh matter, humidity 35%).

2.2 *Experimental design*

The experimental campaign was carried out in the days immediately preceding the flowering phase (LAI-max). On 02 August six plots of 7x7m were delimited in a portion of the field characterized by uniform LAI values. Each plot included 10 maize rows, for a total of about 350 plants. Plots with their identification codes are shown in Figure 1.

On 04 August three plots were thinned (1A-2B-3A) by removing about 50 plants from each of them (thinning -1). Thinning was carried out by cutting at the soil surface one out of seven plants, in different positions for alternate rows, to avoid gaps lined up across rows. Plants in each plot at the beginning of the experiment and those removed were counted (plants remaining in each plot were obtained by the difference between the two values). One half of the plants removed were selected for biomass determination (25x3 plots), for a sub-sample (5x3 plots) the destructive determination of LAI was additionally carried out. At the sunset, under diffuse light conditions, LAI-2000 measurements were taken in all the six plots (thinnings 0 e -1). Ceptometer and hemispherical camera measurements were conducted in the six plots in the morning of 05 August. Afterwards, plots 1B, 2A, 3B were thinned cutting two out of seven plants, always in different positions for alternate rows (thinning -2). As for the previous three plots, plants originally present and those removed were counted and 25 plants for each plot were selected for biomass determination; among these, 5 for each plot were chosen for the destructive determination of LAI. The exercise was continued by thinning progressively the two groups of plots, counting every time the removed plants and calculating the plants remaining in each plot, as five out of seven plants were eliminated (thinning -5). At each level of thinning, ceptometer and hemispherical camera measurements were carried out. At the sunset, in the six plots (1A, 2B, 3A at thinning -3; 1B, 2A, 3B at thinning -5), LAI-2000 measurements were performed.

2.3 *Measurement protocols*

2.3.1 Destructive sampling

Leaves of the 25 plants selected from each plot (25x6 plots) were removed by cutting them at the collar and subsequently put in folders with univocal codes. The 20x6 folders containing leaves not destined to the direct determination of LAI were dried in an oven at 105°C for 48 hours and then weighted to determine their dry biomass.

Leaves of the plants selected for the destructive determination were positioned over a white surface and photographed with a digital camera fixed to a vertical bar with the lens pointed downward. Afterwards they were put back in their folders and oven-dried. Images acquired were elaborated by the software Adobe Photoshop to separate plant leaves from the background and calculate their area. The LA value (Leaf Area; m^2) was obtained for each plant; summing up LA values for the 5 plants of each plot and dividing by their corresponding dry weights, the average SLA value (Specific Leaf Area: LA per unit of dry biomass; $m^2\ kg^{-1}$) was calculated. The average LA value for each plot was then obtained multiplying the SLA value found for the 5 plants by the dry biomass of the 25 plants removed from each plot divided by their number. LAI value ($m^2\ m^{-2}$) for the different thinning levels was finally calculated by multiplying the average LA value for each plot by the plant density (i.e. number of plants in the plot divided by its surface). At the initial time (thinning 0) plant density is very close to the sowing density.

