Ground cover and leaf area index relationship in a grass, legume and crucifer crop

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ABSTRACT

Canopy characterization is essential for describing the interaction of a crop with its environment. The goal of this work was to determine the relationship between leaf area index (LAI) and ground cover (GC) in a grass, a legume and a crucifer crop, and to assess the feasibility of using these relationships as well as LAI-2000 readings to estimate LAI. Twelve plots were sown with either barley (*Hordeum vulgare* L.), vetch (*Vicia sativa* L.), or rape (*Brassica napus* L.). On 10 sampling dates the LAI (both direct and LAI-2000 estimations), fraction intercepted of photosynthetically active radiation (FIPAR) and GC were measured. Linear and quadratic models fitted to the relationship between the GC and LAI for all of the crops, but they reached a plateau in the grass when the LAI > 4. Before reaching full cover, the slope of the linear relationship between both variables was within the range of 0.025 to 0.030. The LAI-2000 readings were linearly correlated with the LAI but they tended to overestimation. Corrections based on the clumping effect reduced the root mean square error of the estimated LAI from the LAI-2000 readings from 1.2 to less than 0.50 for the crucifer and the legume, but were not effective for barley.

Keywords: canopy; digital images; barley; vetch; rape; LAI-2000

The leaf area index (LAI), defined by Watson (1947) as the ratio between the sum of the foliar area and the unit of soil surface, is a key variable for characterizing different plant canopies because it is related to light and energy capture. Efforts that involve measuring the LAI by direct methods are limited to small areas and to a limited number of measurements during the crop cycle (Jonckheere et al. 2004). Indirect methods, either through relationships with more easily measurable variables or using optical devices, are gaining acceptance in many environmental, ecological and agronomical studies (Weiss et al. 2004). Therefore, comparing estimations of the LAI for different crop architectures may help to clarify the reliability and limitations of different indirect methods.

Ground cover (GC), defined as the ground fraction covered by vegetation, proved to be a useful variable in soil protection, weed control, and evapotranspiration estimations (Mullan and Reynolds 2010). The evolution of digital technologies allows monitoring of canopy development and the determination of the GC by putting image automatic interpretation techniques into practice (Karcher and Richardson 2003). In addition, as GC can be easily determined by remote sensing equipments, if solid relationships with other canopy variables were obtained, an enhancement on monitoring crop development with remote sensing could be achieved. However, the spatial distribution of leaves and the mixture of green and non-green vegetation elements might affect the relationship between the GC and LAI for different crop types.

Optical methods of inferring the LAI from the observation of other variables are generally faster, non-destructive and allow automation, but they also proved to be less accurate (Jonckheere et al. 2004). The LAI-2000 (LI-COR, Inc., Nebraska, USA) is an optical instrument that is widely used to estimate the LAI. It is equipped with a fisheye shaped sensor, and light passes through a 490-nm wavelength filter. Evaluation studies in agricultural crops showed different results; some of them indicated that the LAI estimations are reliable (Malone and Herbert 2002), whereas others reported they might be overestimated (Weiss et al. 2004). The

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suitability of the LAI-2000 for LAI estimation in the studied crops will be discussed in this report.

The goal of this work was to determine the relationship between LAI and GC in a grass (i.e. barley), a legume (i.e. vetch) and a crucifer (i.e. rape) crop, and to assess the feasibility of using these relationships as well as LAI-2000 readings to estimate LAI.

MATERIAL AND METHODS

Measurements were taken during a field experiment between the months of April and July 2010 at the farm of the Agronomics Engineering School in Madrid (Spain). The trial had 12 plots (2.4 m × 7 m) distributed into three treatments (crops) with four replicates. The barley (*Hordeum vulgare* L. cv. Vanessa) and vetch (*Vicia sativa* L. cv. Vereda) were sown with a seed drill, and the rape (*Brassica napus* L. cv. Licapo) with a manual seeder. The seeding densities were 100 kg/ha for barley and vetch (~ 279 and 141 seeds/m^2, respectively), and 10 kg/ha for rape (~ 282 seeds/m^2). Eleven rows were sown in each plot with a 20-cm inter-row spacing. Crops were fertilized at cereal tillering with 150 kg N/ha. The measured variables were the LAI, FIPAR and GC. Each sampling date, a square of 0.5 × 0.5 m^2 was marked in each plot, and all of the variables were measured in this sampling area. There were a total of 10 sampling dates from the growth stage of the first unfolded leaf (GS-11) to the end of stem elongation (GS-39, Lancashire et al. 1991). Photosynthetically active radiation (PAR) measurements were conducted with a Sunfleck ceptometer (Delta-T Services, Cambridge, UK) during days with clear skies and close to solar noon. The incident PAR was measured over the crop with the sensors looking up at the sky. The transmitted PAR was calculated as the average of four measurements taken at the same point at ground level below the vegetal cover. The FIPAR, defined as the fraction of the total incident PAR over the sampling area intercepted by the vegetation, was calculated as the complementary of the ratio between transmitted and incident PAR.

