

## Ground cover and leaf area index of maize and sugar beet crops

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**Abstract** — Leaf area index ( $L$ ) is an important variable characterizing the development of a crop and its exchanges with the atmosphere. Direct measurements are destructive and tedious. The relations between  $L$  and the ground cover ( $C$ ) can be described analytically by taking account of leaf angle distribution and leaf clumping. Because it is difficult to characterize these two variables, we have studied the stability of empirical relations between  $L$  and  $C$ . Ground cover was measured from vertical-view photographs. For both maize (*Zea mays* L, var Dea) and sugar beet (*Beta vulgaris*, var Matador), we found the extinction coefficient ( $K$ ) to be robust throughout crop development and only weakly affected by population density and sowing geometry. Thus, measurement of  $C$  appears to be a simple way to estimate  $L$ , once the relation has been established for the variety of interest, and excluding periods of water stress that may modify crop geometry.

**maize / sugar beet / leaf area index / ground cover / photography**

**Résumé** — Taux de couverture du sol et indice foliaire de cultures de maïs et de betteraves à sucre. L'indice foliaire ( $L$ ) est une variable essentielle pour caractériser le développement d'une culture et ses échanges avec l'atmosphère. La mesure directe est destructive et relativement fastidieuse. Les relations entre l'indice foliaire d'une culture et son taux de couverture du sol ( $C$ ) peuvent être décrites par une relation analytique faisant intervenir la distribution d'orientation des feuilles et éventuellement un indice d'agrégation. Compte tenu de la difficulté à caractériser ces deux dernières variables, on s'est intéressé à la stabilité de relations empiriques entre  $L$  et  $C$ , mesurée par l'analyse numérique de photographies prises du dessus de la végétation. Le travail porte sur le maïs (*Zea mays* L, var Dea) et la betterave à sucre (*Beta vulgaris*, var Matador). Dans les deux cas, on observe une remarquable stabilité du coefficient d'extinction ( $K$ ) tout au long du cycle végétatif, et une faible incidence de la disposition spatiale et de la densité du semis sur ce coefficient. Dans ces conditions, la mesure de  $C$  apparaît comme un moyen fiable d'estimation de  $L$ , à condition d'établir une relation expérimentale propre à la variété considérée, et d'effectuer les mesures en l'absence de modification de port liées à des stress.

**maïs / betterave à sucre / indice foliaire / taux de couverture du sol / photographie**

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## INTRODUCTION

Leaves are the interface between a crop and its atmospheric environment. They largely determine the amount of radiation intercepted and transpiration and thus water requirements and crop productivity. Direct measurements of leaf area index ( $L$ ) through planimetric methods are destructive and tedious so that assessments can seldom be repeated often enough in time and space. This is especially so during the early stages of growth when spatial and time variations may be very large. Experimentation, modelling and decision making would all benefit from faster methods for monitoring  $L$ . Indirect methods have been proposed, based on measurements of either gap fraction or reflectance: these were reviewed by Welles (1990) and Andrieu and Baret (1993), amongst others. Much research has been devoted to interpretation of satellite-based measurements, and the use of sensors in the field has also progressed further, with improvements in the theory (Lang, 1991; Chen and Cihlar, 1995), new sensors (Allirand et al, 1997), new methods for image processing (Sevestre, 1993) and relationships with different variables (Boissard et al, 1993).

Radiometric and gap-fraction models use the concept of an extinction coefficient to describe the relation between directional gap fraction and crop geometry. Assuming random leaf positioning, the relation is:

$$P_0(\theta) = e^{-\frac{G(g, \theta)}{\cos(\theta)} L} \quad [1]$$

where  $P_0(\theta)$  is the gap fraction for a view zenith angle  $\theta$ ;  $G(g, \theta)$  is the mean projection of unit leaf area in the direction of view;  $g$  represents the leaf angle distribution. The ratio  $G(g, \theta)/\cos(\theta)$  is the extinction coefficient ( $K$ ). The ground cover  $C$  is simply related to the gap fraction in the vertical direction:  $C = 1 - P_0(\theta)$ .

Several authors have studied how  $L$  could be estimated using equation [1]. The view angle  $\theta = 57^\circ$  is a special case where  $G$  is approximately equal to 0.5, independently of  $g$ , which allows an easy estimate of  $L$  to be made from  $P_0$ . Bonhomme and Chartier (1972) showed how  $L$  could be estimated from the gap fraction measured at a view angle of  $57^\circ$ , using hemispherical photographs.