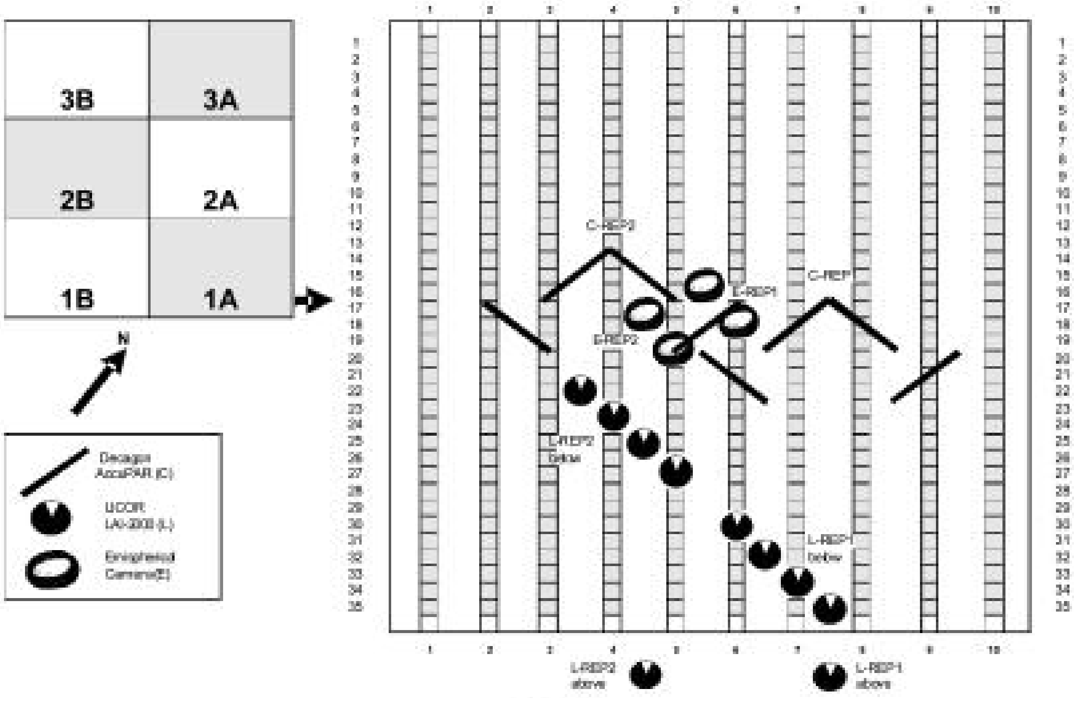

Fig. 1 - Experimental plots and their codes; position of the optical instruments (LAI-2000, AccuPAR-80 and hemispherical camera) for under-canopy LAI readings in each plot.

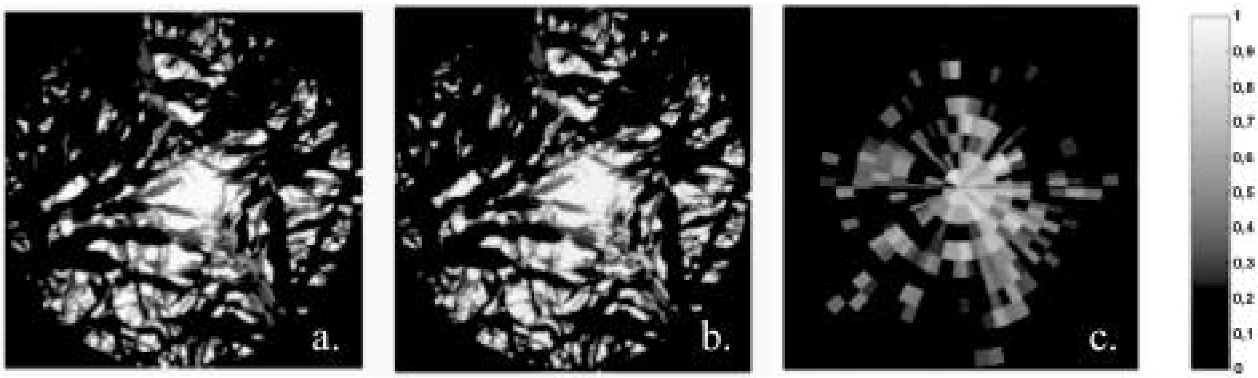

Fig. 2 - Examples of: (a) hemispherical photo after contrast enhancement, (b) uniform grey-colour representing classification of sky, (c) average value of gap fraction (sky portion) for each angular sector.

2.3.2 LI-COR LAI-2000

LAI measurement protocol for the LAI-2000 device consisted of two groups of readings, each including four under-canopy measurements preceded by one above-canopy reading (Fig. 1). Readings were carried out positioning the LAI-2000 meter at the south-eastern edge of the field. A 270° cap was used to restrict the azimuthal field of 270°, so that the operator was not in view and the open portion of the sensor was pointed north-west along the rows. The four under-canopy readings of each group were carried out at an average distance of 35 cm along a transect positioned at a 45° angle with respect to the rows; in the case of the former group (L-REP1) starting from the centre of an inter-row, in the case of the latter (L-REP2) from a row, proceeding in both cases towards west. Each group of readings provided a LAI value, the two LAI values were then averaged. Measurements were always taken at sunset; therefore, since the campaign lasted two-days, they were not available for the –2 and –4 thinnings.