The GC was determined based on digital images of the marked surface taken from a zenithal perspective at a 1.5-m height before cutting the crops. The images were taken with a Ricoh R8 camera with a lens resolution of 3 megapixels attached facedown to a tripod and processed using SigmaScan Pro 5® software. The hue and saturation ranges were selected for each image, creating a layer that included the pixels that matched the selected hue (40–120) and saturation (15–100) values. These values corresponded with green color in the light conditions of an overcast day. The GC was calculated as the number of pixels of the layer divided by the total number of pixels that constitute the image of the marked surface.

The indirect LAI was estimated by means of the LAI-2000 optical instrument (LI-COR, Lincoln, USA). Each measurement was acquired by performing a sequence of one above reading and four below readings (one in each corner of the square area). An opaque mask with a 45° opening adjusted to the fish-eye lens was used to reduce the influence of the operator and of the adjacent plots. The data outputs were processed using the FV2000 software (LI-COR, Lincoln, USA). The standard LAI-2000 outputs (taking into account the five detector rings measurements, 5R) were reprocessed using the software to discard the widest viewing-angle reading and to estimate the four-ring (4R) LAI. Light attenuation measured by LAI-2000 does not distinguish between leaves and stems considering all of them light intercepting elements. The introduction of a clumping index allows compensating this effect (Weiss et al. 2004). A clumping index (λ_0) was calculated for each crop with the formula:

$$L^{eff} = \lambda_0 L$$

Where: L^{eff} – equal to the LAI-2000 reading; L to the direct LAI measurement based on digital images of separated leaves. The λ_0 was obtained as the inverse of the slope of the regression line between LAI and LAI-2000 measurements.

The direct LAI measurements were also determined based on digital images of the surface of leaf blades from the sampling area. The plants were cut by hand at ground level, and the leaf blades were separated from the stems and laid on corkboards marked with a 10-cm long stripe. A digital image was then taken from a zenithal perspective at a 1.5-m height and analyzed following the process previously described for the GC. The LAI was obtained by converting the number of pixels of the created layer in the surface units by using the stripe included in each image as a reference.

The non-linear regression procedure of SPSS (Statistical Package for the Social Sciences) was used to calculate the radiation extinction coefficients (k) for each species with the following equation (Monsi and Saeki 1953):

$$\text{FIPAR} = 1 - e^{-K \times \text{LAI}}$$

Using the same SPSS procedure, continuous (linear and quadratic) and segmented (linear-plateau and quadratic-plateau) models were fitted to study the relationship between the GC and the direct LAI measurements. The comparison of the direct LAI and LAI-2000 estimates was performed by regression analysis. The root mean squared error (RMSE) was calculated to evaluate the model's performance.

RESULTS AND DISCUSSION

FIPAR vs. LAI. The FIPAR and LAI direct measurements followed the Monsi-Saeki equation for the three species, the coefficient of determination being always larger than 0.92 (Figure 1). The *k* values for the legume and the crucifer were very similar, and were larger than for the barley (Monsi and Saeki 1953).

The results obtained for *k* were 0.44, 0.56, and 0.57 for barley, vetch and rape, respectively (Figure 1). These values are within the ranges reported in the literature (Fray et al. 1996, Thomson and Siddique 1997, Kemanian et al. 2004).

The analysis of digital images of the separated leaves used in this experiment allowed determining the LAI in all three species. Even in the vetch, with little leaflets which are hard to manipulate and measure with accuracy. This is an advantage with respect to other methods of direct measurement, where determination of LAI in plants with small leaves may be a limitation. The good relationship with FIPAR and the comparison with previous reported results ensure that the set of LAI data collected was reliable for comparison with indirect methods that facilitate LAI estimation.