Hemispherical photographs are useful for studying various aspects of canopy structure and light microclimate. However, they have a significant drawback: to achieve sufficient resolution,

the hemispherical photographs must be taken either from inside or from a short distance (typically 1 m) above the canopy, so they cover only a small area. The view angle of  $57^\circ$  represents a small region on the photographs, further reducing the area actually sampled. Therefore many replicates are required to obtain data representative of a plot. The method may also be difficult to use on small experimental plots, because the field of view could include leaves from adjacent plots. The plant canopy analyzer (LAI-2000, Li-Cor, Inc, Lincoln, Nebraska) is based on the same principle and permits faster data acquisition, but has similar drawbacks with regard to spatial sampling. Measurement of the gap fraction in the vertical direction from a camera a few metres above the canopy allows for better control of the area covered and for better spatial representation. However, to estimate  $L$  from the vertical gap fraction, using equation [1], the mean leaf angle must be known with a reasonable accuracy.

From a theoretical point of view, the drawback of these methods is that canopy geometry is not well represented by the assumption that leaves are randomly positioned in space. They are generally organized around a vertical stem and usually plants are disposed in rows. The consequence for equation [1] of non-random leaf position is generally denoted as clumping. The vertical direction is probably the more sensitive to non-random patterns in plant shape and sowing geometry (Andrieu and Baret, 1993). Clumping is generally taken into account by incorporating an additional angular parameter,  $\lambda_0(\theta)$ , into equation [1] (Nilson, 1971):

$$P_0(\theta) = e^{-\frac{\lambda_0 G(g, \theta)}{\cos(\theta)} L} \quad [2]$$

This, despite a lack of evidence, comes from the hypothesis that clumping corresponds to a Markov process. Only a few workers (Chen and Black, 1992; Chen and Cihlar, 1995; Kuusk, 1995) have addressed the problem of calculating  $\lambda_0$ , other than adjusting it a posteriori, from measurement of gap fraction,  $L$  and leaf angle distribution. These authors developed theoretical relationships to estimate the clumping parameter from leaf size or gap size analysis; however, there is still insufficient experimental evidence for these approaches.

Finally, using analytical relations, it is difficult to relate vertical gap fraction with known a priori accuracy to  $L$ . Nevertheless,  $P_0$  represents a variable which is easy to interpret and to measure: it is the most obvious variable for an operator walking in a field, and it can be quantified using ordi-

nary photographs. In this paper, we study the stability of an empirical relation between gap fraction and  $L$ . Clearly, from this discussion, such a relation will depend on species and variety; however, it may be useful if it remains stable during the course of crop development and accommodates sufficient variation in spatial arrangement of plants.

## MATERIALS AND METHODS

Sugar beet and maize crops were grown under a range of experimental treatments.  $L$  and  $C$  were measured almost simultaneously.  $C$  was never measured during periods of water stress, which causes sugar beet leaves to wilt and maize leaves to roll longitudinally.

### Maize experiment

The experiment was performed in 1987 at Grignon on a silty loam soil. Four sowing treatments were obtained by combination of two population densities (9 or 20 plants/m<sup>2</sup>) and two sowing geometries (staggered rows or regular rows). In the regular treatment, row spacing was 40 cm (20 plants/m<sup>2</sup>) or 80 cm (9 plants/m<sup>2</sup>). The sowing period was from 24 April to 7 May.

Ground cover was measured five times in July, during the course of leaf area development. Photographs were taken from a height of 10 m with a Hasselblad camera with a 200 mm lens. Each photograph covered approximately 8 m<sup>2</sup> and was taken on colour transparency film. The photographs were digitized with a microdensitometer, using red and green filters. Soil and vegetation were distinguished by plotting a scatter diagram of counts in the red channel against counts in the green channel. The diagrams showed two distinct regions corresponding respectively to soil and vegetation. Using dedicated software (Andrieu, 1982; Benckekroun, 1989), the pixels of the image were then classified as soil or vegetation, according to their position on the diagram (fig 1).

Non-destructive measurements of  $L$  were performed by monitoring daily the increment of leaf length and the corresponding width on all leaves of 16 plants per plot. These data correspond to those described in more detail by Ruget et al (1997).  $L$  ranged from 0.02 to 3.8 at the time of ground cover measurements.