2.3.3 Decagon AccuPAR-80

Two groups of readings were taken, each one composed of four under-canopy measurements preceded by an above-canopy measurement. They were carried out in the eight central rows of each plot, positioning the probe at a 45° angle with respect to them for the under-canopy measurements (Fig. 1). In the case of the former group (C-REP1) the four under-canopy readings started from a row, in the case of the latter (C-REP2) from the centre of an inter-row. Due to the probe length, each under-canopy reading was an average value over 80 cm. To avoid any systematic error due to lighting conditions, at each under-canopy reading the probe was rotated 90°. LAI values obtained by the two groups of readings were then averaged. As reported in the manual of the instrument, for maize leaves a spherical distribution was selected (x=1, i.e. average leaf inclination angle equal to 45°); leaf absorbivity a was set by the instrument at 0.9 for all the crops.

2.3.4 Hemispherical Camera

A high resolution digital camera (Nikon Cool Pix 990, 4 Mega pixel) with a fish-eye lens (Nikon FE-E8 8 mm) equipped with a 20 cm tripod was used in the experiment. The measurement protocol consisted of two groups of readings (Fig. 1), each one constituted by two images taken positioning the tripod with the camera on the ground with the lens oriented upward. The first image of the group (E-REP1) was taken in correspondence of a row, the second (E-REP2) from the centre of an inter-row. After checking the contrast between the canopy and the sky, pictures were stored and later processed using the software package CAN-EYE 3.6. Through the software, hemispherical photographs were divided into angular sectors with respective zenith and azimuth angular resolutions of $\Delta\theta=5°$ and $\Delta\phi=5°$. To avoid large zenith view angles, which have a higher probability of mixed pixels, the hemispherical field of view was restricted between zenithal angles 0° and 60°. Moreover, the selected zenith range is more comparable to the LAI-2000 acquisition geometry. A supervised classification driven by the selection of training samples was then carried out to distinguish between green vegetation elements and sky portions in the images (Fig. 2b). Once calculated the average value of gap fraction (i.e. sky portion) for each sector of the image (Fig. 2c), "effective" LAI was directly retrieved by inversion of a Poisson model using look-up-table (LUT) techniques [Knyazikhin 1998, Weiss 2000]. Finally the "true" LAI was related to "effective" LAI through the clumping index λ_0 [Chen 1992], computed in CAN-EYE using the Lang and McMurtrie [1992] logarithm gap fraction averaging method.

3. Results and discussion

In Figure 3 averages and standard deviations of LAI values determined by each method in the three plots are reported as a function of the thinning level. The figure shows that LAI averages obtained by the AccuPAR ceptometer are always higher than those measured by the destructive method.

The "true LAI" averages obtained by hemispherical images show a good correspondence with the destructive sampling only for high LAI values; for LAI values around 3 $m^2\,m^{-2}$ an overestimate is already evident, which becomes even more marked for lower LAI values. The "effective LAI" averages underestimate the destructively sampled LAI, reaching an agreement only for the lowest LAI values. This behavior for the "effective LAI" was recently reported in literature [Demarez 2008].

Also the LAI-2000 underestimates the destructively sampled LAI for high LAI values, while an overestimation for lower LAI values is found. This behaviour for the LAI-2000 is highlighted also by other authors [Stroppiana 2006]. Values obtained excluding the fifth zenithal ring from LAI calculation are higher than those determined with the standard configuration. As already highlighted, data for -2 and -4 thinnings were not acquired with the LAI-2000 meter.

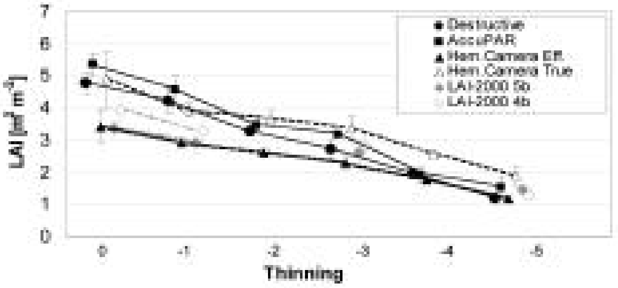

Fig. 3 - Averages and standard deviations of LAI values determined in the three plots (i.e. replicates) by each method, as a function of the thinning level.