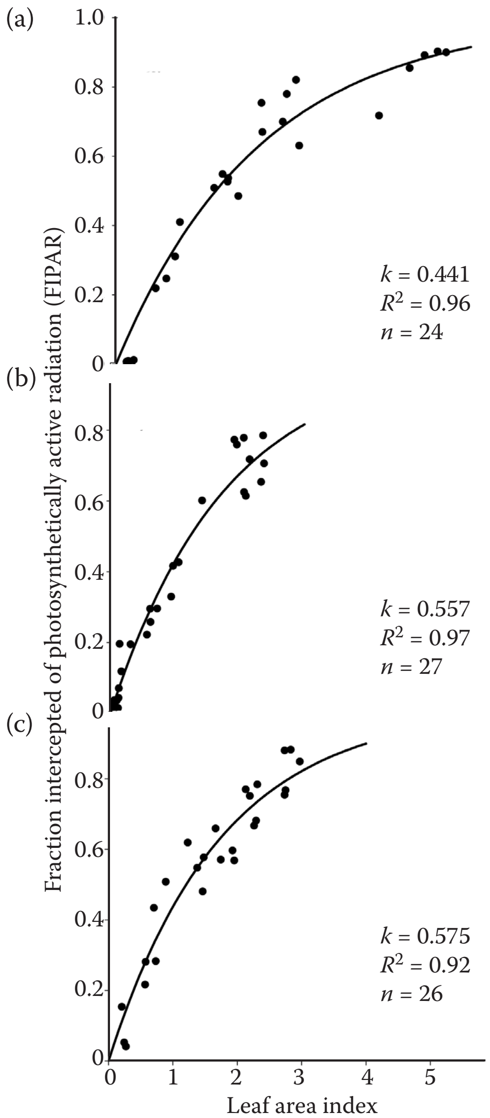

Figure 1. The leaf area index (LAI) versus the fraction of intercepted photosynthetically active radiation (FIPAR) for (a) a grass (barley), (b) a legume (vetch) and (c) a crucifer (raped) crop

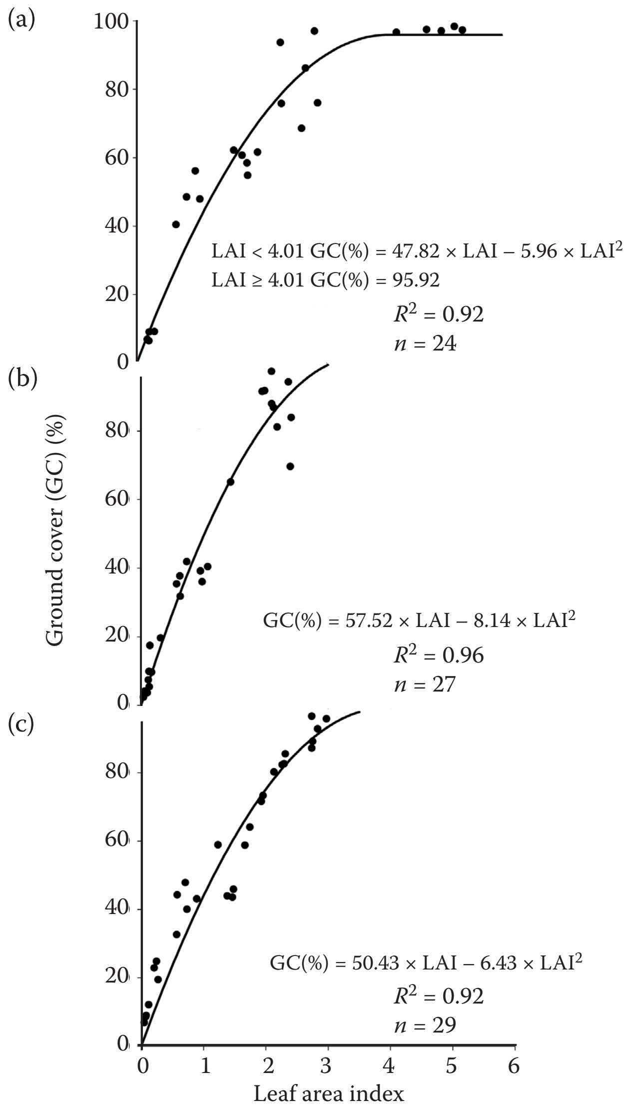

Figure 2. The leaf area index (LAI) versus the ground cover (GC) for (a) a grass (barley), (b) a legume (vetch) and (c) a crucifer (rape) crop

Ground cover vs. LAI. In all of the species, the GC increased with the LAI, but it reached a plateau in the grass when the LAI passed a certain threshold (Figure 2). For the vetch and rape, the linear and quadratic models fitted to the relationship between the GC and LAI were highly significant ($P < 0.001$), and nearly full cover was reached when the LAI was near to 3. For the grass, the segmented models fitted the measurements better than the continuous, because a saturation point was reached when the LAI was over 4. Up to this value, both the quadratic and linear models fitted to the relationship between the GC and LAI in barley.

