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Effects of crop canopy structure on herbicide deposition and performance

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Summary

To explore the relationship between canopy structure of winter wheat and herbicide performance, new indices representing canopy structural characteristics have been devised. Canopy structures of six different wheat cultivars grown in trays were determined and herbicide deposition and performance measured in a split-plot experiment. A canopy index (Cp) was devised as the ratio of growing canopy height to manually extended maximum plant height, as a representation of structure and stem and leaf inclination. Canopy volume was taken as the volume within the canopy consisting of one main stem and two tillers. Canopy index and volume were closely correlated with individual crop growth characteristics. These indices were also closely correlated with each other ($r = 0.80$; $P < 0.001$) and showed relatively consistent correlation with other characteristics, such as leaf area, plant height, canopy area, and light penetration as the wheat grew. Canopy index and volume were closely but negatively correlated with light penetration ($r = -0.87$; $P < 0.001$ and -0.71; $P < 0.001$ respectively), which in turn showed close correlation with herbicide deposition. The amount of herbicide deposition on the soil surface was positively correlated with weed biomass. Surprisingly, the amount on target weeds was uncorrelated with final weed biomass, indicating that herbicide performance was not dependent upon deposition on the target in different crop cultivars with different canopy structures. Our findings thus demonstrate the importance of crop canopy structure, represented by canopy index and volume, in herbicide performance. These new indices should be useful for investigating crop canopy structure in relation to crop competitivity and herbicide performance.

Keywords: winter wheat, canopy structure, canopy index, canopy volume, herbicide, deposition.

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Introduction

As a potential strategy to suppress weeds and reduce dependence on herbicides for weed management, efforts have been made to select more competitive crop cultivars (e.g. Lemerle *et al*., 1996b). The use of a competitive crop in conjunction with mechanical and cultural methods of weed control may provide a viable alternative to weed control by herbicides (Mulder & Doll, 1993). Competitive cultivars may also be useful in situations where herbicides are used by allowing effective weed control with reduced application rates, leading to reduction of the total herbicide use. Many studies have revealed that crop species differ in competitivity and contrasts between cultivars have been found within species (Richards & Whytock, 1993; Lutman *et al*.,

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1994; Lemerle *et al*., 1995; Seavers & Wright, 1997; Bertholdsson, 2010).

With increasing interest in less intensive and organic farming, several recent studies have examined the difference in the competitivities of wheat cultivars in suppressing weed growth and maintaining potential crop yield in the presence of weeds (Huel & Hucl, 1996; Eisele & Kopke, 1997a,b; Seavers & Wright, 1997). In these studies, crop competitivity was examined by measuring either the suppression of weed biomass or crop yield losses caused by weed interference. The difference in competitivity is associated with morphological, phenological and physiological characteristics of crop cultivars. Additional efforts have also been made to identify specific crop traits responsible for crop competitivity, especially morphological characteristics. Plant height has been emphasised by many researchers as an important parameter (e.g. Wicks *et al*., 1994; Seavers & Wright, 1997). Leaf size, area and inclination are closely related to crop competitivity, and cultivars with wide, long and re-curved leaves are more competitive than those with small, short and erect leaves (Cudney *et al*., 1991; Eisele & Kopke, 1997a,b; Seavers & Wright, 1999). It has been proposed that plant height, leaf area and shape may determine shading ability, which was found to be an important component of crop competitivity (Cudney *et al*., 1991; Wicks *et al*., 1994; Eisele & Kopke, 1997a,b). Early seedling vigour (Burnside & Wicks, 1972) and early ground cover (Richards, 1989; Richards & Whytock, 1993) also contribute to differences in crop competitivity. Crop competitivity also depends on other morphological and physiological characteristics, such as dry matter accumulation (Balyan *et al*., 1991; Lemerle *et al*., 1996b), nutrient uptake (Konesky *et al*., 1989) and relative rates of phenological development (Cousens *et al*., 1991; Morishita *et al*., 1991). As these characteristics are related to each other and their importance depends on growth stages and weed species, it is obvious that the competitivity of a crop cultivar cannot be simply explained by a single characteristic, but by combination of many characteristics interacting in the field situation. Competitivity should therefore be considered as a function of crop canopy and composition, determined by the combination of individual morphological characteristics.

It has been assumed that a more competitive cultivar will need less than the recommended herbicide dose for effective weed control. Christensen (1993) reported that a competitive cultivar enabled adequate weed control to be achieved with a herbicide dose significantly lower than the label recommendation. Lemerle *et al*. (1996a) also reported that rates of diclofop-methyl below those recommended gave greater suppression of *Lolium rigidum* Gaud. grown with highly competitive wheat varieties. The work presented by Kim *et al*. (2002) also showed similar results; the competitive wheat cultivar Avalon required less metsulfuron-methyl to achieve a chosen level of crop yield, compared with the less competitive cultivar Spark. Crop competitivity is closely correlated with ground cover and leaf area of the crop, so crop cultivars with well-established ground cover and a high leaf area index will increase shading and thus be more suppressive of weed growth (e.g. Whiting & Richards, 1990). However, it can also be suggested that herbicide spray may be intercepted more by competitive cultivars than by less competitive ones, resulting in less herbicide deposition on the target weeds. Although competitive crop cultivars will suppress more weed growth, the reduced amount of herbicide deposition on the target weed may result in poor weed control. Thus, crop canopy structure may determine not only the competitivity of a cultivar, but also herbicide deposition on the target plants and herbicide performance. However, so far, no studies have reported the relationship between herbicide performance and crop canopy structure in relation to herbicide deposition.

