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Techniques to estimate relative leaf area and cover of weeds in crops for yield loss prediction

L. A. P. LOTZ*, M. J. KROPFF†, J. WALLINGA‡§, H. J. BOS‡¶ AND R. M. W. GROENEVELD*
**Research Institute for Agrobiology and Soil Fertility (AB-DLO), PO Box 14, 6700 AA Wageningen, The Netherlands. †International Rice Research Institute, PO Box 933, 1099, Manila, The Philippines. ‡Department of Theoretical Production Ecology, Agricultural University Wageningen, PO Box 430, 6700 AK Wageningen, The Netherlands.*

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Summary: Résumé: Zusammenfassung

Destructive measurements to collect input data for models that predict yield loss from relative leaf area of weeds can be laborious. Alternative methods were tested in seven field experiments with sugar beet or spring wheat. Weeds with different morphologies showed the same linear relationships between relative leaf area, measured destructively, and cover, assessed by means of a frame, until 3 or 4 weeks after crop emergence. At later growth stages, differences in weed morphology resulted in different relationships. Visual estimates of weed cover corresponded only roughly with cover assessments with a frame. The possibility of estimating relative leaf area of weeds with a reflectance technique was tested, assuming that for early growth stages the leaf area index of weeds can be considered as additional to that of the crop. In spring wheat, relative leaf areas of *Sinapis alba* L., sown at different times and densities, correlated well with characteristics based on infra-red reflectance. In sugar beet, these relationships were not as distinct.

Techniques d'estimation de la surface foliaire relative et de la couverture des mauvaises herbes dans les cultures, en vue de prédictions de pertes en rendement

Des prélèvements destructifs peuvent alimenter en données les modèles qui prédisent les pertes de rendement à partir de la surface foliaire relative des mauvaises herbes, mais ils sont exigeants en temps. Des méthodes alternatives ont été testées lors de sept expériences au champ dans de la betterave ou du blé de printemps. Jusqu'à trois ou quatre semaines après la levée de la culture, des mauvaises herbes possédant différentes morphologies montraient les mêmes relations linéaires entre d'une part la surface foliaire relative mesurée de manière destructive et d'autre part la couverture mesurée grâce à une grille. Aux stades de croissance ultérieurs, du fait des différences morphologiques entre les mauvaises herbes, les relations étaient différentes. Les estimations visuelles de la couverture en mauvaises herbes ne correspondaient qu'approximativement aux mesures de couverture effectuées au moyen de la grille. La possibilité d'estimer la surface foliaire relative des mauvaises herbes avec une technique de réflectance a été évaluée, en supposant que, aux stades de croissance initiaux, l'indice de surface foliaire des mauvaises herbes peut être considéré comme additif de celui de la culture. Dans le blé de printemps, les surfaces foliaires relatives de *Sinapis alba* L.,

§Present address: Research Institute for Agrobiology and Soil Fertility (AB-DLO), P.O. Box 14, 6700 AA Wageningen, The Netherlands.
¶Present address: Department of Agronomy, Agricultural University Wageningen, Haarweg 333, 6709 RZ Wageningen, The Netherlands.

semées à différentes époques et à différentes densités, étaient bien corrélées avec des caractéristiques basées sur la réflectance infra-rouge. Dans la betterave à sucre, ces relations n'étaient pas aussi claires.

Bestimmung der relativen Blattfläche und des Deckungsgrads von Unkräutern zur Prognose von Ertragsverlusten

