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Dosage reduction to improve the selectivity of deltamethrin between aphids and coccinellids in cereals

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Abstract

The toxicity of the pyrethroid insecticide deltamethrin to a cereal aphid and a coccinellid beetle predator was assessed. Deltamethrin gave effective aphid control in winter wheat at dose-rates of 6.25, 3.13 and 1.56 g a.i./ha. The direct exposure of adult *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) to spray drops was estimated at a range of positions in a cereal crop canopy from volumetric analysis of fluorescent tracer deposits. These measurements were used to calculate exposure to deltamethrin at the three experimental dose-rates. Observations of coccinellid beetle distribution through a cereal crop canopy permitted a realistic range of direct contact doses to be calculated and the toxic effects of these levels of exposure to be predicted from laboratory dose-response data. Estimated beetle mortalities from direct exposure were 19, 8 and 3% at the three experimental dose-rates. *In situ* bioassays with adult *C. septempunctata* which exposed beetles continuously to deltamethrin residues on flag leaves, resulted in 100, 94 and 39% mortality respectively at these dose-rates during the 10 days after spray application. Additional *in situ* bioassays exposed beetles to deltamethrin residues on flag leaves for 24 h and then transferred surviving beetles to the soil under the cereal crop canopy for a further 9 days. This resulted in 89, 69 and 29% beetle mortality respectively at the three dose-rates. Mortality predictions combining both direct contact and residual exposure were made for the three dose-rates to determine the maximum impact of summer sprays of deltamethrin on adult coccinellid populations in cereals. These worst case predictions suggested that a reduction in dose-rate by as much as three quarters of the recommended application rate in UK cereals may be necessary to preserve approximately 60% of adult *C. septempunctata* in the crop over the 10 days after a deltamethrin spray application. The methodology described may be appropriate for estimating selective dose-rates for key enemies in a range of crops.

Introduction

It has been demonstrated that reduced dose-rates of certain aphicides in cereals may offer an economic means of aphid control with potential environmental benefits (Poehling, 1986, 1989, 1990; Mann *et al.*, 1991). In addition, spraying at lower dose-rates will, by definition, reduce the impact of pesticides upon nontarget organisms (Burn *et al.*, 1987; van Emden, 1988). Pesticide application in cereals has been shown to reduce natural enemy population densities (Vickerman & Sunderland, 1977; Basedow *et al.*, 1985, Powell *et al.*, 1985; Fischer & Chambon, 1987; Vickerman *et al.*, 1987a, b) and may even lead to local extinctions in some circumstances (Basedow, 1990; Burn, 1992). Also if pesticide applications are made on a large enough scale this may enhance the probability of local pest resurgence (Duffield & Aebischer, 1994). Theoretical modelling has demonstrated that lower dose-rates may reduce the probability of severe impacts on natural enemies and also the risk of pest resurgence (Sherratt & Jepson, 1993).

Current aphicides in cereals differ widely in their toxic effects to natural enemies and in their environ-

mental fate and breakdown (Jepson *et al.*, 1994). It is therefore necessary to derive robust methods that can be used to estimate appropriate selective dose-rates for key natural enemies on a compound by compound basis. Such methodology must take into account the different routes by which natural enemies are exposed to pesticides (Croft, 1990; Mullié & Everts, 1991; Jepson, 1989, 1993), the distribution patterns of predators and pests (Çilgi & Jepson, 1992) and other factors that may alter the exposure of key groups to toxic doses.

In these experiments we assessed the efficacy of the pyrethroid insecticide, deltamethrin as a summer applied cereal aphicide. We sprayed winter wheat plots at the current recommended field rate in UK cereals and two reduced dose-rates. We also measured the toxicity of deltamethrin residues to adult *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) using *in situ* bioassays which continuously confined beetles on deltamethrin treated leaves or soil. *C. septempunctata* was chosen as the test species because it is an important aphid-specific predator in cereal crops (Basedow, 1982; Chambers *et al.*, 1983; Krober & Carl, 1991) and may be among the most common predators of aphids in cereal fields in some years (Dean, 1974). It is also active on the ground and within the crop canopy and permitted both flag leaf and soil surfaces to be chosen as realistic test substrates. Bioassays carried out with these substrates will explore the extremes of toxic risk posed by deltamethrin residues to predators in the cereal crop environment (Wiles & Jepson, 1994a).

We also determined the mean volumetric spray deposition on adult *C. septempunctata* placed in a range of positions in a cereal crop canopy and then used laboratory-derived toxicity data for deltamethrin to predict the mortality that might result at these exposure levels. Direct observations of adult *C. septempunctata* distributions in a mature cereal crop infested with cereal aphids were used to obtain realistic estimates of the pattern of direct exposure to pesticide sprays that might occur and to predict the toxic effects of direct spraying.

Beetle mortality predictions from direct spraying and residual exposure at each dose-rate were combined to estimate the maximum levels of mortality that result from exposure to deltamethrin sprays in cereals. These predictions were based upon estimates of maximum exposure level to obtain realistic worst case predictions for a range of dose-rates.