In comparison with individual studies on a single growth character, a study of crop canopy structure determined by important morphological characteristics should provide a better understanding of the relationship between crop competitivity and herbicide performance. Therefore, this study was conducted to investigate the growth characteristics of winter wheat cultivars with various canopy structures and their changes over time to introduce a new index that can represent important morphological characteristics related to crop competitivity. A second objective was to determine the relationships between crop canopy structure and herbicide deposition, in terms of actual herbicide performance.

Materials and methods

General details of experiment

A tray experiment was carried out at Long Ashton Research Station, United Kingdom, in 1997/98. The experiment consisted of three replicates of a split-plot design; six winter wheat cultivars as main plots were split for three herbicide treatments, consisting of a control and two different timings of herbicide treatment.

Six cultivars of winter wheat (*Triticum aestivum* cvs Abbot, Avalon, Beaver, Cadenza, Soissons and Spark) with different growth characteristics were chosen on the basis of previous studies (e.g. Seavers & Wright, 1997) (Table 1). Four rows of each cultivar were sown into trays (60 × 40 cm) on 14 November 1997 and the trays placed in the glasshouse to compensate for late planting.

Table 1 General growth characteristics of the winter wheat cultivars examined in this study. Information presented was obtained from the lists of cereals published by the UK National Institute of Agricultural Botany (Jarman & Pickett, 1996)

Cultivar	Plant height*	Thickness of stem	Growth habit†	Time of ear emergence‡	Flag leaf attitude§
Abbot	vs–s	Thin	sp	l-vl	se
Avalon	s–m	Thin	i	e	se–sr
Beaver	s	Thin	sp	l	e
Cadenza	l	Thick	se-i	e-m	e
Spark	l	Thick	i	l–vl	h
Soissons	s	Thin	sp	ve–e	e–se

*Plant height: vs, very short; s, short; m, medium; l, long (tall).
†Growth habit: sp, semi-prostrate; i, intermediate; se, semi-erect.
‡Time of ear emergence: ve, very early; e, early; l, late; vl, very late.
§Flag leaf attitude: e, erected; se, semi-erected; sr, semi-curved; h, horizontal.

The trays were transferred outside to natural conditions on 20 December and the plants were thinned to 80 plants per tray (320 plants m^{-2}) on 9 January 1998, when the plants were well established. *Brassica napus* L. (oilseed rape cv. Contact) as a model weed was transplanted between the rows of winter wheat at a density of 16 plants per tray on 2 February, when the plants were at the 2–3 true leaf stage. The trays were watered regularly using a sprinkler system.

Herbicide application and measurement of herbicide deposition

Foliar-spray treatments of metsulfuron-methyl at 1.5 g a.i. ha^{-1} were made on 20 February or 7 March 1998. The sublethal dose was close to the GR_{50} value (Kim *et al*., 2002). The spray solution was made up of 0.05 g a.i. L^{-1} of metsulfuron-methyl (Ally®; DuPont, USA) and 0.25 g L^{-1} of sodium fluorescein (Uranin ex BDH, UK), which was used to measure herbicide deposition. Applications were made using a gear and tooth-driven laboratory track-sprayer fitted with an 80015E even spray nozzle (Spraying Systems, USA), placed 60 cm above the target plants and set to travel at 0.44 m s^{-1}. The sprayer was calibrated to deliver 0.4 L min^{-1} with a compressed air pressure of *c*. 150 kPa, achieving application rates of *c*. 150 L ha^{-1}.

On the dates of herbicide application, and additionally on 23 March, herbicide deposition on the *B. napus* leaves was measured. For the additional assessment of herbicide deposition (on 23 March), only 0.25 g L^{-1} of sodium fluorescein was sprayed. Following spray application, trays were removed from the track-sprayer chamber and the *B. napus* plants allowed to air-dry for 1 h. Eight *B. napus* plants in one half of the tray were sampled at soil level and were washed immediately in 200–400 mL of extraction solution (depending on the size of the plants), 0.05 M NaOH containing 0.1% Triton X-100 (Dow Chemical, Michigan, USA). The amount of fluorescein recovered from the plants was quantified spectrofluorimetrically using a Perkin-Elmer LS-2 fluorimeter with excitation and emission wavelengths set at 450 and 510 nm respectively. Additionally, leaf areas were measured using an image analyser (Optimax, UK), and dry weight (oven-dried for 24 h at 90°C) was recorded. Herbicide deposition was then estimated as the amount of fluorescein deposition (ng) per unit leaf area and unit leaf dry weight (DUE) of weed. The DUE is deposit per unit emission expressed as nanogram fluorescein per gram dry weight foliage per gram fluorescein applied per hectare (Courshee, 1960; Hall, 1998).