Figure 4 shows the correlations between LAI values obtained by the destructive sampling and those obtained through the indirect methods. In particular, correlations considering all the available data (in gray) and the average values for the three replicates (in black) are reported.

For the AccuPAR ceptometer the tendency to overestimate the entire range of the explored LAI values is confirmed. The correlations are nevertheless very good: the angular coefficient of the lines is very close to 1 and R^2 is equal to 0.93 and 0.98 respectively considering all the pairs of data and the averages of the three replicates.

The "effective LAI" retrieved by hemispheric photographs shows an underestimation over the entire range of LAI values, but the correlations are nevertheless good to very good: R^2 is equal to 0.91 when all the available data are taken into account and 0.98 when only the average values of the three replicates are considered. The "true LAI" confirms a good correspondence with the destructive sampling when LAI is high, while at the decreasing of LAI a tendency to underestimate the destructive measurements becomes evident; the R^2 is equal to 0.85 and 0.96 respectively for the two data sets.

The LAI-2000, both including and excluding the 5th zenithal ring, underestimates the intermediate and high LAI values. With the five rings the correlation is fairly good when all the available data are considered ($R^2 = 0.78$) and very good when considering the average values of the three replicates for each thinning

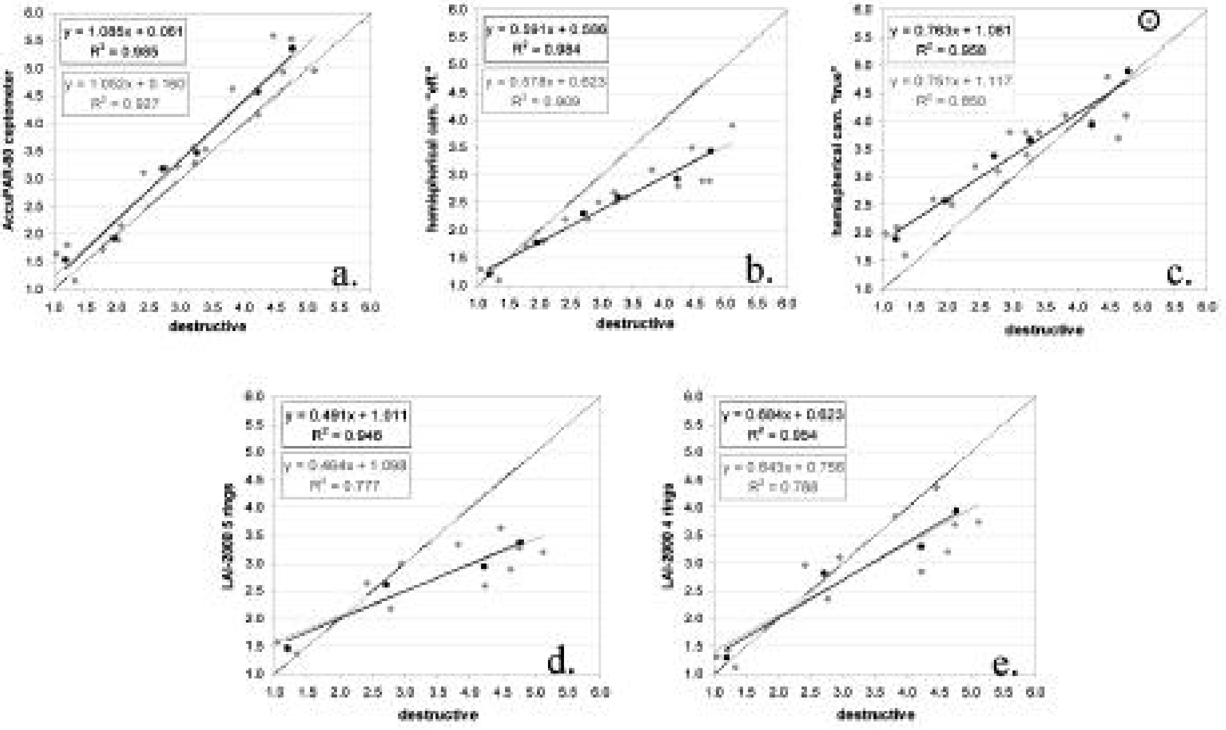

Fig. 4 - Correlation between LAI values obtained by the destructive method and: (a) the AccuPAR ceptometer, (b) the hemispherical camera "effective LAI", (c) the hemispherical camera "true LAI", (d) the LAI-2000 meter considering 5 zenithal rings, (e) the LAI-2000 meter excluding the 5th ring, considering respectively the three replicates for each thinning level (gray dots) and the average value of the three replicates for each thinning level (black dots).