Die destruktive Gewinnung von Daten der relativen Blattfläche von Unkräutern für Modelle zur Vorhersage von Ertragsverlusten sind arbeitsaufwendig. Alternative Methoden wurden in 7 Versuchen in Zuckerrübe und Sommerweizen untersucht. Morphologisch unterschiedliche Unkräuter zeigten bis zu 3 oder 4 Wochen nach dem Auflaufen der Kulturpflanzen dieselben linearen Beziehungen zwischen der destruktiv gemessenen relativen Blattfläche und dem mittels eines Rahmens bestimmten Deckungsgrad. In späteren Entwicklungsstadien führten die morphologischen Unterschiede zu verschiedenen Verhältnissen. Bonituren des Unkrautdeckungsgrads entsprachen nur grob den mit dem Rahmen ermittelten Deckungswerten. Die Bestimmung der relativen Blattfläche der Unkräuter durch Messung der Lichtreflexion wurde geprüft, wobei angenommen werden kann, daß sich in den frühen Entwicklungsstadien der Blattflächenindex der Unkräuter mit dem der Kulturpflanzen summiert. Im Sommerweizen war die relative Blattfläche von zu verschiedenen Zeiten und in unterschiedlicher Dichte gesätem *Sinapis alba* L. mit den Daten der Infrarotreflexion gut korreliert, auf den Zuckerrübenflächen nicht so genau.

Introduction

Weed density is not a very accurate measure from which to predict competition effects, as it does not account for variation in the time of weed emergence, weed size and development. Recently, Kropff & Spitters (1991) proposed a simple, one-parameter model that describes yield loss (Y_L) by weed competition from early observations of the contribution of a weed species to the total leaf area index (here called the relative leaf area of the weed):

$$Y_L = \frac{qL_w}{1+(q-1)L_w}$$

in which L_w is the relative leaf area of a weed species and q the relative damage coefficient. The parameter q measures the competitiveness of the weed with respect to the crop and is thus species-specific. The model can be extended to allow for more weed species. Kropff & Spitters (1991) derived the model from a hyperbolic yield density relationship (Cousens, 1985; Spitters *et al.*, 1989) and they stated that it implicitly accounts for the effects of both density and time of emergence of the weeds. Therefore, the model might be used in situations where weeds emerge in separate flushes, but determining the relative leaf area of the weeds only once (e.g. at the time of spray decisions). Experiments were performed in sugar beet and maize to validate the model (Kropff & Spitters, 1991; Lotz *et al.*, 1992). It was concluded that the model can generally be used to predict yield losses on the basis of the relative leaf area of weed species. However, a second model parameter, determining the maximum relative yield loss, is sometimes required for weed species that have a specific plant structure or developmental characteristic (e.g. a procumbent growth form or early flowering).

Because the relative leaf area model seems to have the potential to become an important tool in future weed management systems that are based on prediction of yield losses (Kropff & Lotz, 1992), a study of methods to estimate relative leaf area of weeds in the field is needed. The input variable L_w requires the measurement of leaf area indices (LAI) of both crop and weeds and therefore involves laborious, destructive sampling. However, preliminary studies demonstrated that for early growth stages, cover, defined as the proportion of the ground occupied by the vertical projection of a species shoot area, can also be used to determine values of the model inputs (Lotz *et al.*, 1992; Lutman, 1992). Cover may be recorded by visual estimates, with cover pins (point quadrats) or from frames with cross wires (Goldsmith *et al.*, 1986). Lutman (1992) determined cover by placing a grid on photographs of experimental plots and counting the number of points covering crop, weed and soil. Simple visual estimates are subjective. Experience of the observer or characteristics of the species (colour, growth form) can bias the data considerably. The use of cover pins, frames or grids is more objective, but very time-consuming.

Thompson *et al.* (1991) reviewed methods for automatic detection of weeds in crops. Two basic approaches have been used to distinguish weed from crop. The first is to detect differences in geometry or position between the crop (rows) and weed plants. Shape features recorded with video cameras and analysed with high-resolution imaging might be possible. Processing requirements and response times with present-day technology, however, appeared to be serious constraints for field-scale application. Moreover, the fact that weed plants were obscured by neighbouring plants was a major limitation of detecting weeds in, and between, rows of a drilled cereal crop (Thompson *et al.*, 1990). This problem had already occurred early in the cropping season, some weeks after sowing in autumn.