In all of the species, the error committed using the linear model to estimate the LAI based on the GC was only slightly larger than with the quadratic model. Linear equations are easy to compare with other evaluation studies and can provide general expressions for wide use. The linear equations were as follows:

– for the rape: LAI = 0.0281 × GC (%); RMSE = 0.29
– for the vetch: LAI = 0.0244 × GC (%); RMSE = 0.20
– for the barley: GC (%) ≤ 97; LAI = 0.0299 × GC (%); RMSE = 0.78; GC (%) ≥ 97; LAI ≥ 2.92

Little information can be found in the literature on the relationship between LAI and GC. Mullan and Reynolds (2010) reported a linear relationship for wheat in a range of GCs between 25% and 90%. The slope of the linear equation was 0.03, similar to our results. Their study focused on early development stages so a saturation point was never reached.

LAI vs. LAI-2000. Measurements with the LAI-2000 instrument overestimated the observed LAI values in vetch and rape (Figure 3). The largest LAI-2000 value measured in the crucifer was 5.6, whereas the largest value obtained by direct measurement was 3.0. In the legume, values as large as 5.1 were registered with the LAI-2000, whereas the largest value obtained by direct measurement was 2.4. The average mean LAI observed, 1.4 for the rape and 1.1 for the vetch, was overestimated by the LAI-2000 as 2.4 and 1.7, respectively (Table 1). Overestimation could occur as a result of the clumping effect (Weiss et al. 2004). LAI-2000 calculations are based on the Poisson equation, which assumes a random distribution of leaves (Welles and Norman 1991), but in agricultural crops sown at commercial densities, patterns of foliage distribution are regular rather than random, and may depend on crop species (Andrieu et al. 1997). Because of that, Weiss et al. (2004) recommended taking into account the clumping effect in agricultural crops when assessing LAI through indirect measurements based on the Poisson model. In our study, the λ_0 was 1.62 for the legume, and 1.61 for the crucifer. The $\lambda_0 > 1$ is due to the clumping effect of the regular foliage distribution, a characteristic of row crops (Weiss et al. 2004). Neglecting the widest ring of the LAI-2000 equipment in the measurements of these two crops did not have a clear effect on its capability to estimate LAI, as suggested by Richardson et al. (2011). The dispersion between both variables increased in the crucifer but diminished in the legume (the r^2 increased from 0.78 to 0.86), whereas