We suggest that this general approach offers a rational basis for selecting optimum dose-rates of insecticides which promotes integrated pest management. The methodology described may also be applicable to other crop types. The need for such approaches has become evident in the tropics with the severe depletion of predators by frequent pesticide applications (Balk & Koeman, 1984) and more recently in Western Europe, USA and Canada with the development of pesticide usage reduction programmes (e.g. Jansma *et al.*, 1993; Hill *et al.*, 1993).

Materials and methods

Test invertebrates. Adult *C. septempunctata* were captured in May and June 1991 from unsprayed cereal fields and field margins on the Leckford Estates, near Stockbridge, Hampshire, and on South Allenford Farm, Damerham, near Fordingbridge, Hampshire, UK, by hand-held aspirator and surface searching (Southwood, 1987). After capture, the beeltes were returned to an insectary and maintained at 19–22°C and 50–70% RH, with a photoperiod of L16 : D8. They were provided with barley seedlings infested with the English grain aphid *Sitobion avenae* (F.) (Homoptera: Aphididae).

Direct exposure studies. To determine the level of volumetric spray deposition on adult *C. septempunctata* spray treatments were made in a 20 m^2 plot of winter wheat crop, cv. Galahad, GS 73 to 75 (Zadoks *et al.*, 1974), with a mean density of 390 tillers/m^2. Approximately 24 h before the experiment, beetles from the insectary were freeze-killed (exposure to −20°C for 4 h). Excess handling of beetles was avoided to prevent damage to cuticular wax layers which may affect spray retention. The beetles were attached to the plant surfaces prior to spraying by small squares of double-sided adhesive tape (0.25 cm^2). This enabled them to be removed easily after spraying. Five crop strata were chosen as attachment sites and 20 adult *C. septempunctata* were exposed per stratum in both the sprayed and unsprayed plots. The strata were: vertical attachment midway up the ear, horizontal attachment in the centre of the adaxial surface of the flag and first leaves, and horizontal attachment in the centre of the abaxial surfaces of flag and first leaves. Beetles were also placed on the ground under the crop canopy.

The deposition of spray on the beetles in or under the cereal crop canopy was measured using a fluorescent tracer 'Fluorescein' (Acid yellow 73, Aldrich) as a 0.05% (w/v) solution with 0.1% wetting agent,

using a procedure similar to that described by Çilgi & Jepson (1992). An Oxford Precision sprayer fitted with four Lurmark 02-F80 nozzles (BCPC Nozzle Code F80/0.80/3) and operated at 2 bar pressure was used to apply a water and tracer spray mixture at a rate equivalent to 200 l/ha (the recommended volume application rate for aphicides in UK cereals).

After application, spray deposits were allowed to dry for approximately 30 min. The beetles were then carefully removed from the crop using forceps and were placed individually in vials containing 10 ml of phosphate buffer solution (pH 6.8, 0.1M anhydrous di-sodium hydrogen orthophosphate with sodium dihydrogen-orthophosphate dihydrate). The vials were returned to the laboratory and stored in cold, dark conditions until analysis.

In the laboratory, a standard calibration curve was obtained from measured volumes of the original spray formulation added to 10 ml of buffer via a microapplicator. Then 3 ml aliquots were taken from each sample vial containing the exposed beetles and the volume of tracer was determined by analysis in a Perkin-Elmer LS-3B fluorescence spectrometer operating at 490 nm excitation and 515 nm emission wavelengths. These readings were corrected for control readings, taken from buffer solutions containing unexposed beetles, and the volume of spray formulation was calculated from the calibration curve in terms of μl per beetle for each crop position.

The estimated dose of deltamethrin that the beetles would have received from direct exposure at each given position in the crop canopy was calculated using the following expression (adapted from Jepson, 1993),

$$D_t = V_f \cdot C$$

where D_t is the dose received (e.g. ng a.i./beetle), V_f is the mean volume of spray impinging upon beetles at a given position in the crop (μl/beetle) and C is the concentration of active ingredient (ng a.i./μl) in the spray mixture. The dose (D_t) was then substituted into 72 h probit equations, obtained from topical bioassays with *C. septempunctata* and deltamethrin (Wiles & Jepson, 1992a), in order to calculate the expected levels of mortality that would result for beetles at each crop stratum.

C. septempunctata *crop distribution.* The distribution of adult *C. septempunctata* in a cereal crop canopy was determined in a cubic cage with 2 metre sides erected in a winter wheat crop, cv. Galahad (GS 70; mean density 380 tillers/m^2). The cage consisted of steel scaffolding poles covered by 'Tygan' netting (1 mm mesh size). The crop within the cage had been artificially infested with the cereal aphids *S. avenae* and *Metopolophium dirhodum* (Walk.) (Homoptera: Aphididae) four weeks prior to the experiment. During the experiment the numbers of aphids were recorded on twenty marked ears and flag leaves in the cage. One hundred adult *C. septempunctata* were released at ground level in the centre of the cage and were left for two days to establish themselves in the crop. This number was chosen because it was a manageable population size for monitoring in a 4 m^2 area of crop. Assessments of beetle distributions in the crop canopy were made on five days; 27th, 28th, 30th June and 1st and 2nd July 1991. The positions of the beetles were recorded at two hourly intervals throughout each day between 09-00 h and 19-00 h British Summer Time (BST) on nine crop strata; the ear, stem (from ground to ear level), adaxial flag leaf, abaxial flag leaf, adaxial first leaf, abaxial first leaf, adaxial second leaf, abaxial second leaf and ground level.