The second approach is the use of spectral reflectance techniques. LAI and cover of various crops (monocultures) can be estimated from reflection in the red and infrared spectral bands (Bunnik, 1978; Steven *et al.*, 1983; Birnie *et al.*, 1987; Clevers, 1989). These estimates can be obtained quickly and in a non-destructive way. Obscurity of weeds by neighbouring plants is not a serious problem to reflectance techniques. Leaves from lower canopy layers also contribute to the total infrared canopy reflectance (Clevers, 1989). In their review, Thompson *et al.* (1991) concluded that differences in reflection characteristics of green leaves are not sufficient to discriminate weeds from crop plants. Only when weeds and crop differ in nitrogen content or in timing of life cycle stages, e.g. flowering weeds in a non-flowering crop or green weeds in a drying crop (straw), are there possibilities to detect weeds in crops (Haggar *et al.*, 1984). However, relative leaf cover of weeds has to be determined at the time when a weed control treatment is considered, i.e. normally early in the cropping season. At that time, differences in life cycle stages between weeds and crop are not usually found.

We suggest that reflectance techniques may still be useful in determining relative leaf area and cover of weeds. If the crop is emerging homogeneously and if weeds and crop are not substantially covering each other, reflectance can be used by comparing the reflectance of a weedy crop to weed-free plots. These requirements can be met at early stages of crop development. However, it must be assumed that at early stages the LAI of weeds can be considered as additional to that of the crop.

The aims of this study were to examine the relationship between the relative leaf area and the relative cover of weeds at early stages of crop development, to compare the relative cover estimates from visual estimation and cover frames, and to estimate relative leaf area of weeds by reflectance techniques, assuming that the crop is homogeneous.

Materials and methods

Study sites and crops

Experiments were conducted on a loamy fine sand at Droevendaal and on a non-calcareous silty clay at De Bouwing. Both experimental stations are near Wageningen, The Netherlands. Crop management was according to standard practices for the region. Sowing dates, crop species and crop cultivars for each experiment are given in Table 1. Distances between rows and between plants within rows were 0·50 m and 0·18 m, respectively in sugar beet. In spring wheat, row distances were 0·13 m and crop density was 250 plants m^{-2}.

Experiments 1 and 2

After pregermination in a growth cabinet, seeds of *Chenopodium album* L., *Polygonum persicaria* L. and *Stellaria media* L. were sown by hand 5, 10, or 15 days after crop emergence. They were thinned to three densities for each sowing date. The weed densities ranged from 2·8 to 88·9 plants m^{-2}. The experiment was a split plot design, with weed species as the main plots, sowing dates and densities of weeds as subplots (3·0×2·2 m). There were two blocks. The weed species were selected for their different growth forms: *C. album* is erect, *S. media* is procumbent and *P. persicaria* is of intermediate growth form. Other weeds were removed by hand during the experi-

Table 1. Experimental details at sites Droevendaal (D) and De Bouwing (DB)

Experiment	Year	Site	Crop	Cultivar	Sowing date
1	1990	D	Sugar beet	Univers	6 April
2	1990	DB	Sugar beet	Univers	9 April
3	1991	DB	Sugar beet	Carla	27 March
4	1992	D	Sugar beet	Univers	22 April
5	1992	D	Sugar beet	Hilde	6 May
6	1992	D	Spring wheat	Baldus	10 April
7	1992	DB	Spring wheat	Baldus	22 April

ment. Cover and LAI of weeds and crop were determined on days 10, 16, 23 and 42 after sowing. Cover was assessed by visual estimates (2–3 persons independently) and by means of a frame (2·50×0·50 m), consisting of 6000 sub-squares (12·5×12·5 mm). Leaf area was measured destructively by using an area meter (type 3100, Licor Inc., Lincoln, Nebraska, USA). Size of area sampled was 2·0×0·5 m (one sample per replicate). Two variables were derived:

$$L_{w(LAI)} = LAI_{weed}/(LAI_{crop} + LAI_{weed}) \text{ and}$$

$$L_{w(cover)} = cover_{weed}/cover_{crop+weed}.$$

Owing to irregular emergence of weeds we omitted 20 plots (28% of the total) in experiment 2 from further analysis.