### Sugar beet experiment

The first experiment was at Broom's Barn (England) in July 1989 on a sandy loam soil. Different canopy structures were obtained by a combination of three sowing dates (28 March, 29 April and 17 May) and three population densities (5, 10 and 20 plants/m<sup>2</sup>).  $L$

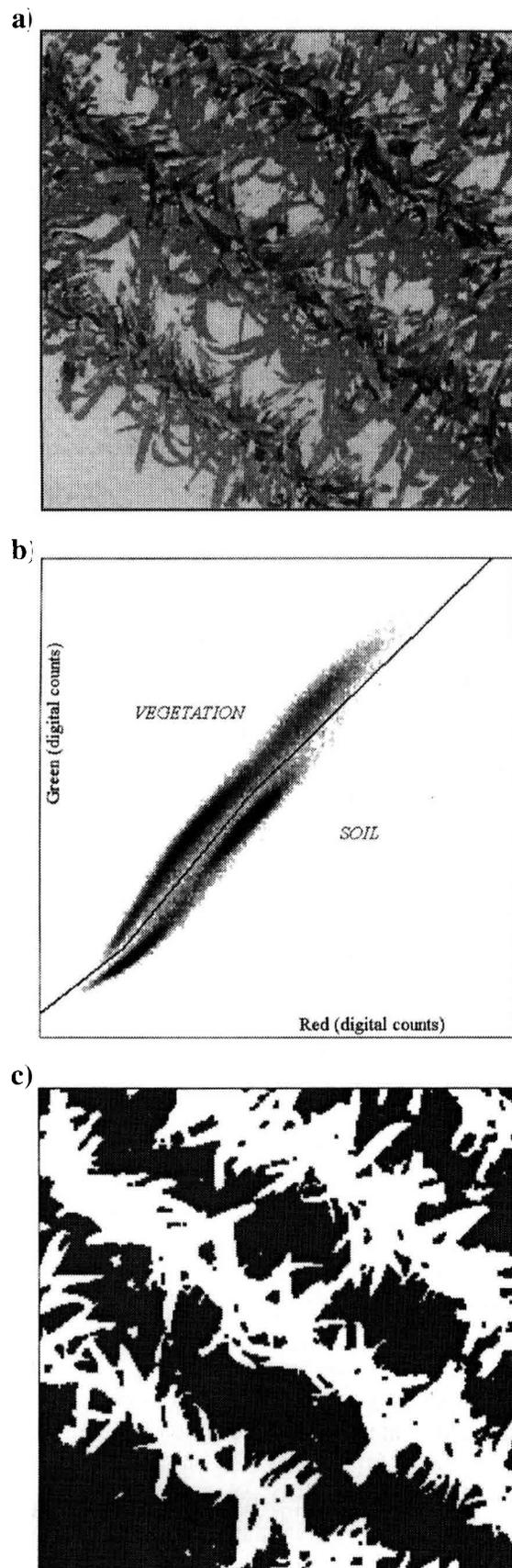


Fig 1. Estimation of  $C$  from a digitized colour photograph: (a) original photograph; (b) scatter diagram of red and green counts, showing the two regions corresponding to soil and leaf elements; (c) classified image (the small patches between maize plants are weeds).

and gap fraction were measured on 5 and 20 July. Additional variations in canopy structure were created artificially at the time of these measurements by thinning to remove every second row, every second plant within the row, or every second row and every second plant within the row.

Altogether, the data set comprised 55 plots at various stages of development, plant population density and thinning treatment.  $L$  ranged from 0.2 to 5.5. Soil reflectance varied according to soil surface water content. In addition, artificial backgrounds of peat or white paper were placed on the soil in order to test the effect of background colour on the estimate of  $C$ . Table I shows the range of soil and background reflectances, measured with a Cimel radiometer in the red and the green wavebands.

Ground cover was measured from vertical photographs, taken either from a height of 5 m with a Hasselblad camera and a 100 mm lens or from 2.5 m with a 35 mm camera fitted with a 50 mm lens. This corresponds to a viewing area per photograph of, respectively, 8 and 2 m<sup>2</sup>. In the first case, a single photograph was taken for each plot, and  $C$  was calculated for the 1.5 m<sup>2</sup> area corresponding exactly to measurements of  $L$ . In the second case,  $C$  was calculated as an average of three replicate photographs, covering an area including that of the  $L$  measurements. On a few plots where both methods were used, ground cover estimates did not differ by more than 0.03 and there was no bias. Therefore all the results were considered together. Photographs were analyzed using the same procedures as for the maize experiment.