	DEVIANCE	DF	VARIANCE	F	*P*
Total	109.39	71	1.54		
Among averages of the replicates	103.38	23	4.49		
Among methods	14.73	5	2.95	23.53	*<0.001*
Among thinning levels	82.40	3	27.47	219.36	*<0.001*
Interaction method-thinning level	6.25	15	0.42	3.33	*<0.001*
Error	6.01	48	0.13		

TABLE 1 - Results for the factorial analysis of the variance.

level ($R^2 = 0.95$), eliminating the 5th ring R^2 values become 0.79 and 0.95. However, in this latter case, the angular coefficients of the regression lines are closer to 1.

Table 1 shows the results of the factorial analysis of variance (two-way ANOVA) carried out considering the LAI measurement method as the first factor (i.e. factor A, treatment) and the thinning level as the second (i.e. factor B, block). Data for -2 and –4 thinnings, for which the LAI-2000 measurements were not acquired, were excluded from the analysis. The sum of the deviances related respectively to the method, the thinning level and the interaction method-thinning level equals the deviance among the averages of the replicates (corresponding to each combination method-thinning level) and represents its decomposition.

All the three F tests are significant. The conclusions that can be drawn for the three null hypothesis are therefore the following: (a) LAI averages obtained by the explored methods (over the entire range of thinning levels) are significantly different among them ($P<0.001$); (b) thinnings are characterized by LAI average values (obtained considering all the methods) significantly different among them ($P<0.001$); (c) the interaction between the two factors is significant ($P<0.001$).

Since the three F tests are significant, it can be argued if one or more of the three-replicates averages (obtained for each combination method-thinning level) would be statistically different from the corresponding average values obtained by the destructive sampling. Tukey's T test for the comparison of averages in the case of two-factor experiments with replicates was therefore applied. Only the differences between averages higher than the minimum significant difference (MSD) calculated by the test: $T_{LAI} = 1.12\ m^2m^{-2}$ were considered significant with a level $\alpha = 0.05$. In particular, Table 2 shows that only the "effective LAI" obtained by the hemispherical camera or the LAI-2000 meter considering all the five zenithal rings, and exclusively for higher LAI values (i.e. thinning levels 0 and -1), can be considered statistically different from the destructively sampled LAI (in bold with the asterisk in the table). Differences between LAI averages for each couple of methods when considering different thinnings were omitted; many of them are obviously significant, especially when the thinning levels are very diverse.

	Thinning 0					Thinning -1					Thinning -3					Thinning -5				
	Destr.uctive	AccuPAR	Hem.C.Eff	Hem.C.True	LAI 2000-5b	Destr.uctive	AccuPAR	Hem.C.Eff	Hem.C.True	LAI 2000-5b	Destr.uctive	AccuPAR	Hem.C.Eff	Hem.C.True	LAI 2000-5b	Destr.uctive	AccuPAR	Hem.C.Eff	Hem.C.True	LAI 2 000-5b
AccuPAR	0.59					0.35					0.46					0.34				
Hem.C. Eff	**1.34***	**1.93***				**1.29***	**1.65***				0.42	0.88				0.00	0.34			
Hem.C. True	0.13	0.46	**1.47***			0.29	0.65	1.00			0.65	0.19	1.07			0.70	0.37	0.70		
LAI2000-5b	**1.41***	**2.00***	0.07	**1.53***		**1.28***	**1.64***	0.01	0.99		0.11	0.57	0.31	0.76		0.27	0.06	0.27	0.43	
LAI2000-4b	0.84	**1.43***	0.50	0.96	0.57	0.93	**1.28***	0.36	0.64	0.36	0.09	0.38	0.51	0.56	0.20	0.09	0.25	0.09	0.61	0.18

TABLE 2 - Differences between average LAI values (three replicates) obtained by the different methods for each thinning level (in bold with the asterisk differences greater than MSD).