Experiment 3

Nine plots (each 1·4×1·4 m) were randomly selected in a sugar beet crop with natural weed infestations (mainly *P. persicaria*, *P. convolvulus* L. and *C. album*). Weed densities ranged from 0 to 225 plants m^{-2}. $L_{w(LAI)}$ was determined 40 days after crop emergence. At the same time, the proportion of incoming radiation reflected by the canopy was measured in each plot with a portable multi-band radiometer (Cropscan, Skye Instruments Ltd, Llandrindod Wells, UK). The hemispherical irradiance (I_h) and the amount of radiation reflected by the crop and soil (I_c) were recorded. The field of view for I_c was 28°. The crop reflectance was obtained as the ratio I_c/I_h. The bands green (545–555 nm), red (644–656 nm) and infrared (844–856 nm) were used to obtain reflectances GR, R and IR, respectively. In each plot a series of five measurements were taken at one position. Means were used to analyse IR and the ratios GR/IR and R/IR. In these ratios the effect of changes in incident radiation during the field measurement period may be reduced compared with the IR (c.f. Birnie *et al.*, 1987).

Experiments 4–7

The experiments were set up with factors sowing date and weed density in a randomized complete block design (three blocks). Plot size was 3×3·6 m. *Sinapis alba* L. cv. Emergo was used as a 'model' weed. Naturally occurring weeds were removed during the experiments.

In sugar beet, *S. alba* was sown 10 and 20 days after crop emergence. The weed densities, resulting from the first sowing date were 0, 2·8, 5·6, 11·1, and 22·2 plants m^{-2} and 0, 5·6, 11·1, 22·2 and 44·4 plants m^{-2} from the second. In spring wheat, *S. alba* was sown 0 and 10 days after crop drilling. In this crop, weed densities were 0, 25, 50, 100 and 200 plants m^{-2} (first sowing date) and 0, 50, 100, 200, 400 plants m^{-2} (second sowing date).

$L_{w(LAI)}$ and $L_{w(cover)}$ (visual estimation by one person) were determined twice: in experiment 4 on days 30 and 44, in experiment 5 on days 30 and 45, in experiment 6 on days 18 and 33 and in experiment 7 on days 16 and 30 after crop emergence. On the same day, reflectance characteristics (see experiment 3) were determined. I_c of plots of about 1 m^2 was recorded five times and mean values per band were used for analysis of IR, GR/IR and R/IR. To adjust for differences in soil moisture and irradiance conditions (e.g solar elevation angle) between observation days the so-called 'weighted difference vegetation index' (Clevers, 1989; Bouwman, 1991) was computed: $WDVI = IR - (IR_s/R_s)*GR$, in which IR_s and R_s are the infrared and red reflectances of bare soil. Analysis of WDVI is based on the assumption that R and IR are equally affected by differences in soil background or incoming radiation.

Results

Relationship between relative leaf area and relative cover of weeds

$L_{w(LAI)}$ and $L_{w(cover)}$ in experiments 1 and 2 are compared in Fig. 1. Weed cover was assessed with a frame. Over the treatments sowing date and weed density, the relationship between $L_{w(LAI)}$ and $L_{w(cover)}$ was linear (correlation coefficients for each observation time: $P<0·05$). This relationship did not differ markedly between the weed species, at least until the third or fourth week after crop emergence. At later phases of crop development, the relatively tall *C. album* had a higher $L_{w(cover)}$ for a given $L_{w(LAI)}$ than *S. media* and *P. persicaria* in experiment 2 (Tukey-test on regression coefficients, $P<0·01$). This difference was not significant ($P>0·10$) in experiment 1. On day 40 after crop emergence, most *C. album* plants were considerably taller