To measure herbicide deposition on an artificial target in the canopy, nine plastic discs (each 16.61 cm^2 and three discs row^{-1}) were placed on the soil surface between the rows of a cultivar in a tray in the absence of weeds. At the third application on 23 March, nine discs were also placed 10 cm above the soil surface. Extraction of sodium fluorescein (in 100 mL of extraction solution per three discs) and its measurement were made as detailed earlier. The remaining *B. napus* plants in the trays (eight plants in a half tray) were sampled on 27 July, oven-dried at 90°C for 24 h and weighed.

Measurement of crop canopy development

Canopy index

Plant and canopy heights of each cultivar were measured approximately every other week from the first measurement on 9 January. Plant height was measured as the length of the maximum vertical height of the main stem extended by hand, and canopy height was the height from the ground to the highest point of the growing plant in the stand. Canopy height was then divided by plant height to assess the longitudinal shape and inclination of the plant canopy, which may determine the structure of the crop community in the field. The value of this calculation was named 'canopy index (Cp)' in Eqn 1.

$$\text{Canopy index(Cp)} = \frac{\text{Canopy height}}{\text{Plant height}}, \quad 0 < \text{Cp} \leq 1 \quad (1)$$

The canopy index (Cp) may differentiate between cultivars in terms of their two-dimensional canopy structure. The maximum Cp is 1, which will be obtained in vertically growing plants. The index is a representation of structure and leaf compaction and stem and leaf inclination within the canopy, so that the larger the value of Cp, the straighter the plant shape.

Canopy area and volume

It was assumed that the main stem and the first and second tillers determine the main three-dimensional canopy structure of winter wheat. The canopy structure of each winter wheat cultivar was measured three dimensionally from 6 February, when the first tiller and second tiller were well formed, along with the third leaf on the main stem. The measurements made were the lengths, l_1, l_2 and l_3, from the stem base to datum points of the main stem, the first tiller and the second tiller respectively. The datum point was the base of the leaf blade; initially, leaf 3, leaf 2 and leaf 1 of the main stem, the first tiller and the second tiller respectively, then moved to the next leaf as a new leaf developed. Heights from the datum points of the main stem and tillers to the soil surface were measured (h_1, h_2 and h_3 respectively).

Distances among the main stem, the first tiller and the second tiller were also measured (d_1, d_2 and d_3). The distance was the length between the datum point of the first tiller and two other points on the main stem and the second tiller. These two other points were the same distance from the ground as the datum point of the first tiller, and the triangle consisting of d_1, d_2 and d_3 was horizontal to the ground. The datum point was changed with plant growth stage, starting from the leaf 2 of the fist tiller and then moved to the next leaf as a new leaf developed.

The angle (θ_1) between the main stem and the soil surface and the angles between tillers and the soil surface (θ_2 and θ_3) were calculated using Eqn 2 and the data of heights (h_1, h_2 and h_3) and lengths (l_1, l_2 and l_3).

$$\theta_1 = \sin^{-1}(h_1/l_1), \theta_2 = \sin^{-1}(h_2/l_2), \theta_3 = \sin^{-1}(h_3/l_3) \quad (2)$$

The overall inclination of the crop canopy was estimated to be the average of the angles (θ_1, θ_2 and θ_3). This inclination is independent of leaf inclination.

Once the distances among the main stem, first tiller and second tiller (d_1, d_2 and d_3) were measured, the semi-perimeter (s) and the top area of the reversed tetrahedron (triangle consisting of d_1, d_2 and d_3, named 'canopy area') were calculated by using Eqns 3 and 4 respectively.

$$s = 1/2(d_1 + d_2 + d_3) \quad (3)$$

$$\text{Canopy area} = [s(s - d_1)(s - d_2)(s - d_3)]^{1/2} \quad (4)$$

Finally, the volume of the tetrahedron named 'canopy volume' was calculated as follows

$$\text{Canopy volume} = 1/3h[s(s - d_1)(s - d_2)(s - d_3)]^{1/2} \quad (5)$$

The main stem and tillers are not vertical but inclined outward from their centre to form the overall inclination of the plant canopy. At the early growth stages when herbicide is applied, this inclination is mainly determined by the angles of the main stem and tillers to the soil surface, as leaves are generally erect. Further details of the measurements are given by Kim (1999).

Number of tillers and leaf area of the crop

The development of tillers at an early growth stage is also important in determining crop canopy structure. Therefore, the numbers of tillers of 10 plants per replicate of each cultivar were counted on the same date of measurement of plant and canopy heights. To minimise errors, the number of tillers of the same plants was recorded at each measurement date.

Leaf area is also an important component of crop canopy. In this study, instead of a destructive measurement of leaf area, an alternative method was employed. The maximum width and length of each leaf on the main stem were measured from the leaf 1 to the flag leaf, consecutively, when each leaf was fully extended. As the number of leaves up to the flag leaf varies with cultivar and individual plants, the measurement was made from leaf 1 to leaf 8 periodically and, when the flag leaf was fully expanded, it was made from the flag leaf to the 4th leaf, inclusively. Then, the width was multiplied with the length. The leaf area derived in this way is an approximate estimate of the leaf area that can only be measured accurately by a destructive measurement.