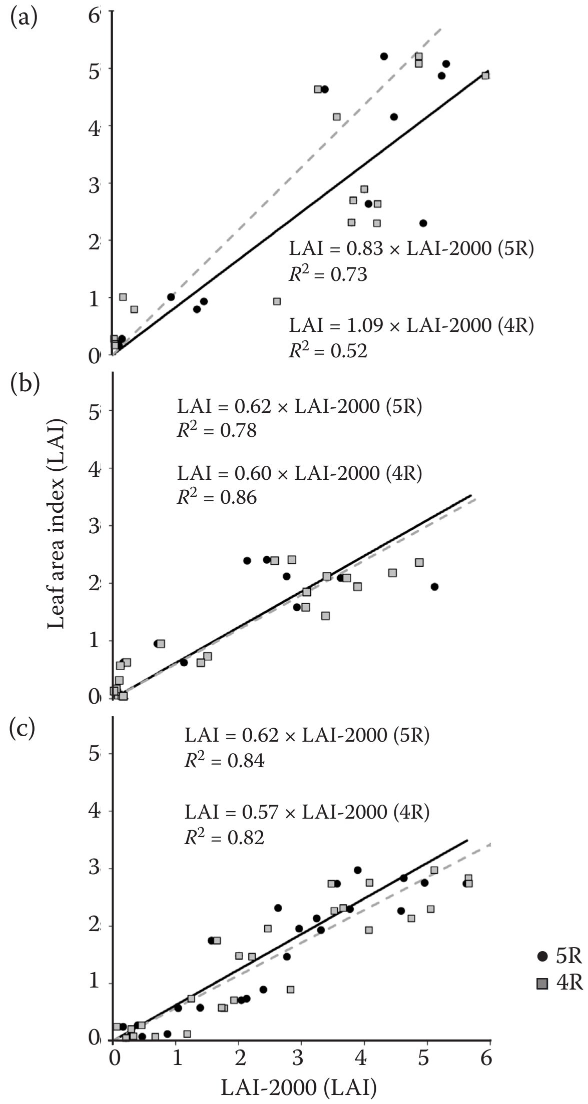

Figure 3. The leaf area index (LAI) measured with an LAI-2000 optical instrument versus the LAI direct measurements for (a) a grass (barley), (b) a legume (vetch) and (c) a crucifer (rape) crop before correcting by the clumping effect. The 5R regression is shown as the black continuous line, and the 4R as the dashed line; 5R means all of the rings were considered, and 4R means the external ring was neglected

Table 1. Regression analysis between direct leaf area index (LAI) and LAI-2000 measurements, before and after correction for the clumping effect, for the different crops: number of data points (*n*), mean direct LAI measured and estimated based on LAI-2000 readings, regression coefficient (R^2), clumping index (λ_0), and the root mean square error (RMSE)

	Grass		Legume		Crucifer	
	4R	5R	5R	4R	5R	4R
n	16		23		26	
Mean direct LAI	2.51		1.08		1.39	
Mean LAI-2000	2.96	2.87	1.70	1.74	2.36	2.55
R^2	0.73	0.52	0.78	0.86	0.84	0.82
λ_0	1.21	0.92	1.62	1.66	1.61	1.74
RMSE	1.07	1.03	1.19	1.12	1.23	1.19
Corrected equations by clumping index						
Mean LAI-2000	2.45	2.64	1.05	1.04	1.46	1.46
R^2	0.72	0.72	0.78	0.86	0.84	0.82
RMSE	0.87	0.96	0.50	0.38	0.43	0.40

Data estimated for both standard LAI-2000 (5R) and reprocessed when the external ring was neglected (4R)

a slight decrease in the RMSE was obtained for both crops. From these results, we inferred that the use of the LAI-2000 optical sensor to estimate LAI in vetch and rape required a calibration or correction based on the clumping effect.

As expected, correcting for the clumping effect greatly improved the statistical indicators when comparing the LAI measurements and LAI-2000 readings for the rape and vetch (Table 1). After calibration, the RMSE obtained when estimating the LAI from the LAI-2000 readings was reduced from 1.23 to 0.43 for the crucifer and from 1.19 to 0.50 for the legume. In the grass, the LAI-2000 also overestimated the LAI due to the clumping effect, but on top of everything else, the error was associated to large data dispersion. The average mean LAI observed was 2.51, whereas the estimation based on the LAI-2000 readings was 2.96, and the clumping index was 1.21. When neglecting the external ring overestimation did not occurred but dispersion was even higher (r^2 decreased from 0.73 to 0.52). These results are only in partial agreement with Stroppiana et al. (2006), who observed that discarding the widest ring improved the LAI estimates in rice. Correction based on the clumping effect decreased the RMSE, but given the large dispersion between readings, the reliability of the LAI-2000 to estimate LAI in barley was limited even after correction.

In this article, we focused on the relationship between LAI and GC for various species, not in the temporal evolution of these variables. LAI and GC evolution will vary greatly with sowing density or cultural techniques (i.e. irrigation or fertilization) but the relationship between these variables will only be affected if the structure of the crop canopy is affected (Andrieu et al. 1997). Nevertheless, the relationships between canopy characteristics (i.e. LAI-GC and LAI2000-LAI) obtained in this article will rarely be modified, and will remain valid under a broad range of cultivation techniques and environments, being useful for other researchers.

As a conclusion, both GC and LAI-2000 were suitable for estimating LAI for the studied crops with specific limitations. Quadratic models fitted to the relationship between the GC and LAI for all the crops, but reached a plateau in the grass when the LAI > 4. The LAI measurements were overestimated by the LAI-2000 in vetch and rape but once corrected by the clumping effect the device worked properly. Caution should be taken when estimating LAI from LAI-2000 measurements in barley, as the error committed was larger than in the other species even after correcting for the clumping effect.

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