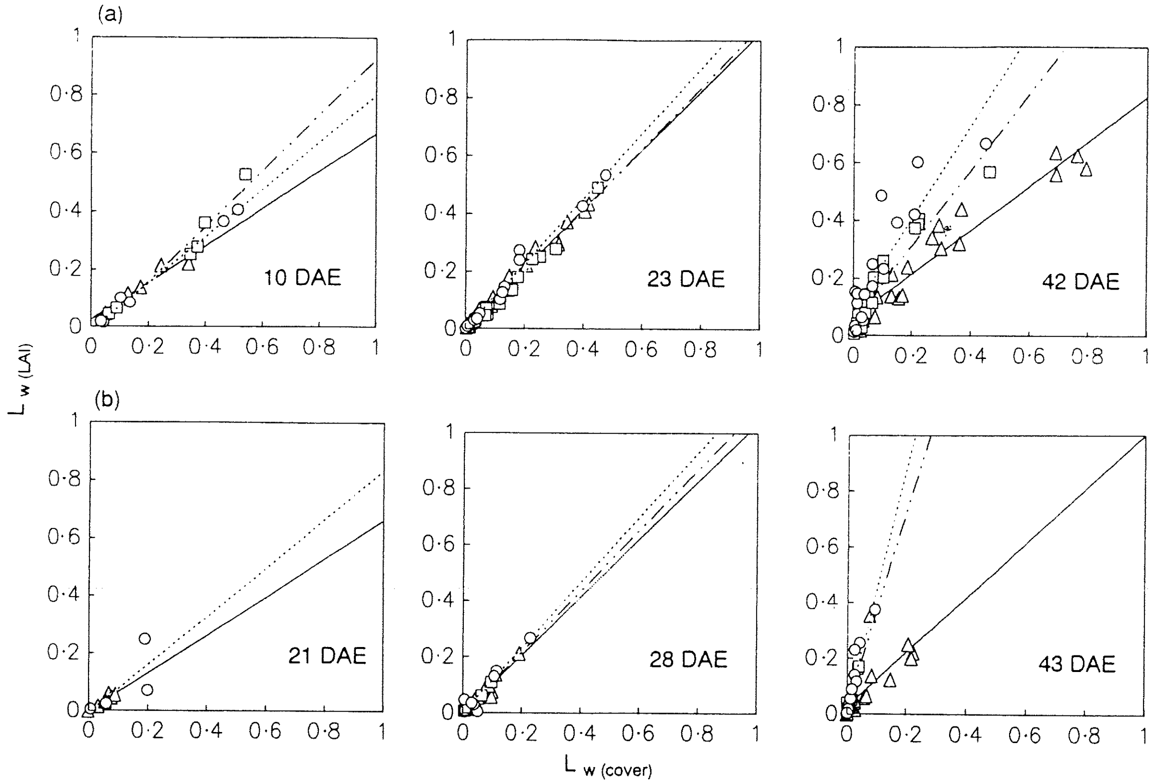

Fig. 1. Relationship between $L_{w(LAI)}$ and $L_{w(cover)}$ in sugar beet in experiments 1(a) and 2(b) at various times (in days after crop emergence, DAE). Weed cover was assessed with a frame. Linear regressions are given to indicate trends. △ indicates *Chenopodium album*, □ *Polygonum persicaria* and ○ *Stellaria media*.