Light penetration

Light penetration into the crop canopy was also monitored regularly at different levels within the canopy, dependent upon the development of the crop, from 3 February. Full light intensity between 13 and 14 h was measured just above the plant canopy with a Sunfleck Ceptometer (Delta-T Devices Ltd., Cambridge, UK), which only measures photosynthetically active radiation. Light intensity within the crop canopy was then measured at different heights (1, 15 and 30 cm above the soil surface, depending on the crop growth stage) between the plant rows. Finally, the per cent light penetration was calculated for each cultivar.

Statistical analysis

Herbicide deposition and weed biomass were subjected to ANOVA. Correlation coefficients (*r*) were calculated between canopy structural characteristics, light penetration, herbicide deposition and the *B. napus* biomass at each of the measurement dates. To investigate the relationships between canopy index (Cp), canopy volume, light penetration and herbicide deposition, linear and non-linear regression analyses were conducted. The canopy index and light penetration were logit-transformed to make the relationships with the canopy volume and herbicide deposition linear. All statistical analyses were conducted using Genstat (Genstat Committee, 1997).

Results

Canopy development

The measurements of plant and canopy height showed significant differences between cultivars (data not shown) but did not provide much information on canopy structure. Therefore, we introduced canopy index (Cp) as a proxy for two-dimensional canopy structure. The differences in canopy structure of the cultivars are shown in Fig. 1A. Up to early February, the Cp values were small but showed differences between cultivars. Soissons had the highest Cp value (about 0.8), followed by Abbot, Cadenza and Avalon (about 0.7). Spark and Beaver had smallest values (about 0.5). After late February, the plants grew longitudinally and the Cp values increased very rapidly. In March, the differences between cultivars, with the exception of Beaver, were closer with a similar order to the earlier growth stage. In early April, except for Beaver, Cp values reached their maximum and the values became similar for all the cultivars up to mid-May with the exception of Avalon, which had a reduced Cp value (about 0.85) at the flag leaf stage.

Estimates of leaf area increased slowly up to leaf 5 and then increased rapidly. Up to leaf 8, the leaf areas of Abbot and Cadenza were larger than that of Soissons, followed by Avalon, and Spark was the same as Beaver. At earlier growth stages, the leaf areas of Spark and Beaver were significantly smaller than those of the other cultivars. At later growth stages, the leaf area of Avalon was significantly larger than that of Abbot, followed by Beaver, Cadenza, Spark and Soissons.

The canopy area (the top area of the reversed tetrahedron in the crop canopy calculated using Eqn 4) increased linearly up to 11 March in a fairly constant order: Cadenza > Abbot > Soissons > Spark ≥ Avalon = Beaver (Fig. 1C). After this stage, the areas of Beaver and Cadenza became larger than those of Spark and Abbot, followed by Avalon and Soissons. The angles from each side of the reversed tetrahedron of the canopy to the ground measured at the early growth stages using Eqn 2 showed significant differences in the mean angles (canopy inclination) between cultivars (data not shown). Soissons had greater angles than the other cultivars, indicating that the main stem and tillers of

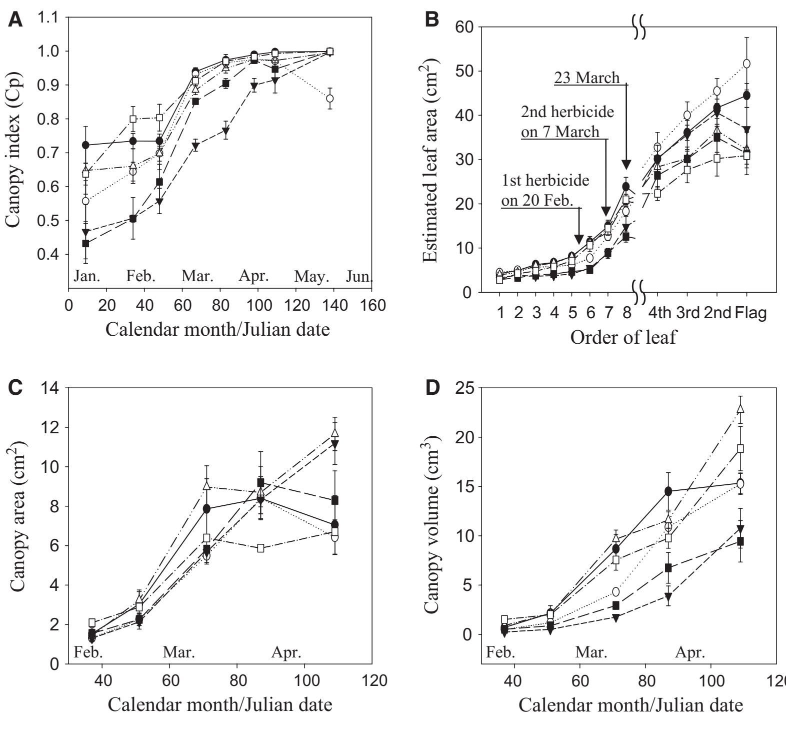

Fig. 1 Canopy index (A), estimated leaf area (leaf length x leaf width) (B), canopy area (C) and canopy volume (D) of winter wheat cultivars, Abbot (●), Avalon (○), Beaver (▼), Cadenza (△), Spark (■) and Soisson (□). Vertical bars are standard deviations of the mean.