Residual exposure studies. These experiments were carried out in a winter wheat crop, cv. Apollo (GS 70 to 71, mean density 412 tillers/m^2). The experimental plots measured 5 m × 2 m and were arranged in a randomized block design with four treatments and four replicates. The treatments included deltamethrin sprays at rates of 6.25, 3.13 and 1.56 g a.i./ha and an unsprayed control.

The cereal plots had natural infestations of the aphid *S. avenae*. Aphid numbers were assessed on five marked ears per plot, i.e. twenty ears per treatment, on the day prior to spray application and the following 12 days to compare the aphicidal efficacy of the three deltamethrin dose-rates tested.

The plots were sprayed using an Oxford precision hand-held sprayer fitted with four Lurmark 02-F80 nozzles. The tank pressure was 2 bar and the sprayer was calibrated to spray at a volume rate of 200 l/ha. The spray deposits were allowed to dry for 30 min before the test invertebrates were exposed. Spray deposition was measured using a fluorescent tracer. The tracer was applied as a 0.05% solution in the spray mixture and deposition was measured on 10 flag leaves collected randomly from each plot. Spray deposition at ground level was also measured, using discs of filter paper. The deposition rates were quantified using the procedure described in the direct exposure studies.

Two types of *in situ* bioassay were carried out to determine the toxicity of deltamethrin residues to adult *C. septempunctata*. These were:

1) Continuous exposure of beetles on flag leaves until mortality levels had stabilised. This was taken to indicate that a toxic endpoint response had been reached. These bioassays enabled quantification of the toxic risk posed by deltamethrin residues on flag leaves to predators remaining in the crop canopy after a spray application.
2) Exposure of beetles on flag leaves for 24 h followed by transfer of surviving beetles to soil chambers under the crop canopy. These are later referred to as 'soil transfer bioassays'. These bioassays determined the toxic risk posed by deltamethrin residues to beetles that had moved from the plant to the soil after a spray application either to avoid further contact with the spray or because food supplies had been depleted (e.g. Wiles & Jepson, 1994b).

A total of 80 adult *C. septempunctata* (20 per plot) were used in each experiment. Multiple-leaf and soil bioassay chambers (Wiles & Jepson, 1992b) were used to expose beetles to spray residues and aphids were provided as food in all chambers.

Multiple-leaf bioassay chambers. These consisted of a glass plate measuring 12 cm × 12 cm which was completely covered with flag leaves collected from individual plots. The flag leaves were excised from randomly selected plants in each plot and attached carefully to the glass plates in parallel, base to tip, adaxial surface upwards, using strips of double-sided adhesive tape. Batches of five adult *C. septempunctata* were released onto the flag leaves and chambers were immediately placed over the plates and secured with adhesive tape. The chambers used to confine *C. septempunctata* consisted of plastic tubs (9.5 cm in diameter and 6.5 cm high) with 'Fluon' (PTFE) coated sides and with gauze-covered ventilation holes in the top. They provided an exposure area of 70.9 cm^2.

After the beetles had been introduced, all of the chambers were placed in the crop within their respective plots and were left to experience field conditions. New plates, with fresh flag leaves, were prepared on each day of the experiment and the batches of beetles were transferred to the fresh surface. This was necessary as the excised leaves tended to become desiccated after 24 h and it also ensured that the deltamethrin residues on the new leaves collected from each plot had been weathered in their natural positions in the crop.

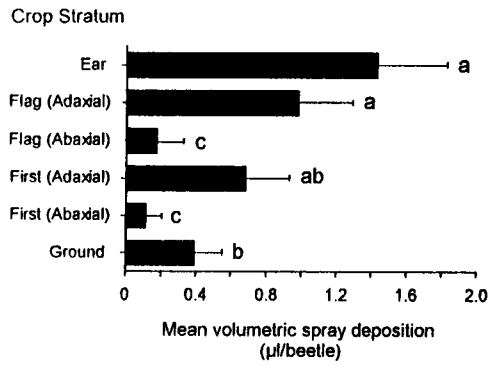
Soil bioassay chambers. These chambers consisted of plastic tubes (9.5 cm diameter × 6.5 cm high) with Fluon-coated sides that had been sunk to a depth of 1 to 2 cm into the soil surface under the crop canopy in the experimental plots. The chambers were filled with a 1 cm layer of sandy loam soil collected from the field site. This was then lightly compacted into the bottom of the chamber making sure that any stones were removed. Plastic inlays, consisting of identical tubs with their bottoms removed, were placed in each chamber prior to spray application. The purpose of these was to avoid spray contamination of the sides of the chambers above the ground surface. The inlays were removed immediately after the spray application. Batches of five *C. septempunctata* were transferred from the flag leaf exposure chambers, after a 24 h initial exposure period, to the soil exposure chambers. Lids with gauze-covered ventilation holes were then placed over each chamber to prevent the beetles from flying out of the chambers. The beetles remained in the same chambers for the duration of the assessments.