In 1990 a similar experiment was conducted at Grignon (France). There were two population densities (8 and 32 plants/m<sup>2</sup>) and four thinning treatments. Seeds were sown on 3 May and measurements made on 19 July, when  $L$  ranged from 0.3 to 3.3. Experimental constraints meant that  $C$  and  $L$  were measured in different parts of the plot. The method used to estimate  $C$  was the same as that used at Broom's Barn, except photographs were taken from 5 m above soil surface and were digitized with a three-colour camera instead of the microdensitometer.

For both experiments,  $L$  was measured by collecting all the plants from a 1.5 m<sup>2</sup> sample area of each plot. When there were more than five plants, a sub-sample of five was chosen at random and the laminae were

separated from the petioles. These were immediately weighed and then photographed against a white background. The remaining laminae were then detached from the petioles and also weighed immediately. The black and white photographs were digitized and the area of the laminae of the whole sample was estimated from fresh weight and the area/weight ratio measured on the sub-sample. The area of petiole was not included in the measurements.

## RESULTS

### Ground cover estimates over various backgrounds

Visual comparison of the original photographs with the classified images showed that the leaves were identified accurately against the peat background and against the natural soil, irrespective of surface wetness. Replicate measurements of  $C$  performed against the natural soil and the dark peat background were very consistent (fig 2). However, leaves could not be properly distinguished from the white background, because the shadow of leaves on the white paper appeared green and was confused with real leaves. We concluded that the method enables reliable estimates of  $C$  to be made in a large range of soil conditions, but may not work on very light coloured, chalky soils.

### Ground cover and leaf area index of sugar beet

Equation [1] could fit all gap-fraction data and  $L$  from Broom's, with an adjusted extinction coefficient  $K = 0.732$ , which gave  $P_0$  a standard deviation of 0.038. When adjusting  $K$  separately for plots of different population density ( $d$ ), we found a tendency for  $K$  to decrease with increasing  $d$  (fig 3). However this was only a 10% change in  $K$  (0.75–0.67) for a two-fold increase in  $d$  (from 7 to 14 plants/m<sup>2</sup>).

The results from Grignon were very similar. Data were best fitted by an extinction coefficient of 0.736, with the standard deviation of  $P_0$  again being  $\pm 0.038$ . The relationship between  $C$  and  $L$  for both experiments is shown in figure 4. Figure 5 plots  $L$  estimated as  $L = -(1/K) \log(P_0)$ , with  $K = 0.732$ , against measured  $L$ . The estimate is accurate for  $L < 3$ ; in this case the standard error on  $L$  is  $\pm 0.24$ . Errors increase for  $L > 3$ . This corresponds to a reduced sensitivity of  $C$  to changes in  $L$  and also to larger errors in the measurement of  $C$

**Table I.** Reflectance of natural soil and artificial backgrounds, measured from the vertical and with a solar zenith angle of 30°, in the green (500–590 nm) and the red (620–680 nm) wavebands.

Location	Background	Green	Red
Broom's Barn	dry soil	0.142	0.205
	wet soil	0.705	0.104
	peat	0.032	0.043
	white paper	0.953	0.943
Grignon	dry soil	0.131	0.188

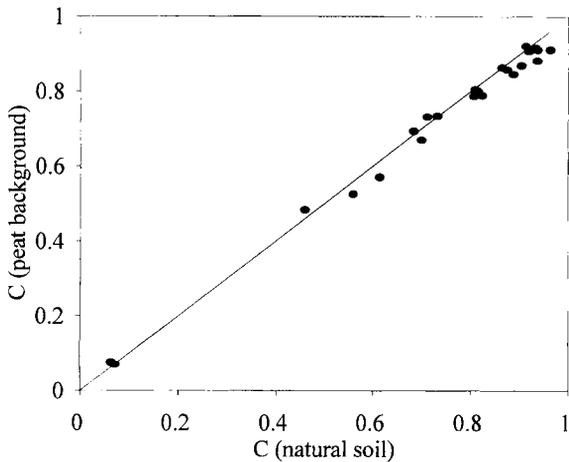


Fig 2. Scatter plot of  $C$  estimated on natural soil against  $C$  estimated on a peat background. The 1:1 line has been drawn to illustrate perfect agreement.