Soissons were more erect than those of the others. The following order of the extent of inclination was then Abbot = Avalon ≥ Cadenza > Spark > Beaver.

Canopy volume (Eqn 5) also showed significant differences between cultivars and changes with time (Fig. 1D). Early on, Soissons, Cadenza and Abbot were similar but bigger than Avalon, followed by Spark and Beaver. Later, particularly on 18 April, Cadenza had a larger volume than Soissons, followed in order by Abbot ≥ Avalon > Beaver > Spark. The smaller canopy volumes of Beaver and Spark appeared to be because of their shorter height and prostrate growth habit.

Light penetration

Light penetration to 1 cm above the soil surface was reduced after 7 March (Julian date: 66), when the plants grew vigorously with stem elongation after maximum tillering (Fig. 2A). Light penetration to 1 cm in Beaver and Spark was significantly more than Avalon, followed by Cadenza = Soissons > Abbot at the early stages, becoming similar for all cultivars after mid-March. Light penetration to 15 cm above the soil surface was also high for Beaver and Spark, followed by Cadenza > Avalon > Abbot = Soissons (Fig. 2B). Light penetration to 30 cm above the soil surface was more in Beaver and less in Soissons than the other cultivars, except for the measurement on 18 May (Julian date: 138), when more light was intercepted by Avalon (Fig. 2C).

Herbicide deposition

Herbicide deposition on the artificial target

Herbicide deposition (%) on the target discs placed on the soil surface between crop rows decreased with time (Table 2) in a similar pattern to the light penetration measurement. Although each cultivar had a different canopy structure, no significant difference in herbicide deposition was observed between the cultivars on 20 February, when the crop canopy was not closed between crop rows. However, on the later application dates, there were significant differences in the herbicide deposition between crop cultivars.

On 7 March, significantly more herbicide was recovered from the discs in Spark (60%) than in Soissons, followed by Abbot, Beaver, Avalon and Cadenza. In Spark and Beaver, the light penetration to 1 cm above the soil surface was greatest, *c.* 28% (see Fig. 2A). The light penetration in Spark appeared to be correlated with herbicide deposition (60%). In the case of Soissons, herbicide deposition (50%) also appeared to be correlated with light penetration (20%). However, herbicide deposition (38%) in Beaver was unlikely to be correlated with the light penetration. The light penetration was measured at 1 cm above the soil surface, whereas the herbicide deposition was measured on the soil surface. Beaver had prostrate leaves with well-established tillers between the soil surface and 1 cm above at this stage.

On 23 March, less herbicide was deposited on the soil surface owing to more interception by the crop canopy. Less light penetrated into Beaver and Cadenza canopies on 27 March (around 10%, see Fig. 2A), which was reflected in the herbicide deposition amounts (20% and 24% for Beaver and Cadenza respectively). The herbicide deposition 10 cm above the soil surface also showed different trends from the deposition on the soil surface, with significant differences between cultivars. In Beaver, 84% of herbicide sprayed was deposited on the discs, compared with 54% in Soissons, which appeared to be related to light penetration to 10 cm above the soil surface and plant height.

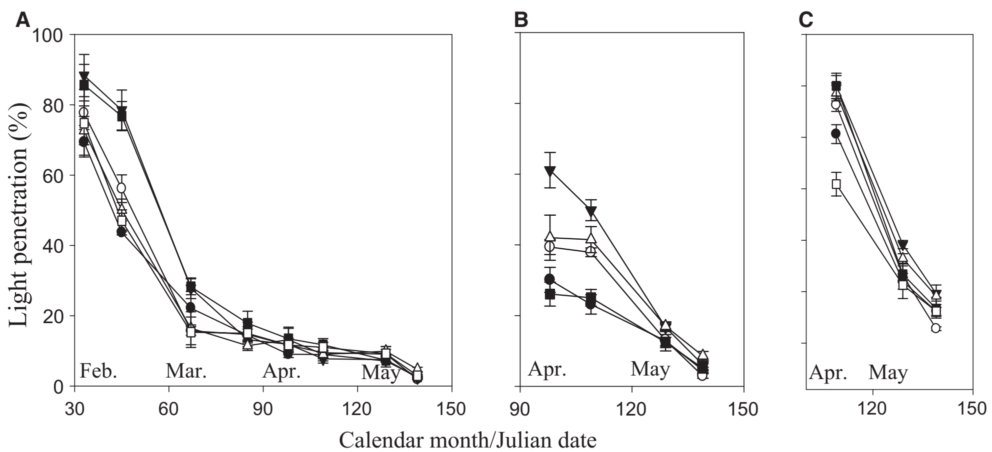

Fig. 2 Light penetration (%) into the plant canopies of different winter wheat cultivars, Abbot (●), Avalon (○), Beaver (▼), Cadenza (△), Spark (■) and Soisson (□), to 1 cm (A), 15 cm (B) and 30 cm (C) above the soil surface. Vertical bars are standard deviations of the mean.