The responses of beetles in the chambers were assessed in the field at 24 h intervals. Individuals were recorded as unaffected (moving as normal), or affected (either knocked down or dead). Mortality values were calculated from the total numbers of dead individuals and were corrected for control mortality using Abbott's formula (Abbott, 1925).

Results

Direct exposure bioassays. The $\log(x+1)$ transformed spray deposition data were analysed for differences in deposition patterns between crop strata by one-way ANOVA. Significant differences were evident between positions in the crop canopy for *C. septempunctata* ($F = 33.6$; $df = 5, 114$; $P < 0.001$) with significantly higher spray depositions occurring on beetles on the ear compared to those on abaxial leaf surfaces or on the ground (Fig. 1). No significant differences were evident between spray deposition rates on beetles on the ear and adaxial surfaces on the flag and first leaves, although a trend of declining deposition rate was evident through the crop canopy. The lowest spray deposition rates occurred on beetles attached to the abaxial leaf surfaces.

For deltamethrin sprayed at 6.25 g a.i./ha in 200 l water, the estimated dose of deltamethrin received per beetle varied between 45 ng a.i. on the ear and 4 ng a.i. on the abaxial surface of the first leaf. These doses gave predicted mean mortality levels of between 26%



Estimated mean deltamethrin dose received (ng a.i./beetle) at each crop stratum for given dose-rates (g a.i./ha)			Predicted % mortality of beetles at each crop stratum caused by dose received for given dose-rates (g a.i./ha)		
6.25	3.13	1.56	6.25	3.13	1.56
45.0	22.5	11.3	26	12	4
30.9	15.5	7.8	18	7	2
5.6	2.8	1.4	1	0	0
21.6	10.8	5.4	11	4	0
3.8	1.9	1.0	0	0	0
12.5	6.3	3.1	5	1	0

Fig. 1. Mean volumetric spray deposition on adult *C. septempunctata* in a mature cereal crop canopy (GS 73) and the predicted mortality levels that may result from deltamethrin sprayed at rates of 6.25, 3.13 and 1.56 g a.i./ha in 200 l water. Error bars indicate 95% confidence limits. Different letters indicate significant differences in mean spray deposition rates on beetles between crop strata according to Tukeys' HSD test.

(on the ear) and 0% (on the abaxial surface of the first leaf) as a result of direct contact exposure (Fig. 1). For deltamethrin sprays of 3.13 and 1.56 g a.i./ha, however, the predicted mean mortality levels were reduced to approximately 12% and 4% on the ear, with little or no mortality predicted for beetles present towards the bottom of the crop canopy or on the abaxial surfaces of leaves (Fig. 1).

C. septempunctata *crop distribution.* Between 82 and 100% of the beetles released in the field cage were active in the crop during the assessments. Beetles were occasionally observed on the sides of the cage, however, at the end of the experiment 97 of the 100 beetles were recaptured. Temperature and light conditions varied little between days (mean daily temperatures approximately 24°C and bright sunlight) with the netting making the light diffuse. The crop distribution patterns of beetles in the field cage were similar between the assessment days. At any one time between 50 and 84% of the beetles were observed on the ears and flag leaves, whereas less than 10% were observed on the stem, the abaxial surface of the first leaf or on the second leaf. Beetle distribution patterns varied within days between different assessment times, particularly between the ear and ground levels. Contingency χ^2 analysis of the beetle distribution data indicated significant changes in beetle distributions throughout the day ($\chi^2 > 3.9$, $df = 1$, $P < 0.05$) on each of the five days of assessment. The proportion of beetles on the ear tended to increase between 09-00 h and 15-00 h and declined after this time whereas the opposite trend occurred for beetles observed on the ground. Over the five days of assessment the mean pest densities in the cage declined from 29 to 18 aphids/ear and from 15 to 12 aphids/flag leaf.

Mean adult *C. septempunctata* distribution patterns were calculated for each assessment time between 09-00 h and 19-00 h by combining data from all five days of observation. Data concerning the numbers of beetles on the stem and the second leaf were excluded because the volumetric spray deposition on beetles had not been quantified for these crop strata. Additionally, these strata only accounted for 6–8% of the total observations. The distribution of a hypothetical population of 1000 beetles was calculated from the overall of beetles on six crop strate (Fig. 2). Mortality predictions were then made from these distributions for the effect of deltamethrin sprays applied at rates of 6.25, 3.13 and 1.56 g a.i./ha in 200 l water. The predictions indicated that the population of beetles would suffer overall reductions of between 17 and 21%, 7 and 9% and 2 and 3% from direct contact for the three dose-rates respectively, depending on the time of day at which the spray was applied (Fig. 3). Marginally lower levels of mortality were predicted if the spray was applied at 09-00 h or 19-00 h because lower numbers of beetles were present on the ear at these times.