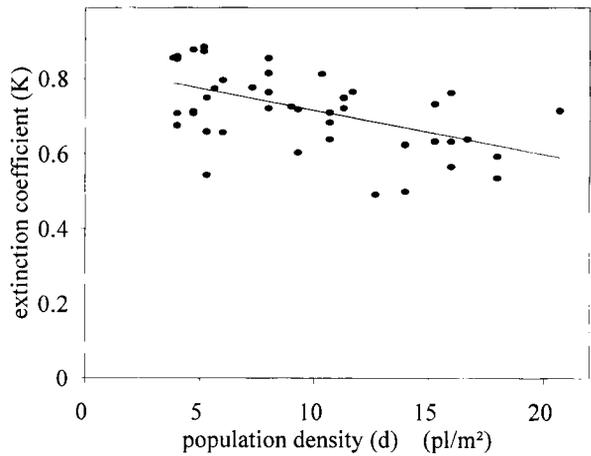


Fig 3. Effect of population density on  $K$  for sugar beet at Broom's Barn. The equation for the linear regression is  $K = 0.833 - 0.0118d$  ( $r^2 = 0.26$ ) where  $d$  is plants/m<sup>2</sup>.

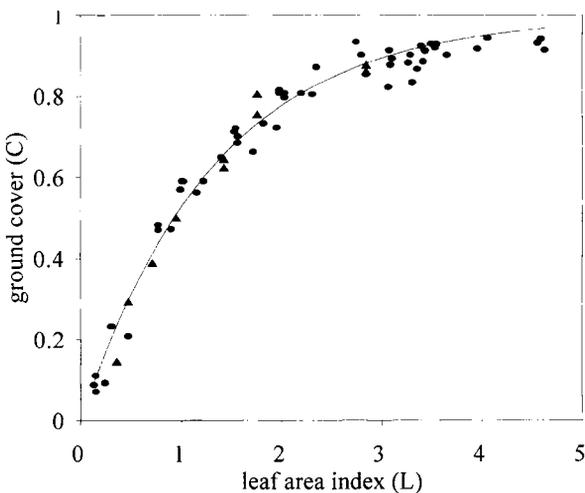


Fig 4. Relationship between  $C$  and  $L$ , for sugar beet crops. ●, Broom's Barn; ▲, Grignon.

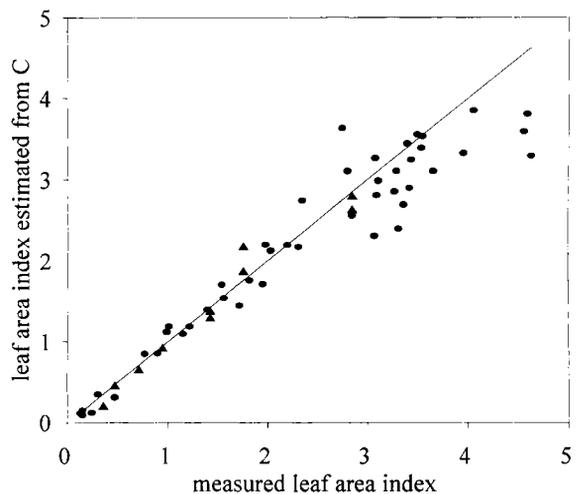


Fig 5. Scatter plot of measured values of  $L$  against corresponding values estimated from  $C$ , for sugar beet crops grown at Broom's Barn (●) and Grignon (▲). The 1:1 line is shown.

because the soil and the leaves at the bottom of dense canopies were poorly illuminated.

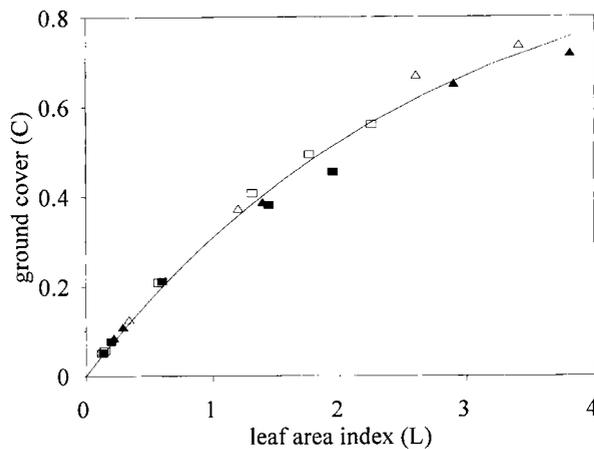
#### Ground cover and leaf area index of maize

Figure 6 shows the relation between  $C$  and  $L$  for maize. Adjusting  $K$  separately for each treatment showed no effect of  $d$ , but  $K$  for the staggered row treatments was slightly larger (0.39) than for the regular rows (0.34). The extinction coefficient calculated for the whole data set was 0.385 and the standard deviation between measured and adjusted  $C$  was 0.023. Figure 7 shows the agreement between estimated and measured  $L$ .