Table 2 Herbicide deposition (%) on the target discs placed within the crop canopy compared with the bare ground deposition

Application date	Cultivars						SED*
	Abbot	Avalon	Beaver	Cadenza	Spark	Soissons	
Deposition on soil surface							
20 February	58.6	64.6	60.8	62.2	63.6	59.6	4.29
7 March	43.0	35.7	38.3	32.4	60.0	50.1	3.67
23 March	30.3	32.6	19.7	24.0	30.9	26.2	2.56
Deposition on 10 cm above the soil surface							
23 March	74.9	62.3	84.0	71.6	76.7	54.3	5.50

*SED, Standard errors of differences of means (d.f. = 18).

*Herbicide deposition on the target plant (*B. napus*)*

Herbicide deposition was not significantly different on 20 February, but there were differences between cultivars at later dates (Table 3). Herbicide deposition on the target leaves at both the first and second applications appeared to be similar to each other but decreased significantly for the last application (23 March). Although there was no significant difference in herbicide deposition on 20 February, the herbicide deposition in Beaver appeared to be greater than that in the other cultivars. On 7 March, herbicide deposition in Spark and Beaver was significantly greater than that in the other cultivars, which may be correlated with the difference in the canopy structure of the cultivars. On 23 March, herbicide deposition showed a somewhat opposite trend to that on 7 March, with significantly greater deposition in Abbot (DEU: 452.9), but significantly smaller deposition in Spark and Beaver (DEU: 301.5 and 357.8 respectively). This suggests that changes in canopy as the crop grows determine herbicide deposition on weeds.

Weed biomass

Overall, as seen in other sulfonylurea herbicides, which generally perform well under warmer weather (e.g. Lee *et al.*, 2006), the herbicide application on 7 March showed better results in terms of weed control than the application made on 20 February and significant differences between cultivars were also seen (Table 4). On 20 February, the herbicide performance for weed biomass reduction was better in Cadenza and Avalon, with weed biomasses of 136 g and 212 g m^{-2} respectively. Biomass of *B. napus* sprayed on 7 March was significantly smaller in Avalon, Beaver and Soissons than in Cadenza and Abbot, followed by Spark. At both application dates, weed biomass was greater in Spark than in Avalon, indicating that weed control was greater in Avalon than in Spark. Biomass of *B. napus* grown in wheat without herbicide treatment was between 400 and 480 g m^{-2}, smaller than 740 g m^{-2} of *B. napus* grown in monoculture with herbicide treatment on 20 February.

Relationships between crop canopy structure and herbicide performance

Among canopy structural characteristics, canopy index (Cp) and canopy volume showed relatively consistent significant correlations with other characteristics. These were positively correlated with each other and negatively correlated with light penetration and herbicide deposition. To understand the relationships between these measurements, linear or non-linear regression analyses were conducted.

Table 3 Herbicide deposition on the leaves of *Brassica napus*. Herbicide deposition was described as the amount fluorescein deposition (ng) per unit leaf area and unit dry weight of weed (DEU)

Date	Cultivars						SED*
	Abbot	Avalon	Beaver	Cadenza	Spark	Soissons	
Deposition ng mm^{-2} leaf area							
20 February	1.059	1.174	1.274	1.141	1.169	1.153	0.0894
7 March	1.032	1.129	1.366	1.169	1.442	1.169	0.0975
23 March	0.097	0.075	0.076	0.080	0.084	0.076	0.0704
DUE values†							
20 February	689.3	707.5	698.5	787.5	665.8	741.4	60.99
7 March	622.1	686.2	764.8	731.6	840.6	737.3	64.38
23 March	452.9	381.2	301.5	431.0	357.8	425.3	32.75

*SED, Standard errors of differences of means (d.f. = 18).
†DUE, Deposit per unit emission: ng fluorescein g^{-1} dry weight foliage g^{-1} fluorescein applied ha^{-1} (Courshee, 1960; Hall, 1998).

Table 4 Comparison of the biomass (g m^{-2}) of *Brassica napus* at harvest, as affected by winter wheat cultivars and herbicide treatments on 20 February and 7 March 1998

Application date	Biomass of *B. napus* in mixed stand with winter wheat							
	Abbot	Avalon	Beaver	Cadenza	Spark	Soissons	SED*	Single stand†
20 February	279.7	212.3	333.6	136.0	423.5	352.8	47.10	737.3
7 March	88.8	15.7	12.8	76.0	107.2	37.6	27.12	322.4
Control	468.8	426.4	448.0	394.4	484.0	466.0	102.69	2166.0

*SED, Standard errors of differences of means (d.f. = 18).
†Biomass of *B. napus* grown in monoculture at the density of 16 plants per tray.

The regression analyses revealed that canopy index had linear relationships with light penetration and herbicide deposition (Fig. 3A and B respectively); light penetration and herbicide deposition decreased linearly with increasing canopy index. In comparison, canopy volume had exponential relationships with light penetration and herbicide deposition (Fig. 3C and D respectively), and light penetration and herbicide deposition decreased exponentially with increasing canopy volume.

Logit-transformed canopy index showed a linear relationship with canopy volume; canopy volume increased linearly with increasing transformed canopy index (Fig. 3E). Similarly, logit-transformed light penetration had a linear relationship with herbicide deposition; herbicide deposition increased linearly with increasing transformed light penetration (Fig. 3F).