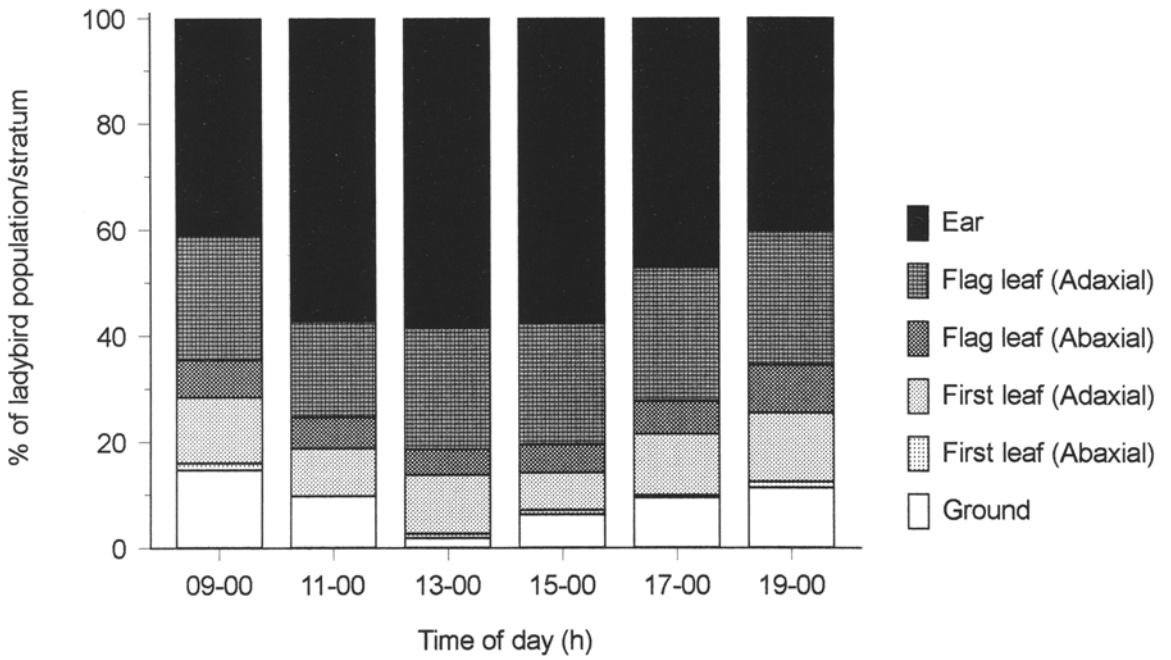


Fig. 2. Estimated distributions of a population of 1000 adult *C. septempunctata* in a cereal crop between 09-00 and 19-00 h.

Residual exposure bioassays. The spray deposition rates in the experimental plots were homogeneous on the flag leaves ($F = 1.4, df = 11, 108; P > 0.05$) and on the soil ($F = 1.0; df = 11, 108; P > 0.05$). The mean spray deposition rates were higher on the flag leaves than on the soil and varied between 0.26 and 0.33 μl/cm^2, compared with mean deposition rates on the soil which varied between 0.20 and 0.26 μl/cm^2. Samples of flag leaves and filter paper on the soil in the control plots were found to have no tracer deposited on them indicating that no spray drift had occurred into the control plots. Because no differences in spray deposition rates were found between treated plots, beetle mortalities for the same treatment were combined and corrected for beetle mortality in the control plots. The maximum observed beetle mortality in any control plot over the 10-day assessment period was 8%.

Levels of beetle mortality in the flag leaf exposure bioassays and the soil transfer bioassays were similar in the first 24 h of exposure within each dose-rate treatment. Beetle mortality levels were approximately 80, 50 and 20% in the plots treated with 6.25, 3.13 and 1.56 g a.i./ha respectively (Fig. 4). In both exposure studies mortality levels appeared to stabilise after 10 days indicating that an endpoint of toxic effects had been reached (Fig. 4). Coccinellid beetle mortality levels in the flag leaf bioassays reached 100, 94 and 39% in the plots sprayed at 6.25, 3.13 and 1.56 g a.i./ha whereas in the soil transfer bioassays mortality levels reached 89, 69 and 29% respectively.