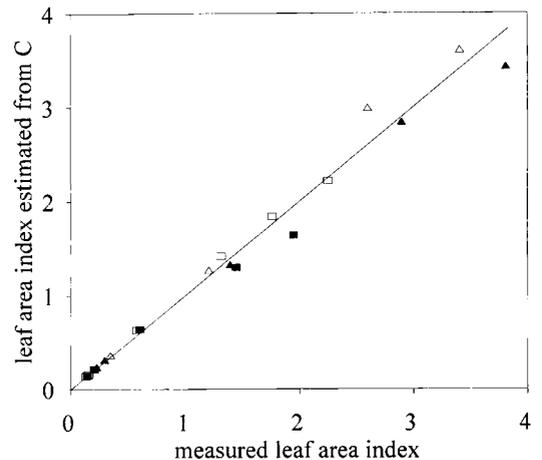
Consistent with figure 5,  $L$  corresponding to the regular row treatments tended to be underestimated, whereas values for staggered row treatments were overestimated. This effect only occurred for  $L > 1.5$ , when plant-to-plant interactions became significant. However, these errors remained moderate, and overall the standard error in  $L$  estimates was only  $\pm 0.16$ .

#### DISCUSSION AND CONCLUSION

The photographic method enabled consistent estimates of  $C$  to be made against peat and soil backgrounds independent of surface moisture content.



**Fig 6.** Relationship between  $C$  and  $L$ , for maize crops. Staggered rows:  $\triangle$ , 9 plants/m<sup>2</sup>;  $\blacktriangle$ , 20 plants/m<sup>2</sup>. Normal rows:  $\square$ , 9 plants/m<sup>2</sup>;  $\blacksquare$ , 20 plants/m<sup>2</sup>.



**Fig 7.** Same as figure 5, for maize crops; symbols as in figure 6.

The method was accurate in the range 0–0.85 for  $C$ , corresponding to  $0 < L < 3$  for sugar beet, and including the full range of  $L$  (0–4) available in our maize experiment. The results obtained on the white background indicate that the technique may not be applicable to very light coloured soils.

In both sugar beet and maize, the relation between  $C$  and  $L$  was accounted for by an extinction coefficient that was constant over the whole growing season. A similar conclusion was reached by Flénet et al (1996), using measurements of transmitted PAR, but they considered only the later stages of canopy development ( $L$  always larger than one and generally larger than two). Baret et al (1993), using various angles and hemispherical photographs, also found that the extinction coefficients of sugar beet and wheat were stable. However, the improved spatial sampling offered by vertical photographs makes the results clearer in our case. This stability is surprising because row structure and leaf angle distribution change noticeably as the canopy grows [for sugar beet, see Hodanova (1972)], and some compensation must take place. In these conditions, empirical relations such as those established here probably give more accurate estimates of  $L$  from measurements of  $C$ , compared to analytical solutions that depend on estimates of leaf angle distribution and a clumping parameter.

The extinction coefficient is only stable if sufficient water is available: in an earlier study (Andrieu and Boissard, 1986) there was a strong effect of wilting on ground cover of sugar beet. In the maize experiment here, the extinction coefficients were small, 0.22–0.25, during a period

when the leaves rolled in response to water stress. However, symptoms of stress can generally be avoided by performing measurements in the morning.

Sowing geometry is unlikely to affect the extinction coefficient in the first stages of development (eg, for  $L < 1.0$ ) because there is no overlap between adjacent plants. Thus a constant extinction coefficient through the full course of crop development is incompatible with a noticeable effect of sowing parameters. However, we found a small effect of plant density in the sugar beet experiment and of sowing geometry in the maize experiment. The decrease of  $K$  with plant density on sugar beet is consistent with the results of Flénet et al (1996) for several crops, including maize. Our maize data did not show an effect of plant density on  $K$ , perhaps because we used a smaller range of row spacing. Finally, vertical photographs capture information on plant density and row spacing, which can be used to apply empirical functions, such as those proposed by Flénet et al (1996). They also capture the gap size information required for analytical models of the clumping parameter. However, for maize and sugar beet, crops having very different canopy architecture, large variations in plant population and spacing resulted in only very moderate effects on the extinction coefficient: these effects can be ignored in most cases for the purposes of estimating leaf area index.

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