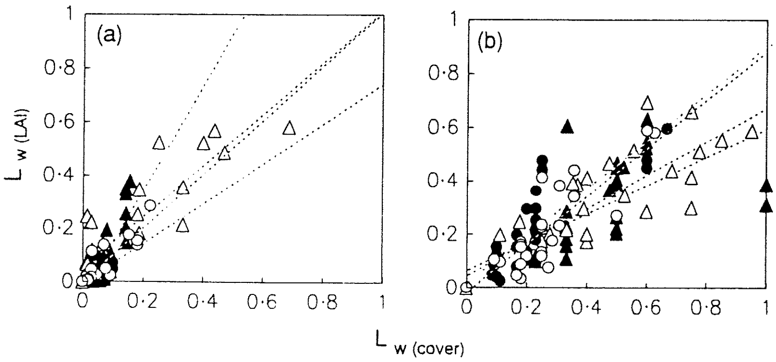

Fig. 2. Relationship between $L_{w(LAI)}$ and $L_{w(cover)}$ of *Sinapis alba*. Filled symbols indicate first observation time, open symbols indicate second observation time. Key: for sugar beet (a), experiment 4 ▲ and △, experiment 5 ● and ○; in spring wheat (b), experiment 6 ▲ and △, experiment 7 ● and ○. Weed covers were assessed by visual estimation. Linear regressions are given to indicate trends.

than the sugar beet, in contrast to the other weeds.

In experiments 4–7, the relationship between $L_{w(LAI)}$ and $L_{w(cover)}$ for *S. alba* could be best described as being linear (Fig. 2). Linear regressions resulted in r^2 values ranging between 0·5 and 0·8 (each $P<0{\cdot}001$). In both sugar beet and spring wheat no marked differences between observation times were found (Tukey-test on regression coefficients: $P>0{\cdot}10$). Since the residuals from the regressions are relatively large, determination of L_w with visual estimates is not very accurate.

Comparison of relative cover records by visual estimation and by cover frames

Over the total range of relative weed covers in experiment 1, records based on visual estimation corresponded roughly with those based on the frame assessment (Fig. 3). Visual estimates were slightly higher than the frame estimates (χ^2-test,

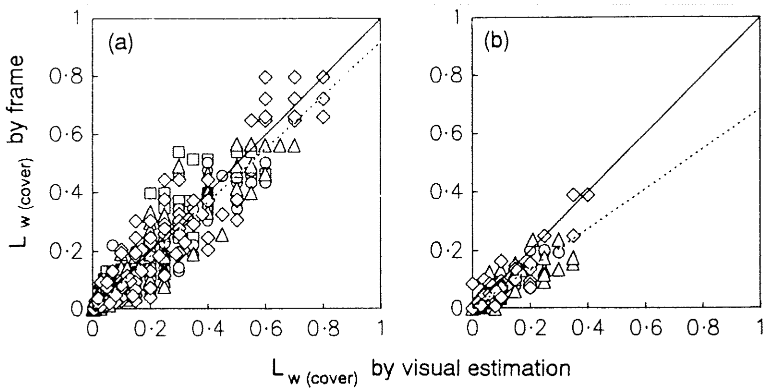

Fig. 3. Comparison of relative cover records ($L_{w(cover)}$) by visual estimation and by cover frames in (a) experiment 1 (□ 10, ○ 17, △ 28 and ◇ 37 days after crop emergence) and (b) experiment 2 (○ 21, △ 30 and ◇ 37 days after crop emergence). Regression (- - -) and 45° lines (——) are given.