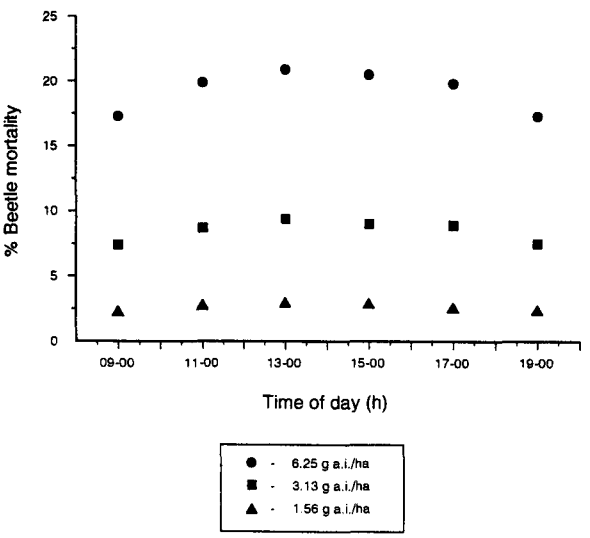


Fig. 3. Predicted mortality levels of a population of adult *C. septempunctata* from direct contact exposure to deltamethrin sprayed at rates of 6.25, 3.13 and 1.56 g a.i./ha in a cereal crop.

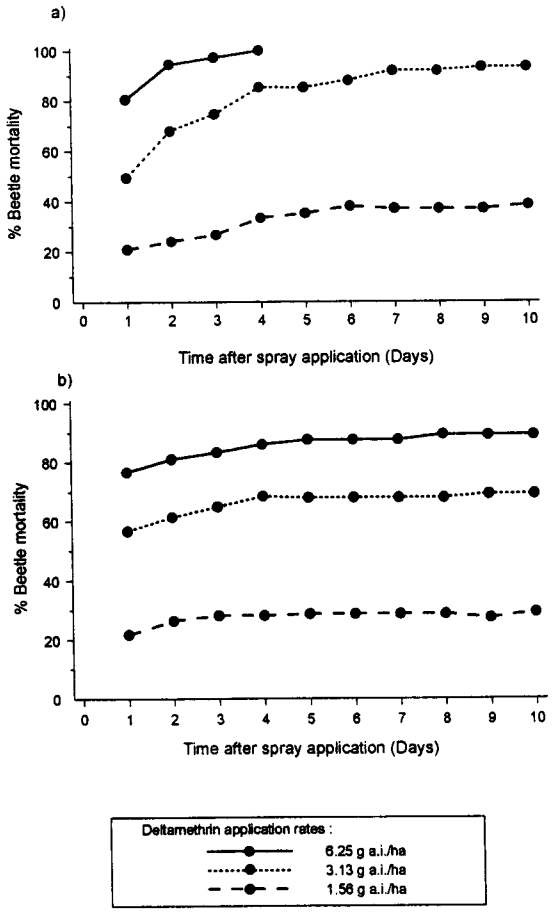


Fig. 4. Percentage mortalities of adult *C. septempunctata* that were, a) exposed continuously on flag leaves or b) exposed for 24 h on flag leaves before being transferred to treated soil, in plots sprayed with deltamethrin at 6.25, 3.13 and 1.56 1.56 g a.i./ha.

Aphicidal efficacy of deltamethrin. Prior to spraying, mean aphid numbers in the experimental plots ranged between 13 and 16 aphids/ear and did not differ significantly between the treatment plots ($F = 1.4$; $df = 3, 79$; $P > 0.05$). On the day after spray application mean aphid numbers were reduced to 2.2, 4.3 and 3.7 aphids/ear in the plots sprayed at 6.25, 3.13 and 1.56 g a.i./ha and by three days after spray application mean aphid numbers had declined to approximately 1 aphid/ear in all treatments (Fig. 5). One-way ANOVA was carried out for $\log(x + 1)$ transformed aphid count data that met the requirements of normal distribution and equal variances. Tukey's HSD test was used to determine the significance of differences in aphid numbers between treatments within each day. Significant differences ($P < 0.05$) were found between aphid counts in the control and deltamethrin treated plots on all occasions after spray application indicating that all three deltamethrin dose-rates provided effective aphid control (Fig. 5). Over the 12 day post-spray assessment period few significant differences were evident between aphid counts in the plots sprayed with deltamethrin at 6.25 and 3.13 g a.i./ha indicating that aphid control was similar at these dose-rates. Aphid numbers in the plots sprayed at 1.56 g a.i./ha were significantly higher than in the other sprayed plots on several days, however (Fig. 5).

Table 1. Regression parameters for the function $y = mx/(b+x)$ fitted to *C. septempunctata* mortality data from continuous exposure to deltamethrin residues on flag leaves and soil.

Exposure method	Deltamethrin application rate (g a.i./ha)	Value of m (± S.D.)	Value of b (± S.D.)
Flag leaf bioassays	6.25	109.1 (± 0.32)	0.345 (± 0.066)
	3.13	104.6 (± 1.29)	1.099 (± 0.061)
	1.56	43.9 (± 0.45)	1.396 (± 0.014)
Soil transfer bioassays	6.25	90.5 (± 0.51)	0.198 (± 0.018)
	3.13	70.9 (± 0.50)	0.260 (± 0.024)
	1.56	30.0 (± 0.47)	0.328 (± 0.006)

Estimation of optimum dose-rates. In order to estimate mortality levels for *C. septempunctata* after given periods of exposure, a non-linear regression was fitted to the continuous exposure mortality data. A hyperbolic function of form $y = mx/(b + x)$ was found to provide the best fit to these data. The regression parameters from each bioassay are given in Table 1.