4. Conclusions

In this study, three indirect methods for LAI determination (Decagon AccuPAR-80 ceptometer, hemispherical camera and LICOR LAI-2000) were compared with destructive sampling for a maize crop located in Northern Italy. Measurements with each method were carried out in three plots (i.e. replicates) before and after successive thinnings of the plants.

Correlation analysis conducted on the experimental data highlighted some relevant issues: (a) the LAI-2000 meter measurements confirmed what was already reported in literature, that is an underestimation of the destructive measurements for high LAI values and a tendency towards an overestimation at low LAI values; (b) for the same probe, the re-processing of the data after the elimination of the 5th zenithal ring took to a clear improvement of the estimates; (c) for the AccuPAR-80 ceptometer a "saturation" threshold for the LAI value was never reached; (d) the LAI overestimation characterizing the ceptometer acquisitions over the whole LAI range was probably due to the value of the empirical parameters adopted which could be calibrated *in-situ*; nevertheless, even by using the default values, estimates were very good; (e) the "effective LAI" values estimated by hemispherical camera proved to underestimate the destructively sampled LAI, as recently shown in literature for maize crops; (f) the "true LAI" obtained from the same hemispherical images provided a good estimate of the destructively sampled one for high LAI values, but tended towards an overestimation for lower LAI values; this effect could be due to some choices made in the image-processing (for instance $\Delta\theta$ and $\Delta\phi$), or to the algorithm adopted by the CAN-EYE software for the clumping index calculation, which could lead to inaccurate results when the plant density in the field becomes very low. Anyway, scarce information is provided by the literature on this issue, and further research is certainly needed.

Despite all these relevant observations, results from the ANOVA and the Tukey T test for two-factor experiments with replicates showed that all the indirect methods, when used in the most appropriate way, provided estimations which were not statistically different from the values obtained by destructive sampling. As a matter of fact, only the determinations carried out with the LAI-2000 meter in the standard configuration (i.e. 5 zenithal rings) as well as the "effective LAI" obtained by the hemispherical images, and exclusively for higher LAI values (LAI > 3-4 m^2m^{-2}), proved to be significantly different from the direct measurements.

A last consideration concerns the usability of the indirect methods explored in this study. The LAI-2000 requires acquisitions to be conducted in diffuse light conditions and, at least for our case study, the re-processing of the data eliminating the 5th zenithal ring. Data collected by the hemispherical camera need a post-elaboration by using a dedicated software operating image classification, thus a certain experience of the operator is fundamental. The ceptometer allows taking measurements in direct light conditions and, in spite of the inability to provide data about the canopy structure, in our study it supplied reliable results also without a site-specific calibration; these properties are undoubtedly advantageous if compared with the requirements of other methods.

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SUMMARY

Leaf area index (LAI) is a crucial variable in the modelling of many hydrological processes. Destructive sampling of LAI is extremely time-consuming, thus not suitable for monitoring temporal/spatial variations of the variable. In the last fifty years optical instruments retrieving LAI from more easily measurable variables (i.e. transmitted radiation through canopies) have been developed. Several instruments are available on the market, but very few are the studies comparing LAI estimates in agricultural crops. In this paper three optical instruments are compared with destructive sampling for a maize crop located in Northern Italy. Determinations were carried out on three plots (replicates) before and after successive thinning of plant populations. Destructively sampled LAI ranged from 4.9 m^2m^{-2} (no thinning) to 1.2 m^2m^{-2} (maximum thinning). Correlation analysis showed that estimates by the AccuPAR-80, the hemispherical camera ("effective" and "true" LAI) and the LAI-2000 (in the standard configuration, i.e. five zenithal rings, and excluding the fifth ring) were well correlated with destructive measurements ($R^2 \geq 0.95$). Anyway, if for the AccuPAR-80 the regression line was close to the 1:1 line, the "true LAI" by hemispherical photography tended to overestimate destructively sampled LAI for low values while the "effective LAI" and the LAI-2000 to underestimate it for high values (in a minor way for the LAI-2000 when the fifth ring was removed). Results from the ANOVA and the Tukey T test for two-factor experiments with replicates showed that only the "effective LAI" retrieved by hemispherical photographs and the estimates provided by the LAI-2000 in the standard configuration (five rings) were statistically different from destructive measurements.

Keywords: LAI, destructive sampling, indirect estimation methods, Zea Mais, ANOVA.