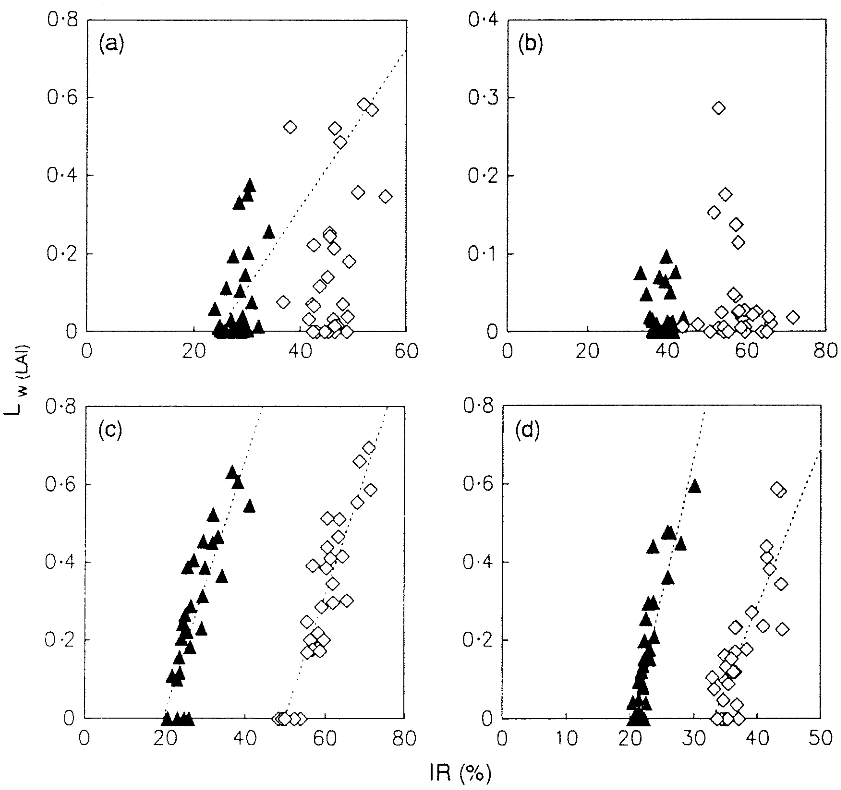

Fig. 4. Relationship between $L_{w(LAI)}$ and the reflectance at the infrared band on two observation dates (▲ first, ◇ second) in sugar beet (experiments 4(a) and 5(b)) and spring wheat (experiments 6(c) and 7(d)). Linear regressions (Table 2) are given to show significant trends.

P<0·001). In experiment 2, patterns of weed emergence were more irregular, but the tendency for visual estimates to be higher was more pronounced (Fig. 3). Graphical analyses of residuals did not reveal any trends with respect to observation time, weed species or observer on the correspondence between the two methods of determination.

Estimation of relative leaf area of weeds by reflectance techniques

$L_{w(LAI)}$ of naturally occurring weeds in sugar beet was significantly correlated with three different characteristics based on GR, R and IR (experiment 3, Table 2). Subsequently, experiments 4 and 5 in sugar beet showed that the rela-

Table 2. Results of regressions between reflectance characteristics and $L_{w(LAI)}$ of *Sinapis alba*. Gr, R, and IR indicate reflection at the green, red, and infra-red bands, respectively.

Experiment	Crop	Reflectance characteristic	Regression coefficient observation 1	Regression coefficient observation 2
3	Sugar beet	GR/IR	−3·19***	
		R/IR	−2·31***	
		IR	0·09*	
4	Sugar beet	GR/IR	−1·44 NS	−0·20 NS
		R/IR	−0·99 NS	−1·59 NS
		IR	0·02*	0·02 NS
		WDVI	0·02*	0·03 NS
5	Sugar beet	GR/IR	0·85*	2·13**
		R/IR	0·40 NS	0·95 NS
		IR	−0·00 NS	−0·00 NS
		WDVI	−0·00 NS	−0·01 NS
6	Spring wheat	GR/IR	−5·91***	12·93***
		R/IR	−2·22***	−15·92***
		IR	0·03***	0·03***
		WDVI	0·03***	0·03***
7	Spring wheat	GR/IR	−6·13***	−0·13 NS
		R/IR	−2·68***	−4·61***
		IR	0·07***	0·04***
		WDVI	0·07***	0·07***

WDVI=weighted difference vegetation index.
Levels of significance of corresponding correlation coefficients: NS not significant, *$P<0·05$, **$P<0·01$, ***$P<0·001$.

tionships between $L_{w(LAI)}$ of *S. alba* and the reflectance characteristics were variable. In experiment 4, $L_{w(LAI)}$ only correlated with IR and in experiment 5 with the ratio GR/IR (Table 2). In spring wheat (experiments 6 and 7) $L_{w(LAI)}$ of *S. alba* was highly correlated with all reflectance characteristics, with the exception of GR/IR at the second observation. Figure 4 illustrates the regressions for IR.