Mortality values were calculated from the regression formula for 1, 5 and 10 days of continuous exposure of *C. septempunctata* in the flag leaf and soil transfer bioassays. The predicted percentage mortality values were plotted against the deltamethrin dose-rate that had been applied to enable a range of possible effects to be defined at each dose-rate (Fig. 6). We considered that the bioassays indicated maximum possible effects because they enforced continuous exposure to deltamethrin residues for the duration of the bioassays. The zones in Fig. 6 therefore should be viewed as indicating the range of effects that may occur at or between given dose-rates, rather than being an exact prediction of toxicity. The predicted mortality ranges suggested that beetles exposed to deltamethrin residues continuously on flag leaves for 10 days after a deltamethrin spray of between 3.13 and 6.25 g a.i./ha may suffer

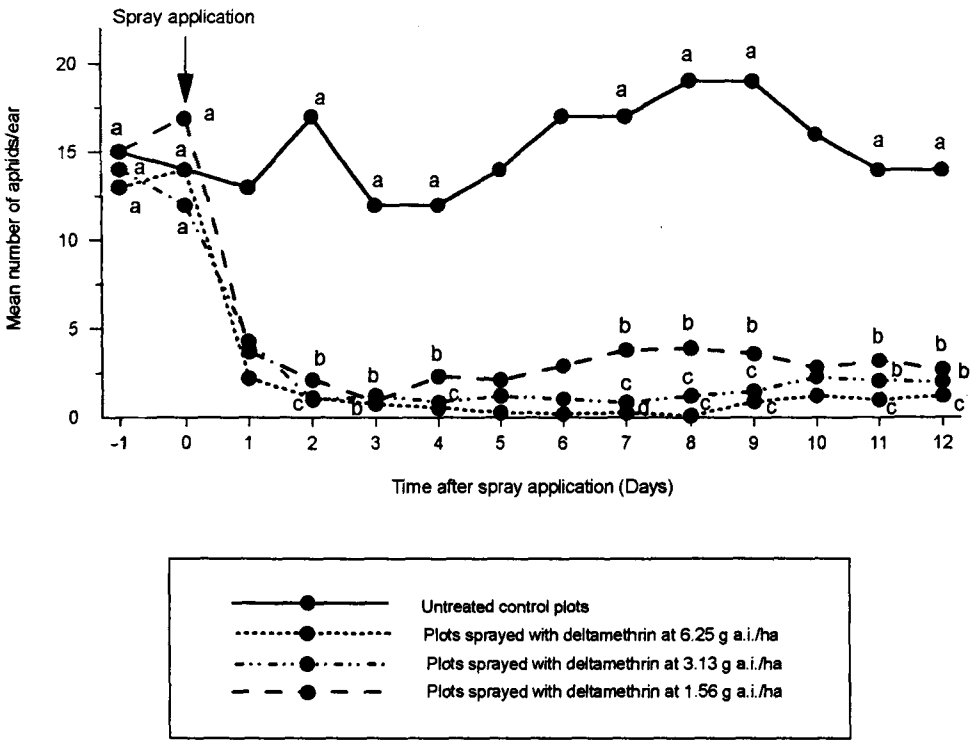


Fig. 5. Mean aphid numbers on whear ears in the control and deltamethrin sprayed plots. Different letters indicate significant differences in mean aphid numbers between different treatments according to Tukeys' HSD test.

between 94 and 100% mortality. Deltamethrin spray applications of between 1.56 and 3.13 g a.i./ha were predicted to cause between 39 and 94% mortality whereas doses lower than 1.56 g a.i./ha were predicted to cause less than 39% mortality (Fig. 6a).

The predicted zones of mortality from the soil transfer bioassays indicated that beetles would suffer lower effects from deltamethrin if they moved from the foliage to the ground. The mortality zones predicted that between 69 and 89% mortality would occur for beetles exposed to deltamethrin residues sprayed at rates between 6.25 and 3.13 g a.i./ha, between 29 and 69% mortality between 3.13 and 1.56 g a.i./ha and less than 29% mortality at rates lower than 1.56 g a.i./ha (Fig. 6b).

In the field *C. septempunctata* adults will not only be exposed to spray residues in a cereal crop but are also likely to suffer mortality from direct exposure to deltamethrin during a spray application. Therefore, the predicted mortality levels from direct and residual exposure were combined for each respective dose-rate. By doing so we assume that the toxic effects of doses received by different routes of exposure were additive. Combined mortality estimates for beetles exposed to flag leaf residues ranged from 42 to 100% for doses between 3.13 and 1.56 g a.i./ha, whereas mortality estimates were less than 42% for dose-rates below 1.56 g a.i./ha (Fig. 7a). The estimated mortality levels for beetles exposed to residues on flag leaves and transferred to the soil varied from 77 to 100% for dose-rates between 6.25 and 3.13 g a.i./ha, from 32 to 77% for dose-rates between 3.13 and 1.56 g a.i./ha and less than 32% mortality for dose-rates lower than 1.56 g a.i./ha (Fig. 7b).