There was no significant correlation between herbicide deposition on targets and *B. napus* biomass (data

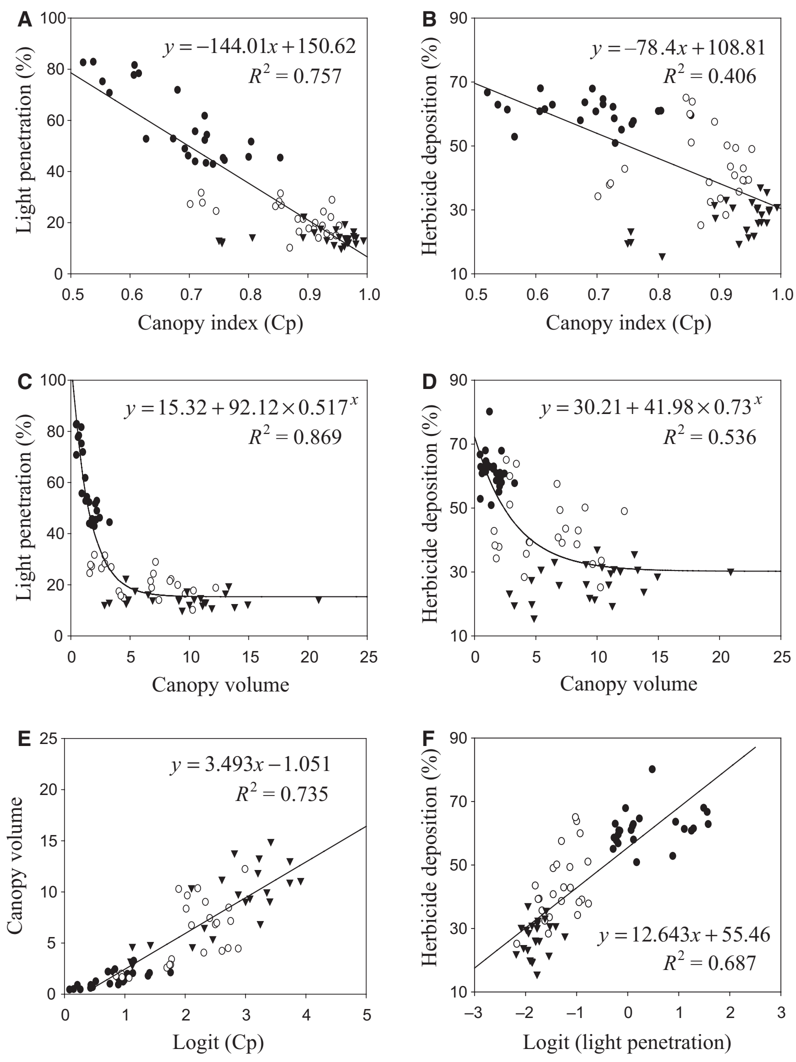

Fig. 3 Relationships between the canopy volume, canopy index (Cp), light penetration and herbicide deposition, which were measured approximately the same date as the herbicide application on 20 February (●), 7 March (○) and 23 March (▼) 1998.

not shown). Without exception, herbicide deposition on the target plants was not significantly correlated with *B. napus* biomass.

Discussion

Correlation between canopy characteristics, canopy index and canopy volume

The results show close correlation between the novel indices devised for this study, canopy index and volume and other growth characteristics (Fig. 4). There were positive correlations with canopy area, canopy inclination, plant height and leaf area, but negative correlation with number of tillers. Several studies have reported morphological and growth characteristics of crop cultivars responsible for the ability of crop competition with weeds, such as plant or canopy height (Appleby *et al.*, 1976), leaf area (Cudney *et al.*, 1991), ground cover (Richards & Whytock, 1993) and number of tillers (Lemerle *et al.*, 1996b). Characteristics related to height and leaf size have most frequently appeared in the literature, showing generally positive correlations with crop competitivity, either in suppressing weeds or in preventing crop yield losses. Some studies have suggested tiller number is important for crop competition, but it has been found to be either negatively or not significantly correlated with competitivity (Champion *et al.*, 1998). In our study, number of tillers was also negatively correlated with the other characteristics of the canopy. Although many aspects of the results in this study are in agreement with previous studies, it is obvious that a single characteristic cannot simply explain crop competitivity. The new indices introduced in this study represent several canopy characteristics at once. Canopy index (Cp) is determined by plant height (maximum) and canopy height, so that it represents stem and leaf inclination together. The results show a close correlation between canopy volume and canopy index ($r = 0.80$; $P < 0.001$). These indices (particularly canopy index) show relatively consistent correlation with other characteristics and light penetration over time. It is therefore suggested that these alternative indices may be useful parameters with which to investigate the relationship between crop canopy structure and competitivity.