The regression coefficients for the characteristics based on GR and R differed markedly between the two observation days (Table 2). In experiment 6 these differences were significant at $P<0·01$ (Tukey-test). For IR and WDVI, however, differences between the regression coefficients were much smaller (for IR in experiment 6, difference significant at $P<0·01$) or absent ($P>0·05$).

Discussion

The relationship between relative weed cover, determined with a frame, and relative leaf area measured destructively were consistent for early growth stages of weeds. Weed species with different plant architectures (*C. album*, *P. persicaria* and *S. media*) showed the same linear trends until 3 or 4 weeks after crop emergence. For later growth stages, when leaves overlapped with neighbouring plants, the species with an erect growth form had the highest $L_{w(cover)}$ at the same $L_{w(LAI)}$. If cover is used rather than leaf area, the model parameter q or the inclusion of a second parameter that determines the maximum yield loss (see Introduction), should allow for such growth and development dependent differences (Kropff & Spitters, 1991; Lotz *et al.*, 1992). Unfortunately, the cheapest method, visual estimation of weed cover, induces a bias that may seriously constrain the practical use of the crop–weed competition model (Figs 2 and 3). The fact that the relationship between relative cover records by visual estimation and by frame could not be improved by accounting for weed species and observer, might indicate that observer training will not considerably contribute to an accuracy increase. However, from comparison of visual and photographic measurements of cover of oats in beans and linseed, Lutman (1992) suggested that trained observers can visually assess weed covers with an acceptable level of accuracy.

Spectral reflectance techniques are realistic alternatives to obtain estimates of relative leaf areas of weeds without laborious destructive harvests or frame assessments. The results demonstrate that in spring wheat $L_{w(LAI)}$ can be relatively accurately estimated by reflection records.

Clearly, the homogeneity of the wheat crop is sufficient to detect quantitatively weed leaf area as additional to the total leaf area of the crop. For both IR and WDVI the differences in the regression with $L_{w(LAI)}$ between experiments and observation times were small, suggesting that these relationships need not be adjusted for assessment date at early crop stages. Further studies should test whether regressions based on WDVI are more consistent because of adjustment for differences in soil moisture and irradiance conditions (cf. Clevers, 1989; Bouwman, 1991).

In sugar beet, the relationships between reflectance characteristics and $L_{w(LAI)}$ were poorer. In experiment 3, $L_{w(LAI)}$ of naturally occurring weeds could be estimated well by GR/IR, R/IR and IR. This result was not obtained in experiments 4 and 5. The lack of distinct relationships in sugar beet may be due to the low crop plant density (11 plants m^{-2}). Plant densities in spring wheat (*c.* 250 plants m^{-2}) will average out individual plant traits, resulting in a more homogeneous background of crop plants per plot. The prospects for use of reflection techniques in sugar beet may be improved by either increasing the plot size (e.g. by sensing from a greater height), by decreasing the between-plant heterogeneity through agronomic practices (e.g. improving homogeneity in seed quality and disposition of nutrient gifts) or by increasing the number of samples.

Various advisory systems have been developed to support decision-making in weed management (Aarts & De Visser, 1985; Daandrup & Baalegaard, 1990; Gerowitt, 1992). Their general objective is to reduce the amounts of active ingredients used for weed control. Introduction of such systems into practice will be enhanced when an accurate method to predict yield loss by weeds can be used. The simple approach based on relative leaf area would be very powerful if user-friendly methods to detect weed leaf area are available. Tractor-mounted reflection sensors have been developed to trigger individual spray jets to spray or not to spray while driving over fields, by distinguishing between weed patches and bare soil, e.g. in fallow situations (Felton, 1991). In homogeneous crops this spraying technology can be easily extended to a system that distinguishes areas in which yield loss due to weeds is expected. An effective combination of models to predict yield loss due to weeds by remote sensing techniques and a suitable spraying technology will be essential for the development of advanced weed management systems with low input of herbicides.

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