Effects of crop canopy structure on light penetration and herbicide deposition

Light interception or penetration has been examined as a measure of crop shading ability in relation to crop competition (Eisele & Kopke, 1997a,b). Light interception can be described by Beer's Law (Monsi & Saeki, 1953) as follows

$$I = I_o e^{-kF} \qquad (6)$$

where I is the light intensity within the crop stand below the canopy, I_o is the light intensity above the canopy, F is a given layer of leaves or leaf area index, and k is the extinction coefficient. The extinction coefficient k depends on the architecture of the canopy, i.e. its leaf inclination (Monteith, 1973). According to this law, ground shading is influenced by leaf area index and leaf inclination of a cultivar and its spacing (Lotz *et al.*, 1991; Kropff & Lotz, 1992). In this study, canopy volume and canopy index (Cp) are closely but negatively correlated with light penetration ($r = -0.71$; $P < 0.001$ and -0.87; $P < 0.001$ respectively), showing linear and exponential decrease in light penetration with increasing canopy index and canopy volume respectively (Fig. 3). They were also positively correlated with leaf area, indicating that canopy index and canopy volume

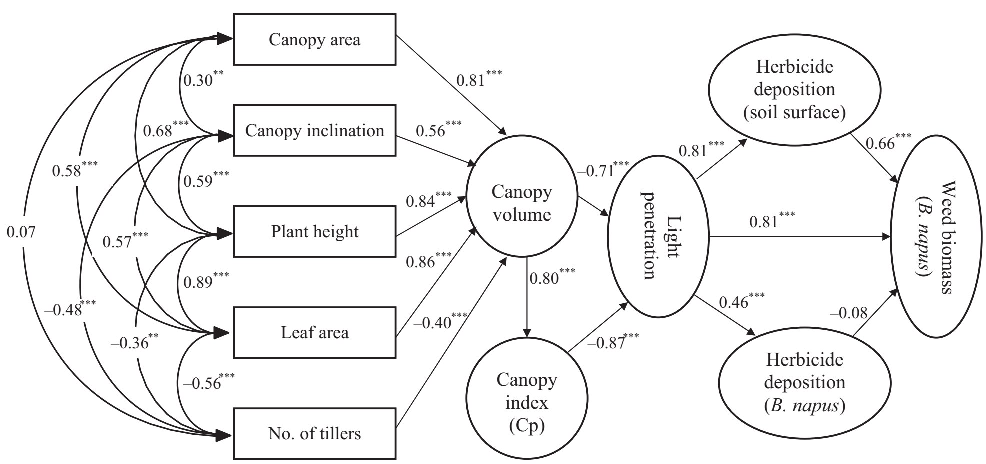

Fig. 4 Schematic representation of the correlation between major canopy characteristics, light penetration, herbicide deposition and weed biomass. $^{**}P < 0.01$; $^{***}P < 0.001$.

may be good indicators of crop shading ability. The close correlation between light penetration and herbicide deposition on the soil surface ($r = 0.81$; $P < 0.001$) also indicates that a canopy with higher canopy index and greater canopy volume may allow less herbicide deposition on the target plants. Hutchins and Pitre (1984) found decreased insecticide coverage of soyabean planted in narrow rows compared with wide rows. Royal *et al.* (1997) and Grymes *et al.* (1999) also showed reduced pesticide deposition on the crop canopy because of weed infestation. Therefore, more competitive crop cultivars with well-established canopy structure may allow less light penetration into their canopy and lower herbicide deposition on the target weeds below their canopy.

Relationship between herbicide deposition and weed control

It is obvious that weed plants receive significantly different amounts of herbicide in different crop cultivars. However, no significant correlation between herbicide deposition on the target plants and weed control ($r = -0.08$) was observed in this study, although there was a difference in weed control between different cultivars. *Brassica napus* in Spark received more herbicide than in Avalon, but final *B. napus* biomass was greater in Spark than in Avalon. This indicates that herbicide performance in different crop cultivars may be related to crop competitivity, rather than simply to the amount of herbicide deposited on the target plant. Courtney (1994) found that increasing crop density enhanced herbicide activity, although he supposed that herbicide interception by the weed would be reduced. He suggested a need for more information on the significance of herbicide deposition in herbicide performance.

It can be deduced from the present study that more herbicide may be intercepted by well-established and bigger crop canopies. However, herbicide performance was greater in more competitive cultivars (i.e. Avalon compared with Spark) and with the plants grown at higher nitrogen levels (Lutman, 1971; Kim *et al.*, 2006a,b). Therefore, the results from the relationship between herbicide deposition and herbicide performance may be explained by accounting for direct competition effects of the crop and microclimatic conditions in crop community, which may provide better condition for herbicide activity.

Conclusions

In this study, two new canopy indices representing several characteristics are introduced: canopy index (Cp) representing stem and leaf inclination together and canopy volume representing the volume within the canopy consisting of one main stem and two tillers. Canopy index and volume were cross-correlated, and these indices (particularly canopy index) showed relatively consistent correlation with canopy characteristics and light penetration over time between cultivars. These indices may be useful for investigating the relationship between crop canopy structure and competitivity. They also helped to explain the relationship between crop canopy structure and herbicide performance relative to herbicide deposition. Our findings thus clearly demonstrate the importance of crop canopy structure in weed and herbicide performance. Whilst the data are derived from a single experiment, they nevertheless represent a sound comparison of six wheat cultivars under the particular conditions described. The extensive data collection on crop canopy elements gave good measures of error, but unfortunately time constraints precluded repetition of the work. Nevertheless, the correlation and regression analyses provided logical results and clear insights into deposition modification. This study presents a valid approach in principle, which now should be applied more generally to take forward particular studies on crop canopy, weed competition and herbicide interactions.

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