Discussion

C. septempunctata *crop distribution.* Coccinellid beetle activity and distribution in cereal crops is known to be highly influenced by climatic conditions, especially for thermophilic species such as *C. septempunctata*, as well as the distribution of their aphid prey (Honek, 1985; Ferran *et al.*, 1989). Beetle distribution patterns remained reasonably consistent in the field cage over the assessment period. This may be because the mean daily temperatures and light conditions were similar over this period and aphid numbers remained high.

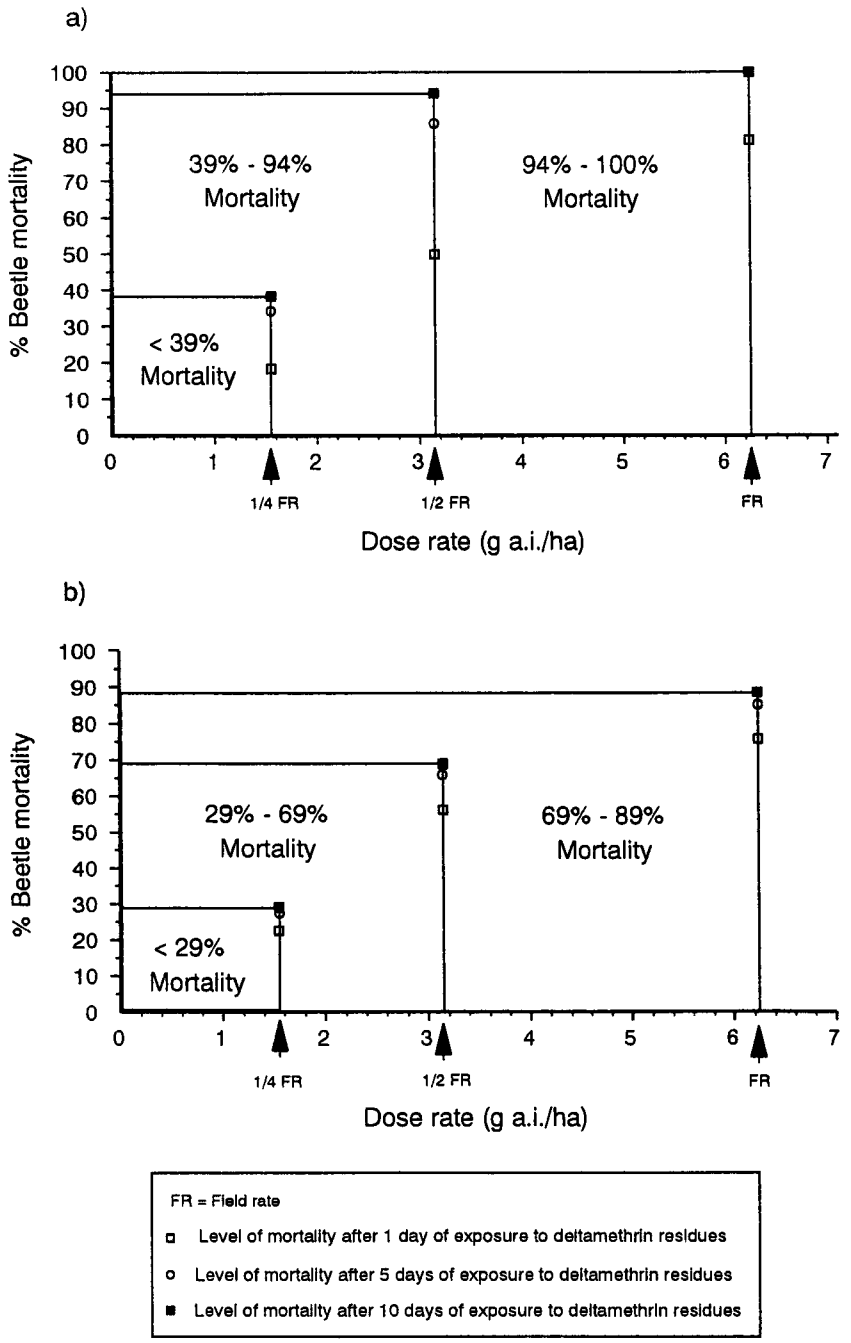


Fig. 6. Dose-response predictions for adult *C. septempunctata* a) exposed continuously to deltamethrin residues on flag leaves or b) exposed to deltamethrin residues on flag leaves for 24 h before being transferred to treated soil.

In the crop, significant changes in beetle distribution patterns were evident within days. With, for example, higher numbers of beetles on wheat ears in the middle compared with the beginning and end of the day. These differences in crop distribution are likely to have been caused by subtle changes in thermoregulatory behaviour of the beetles mediated by environmental factors, such as changes in microclimate and/or light intensity (Honek, 1983, 1985).

On all assessment occasions a high proportion (70 to 85%) of beetles was present on flag leaves and wheat ears. This may make them vulnerable to direct contact

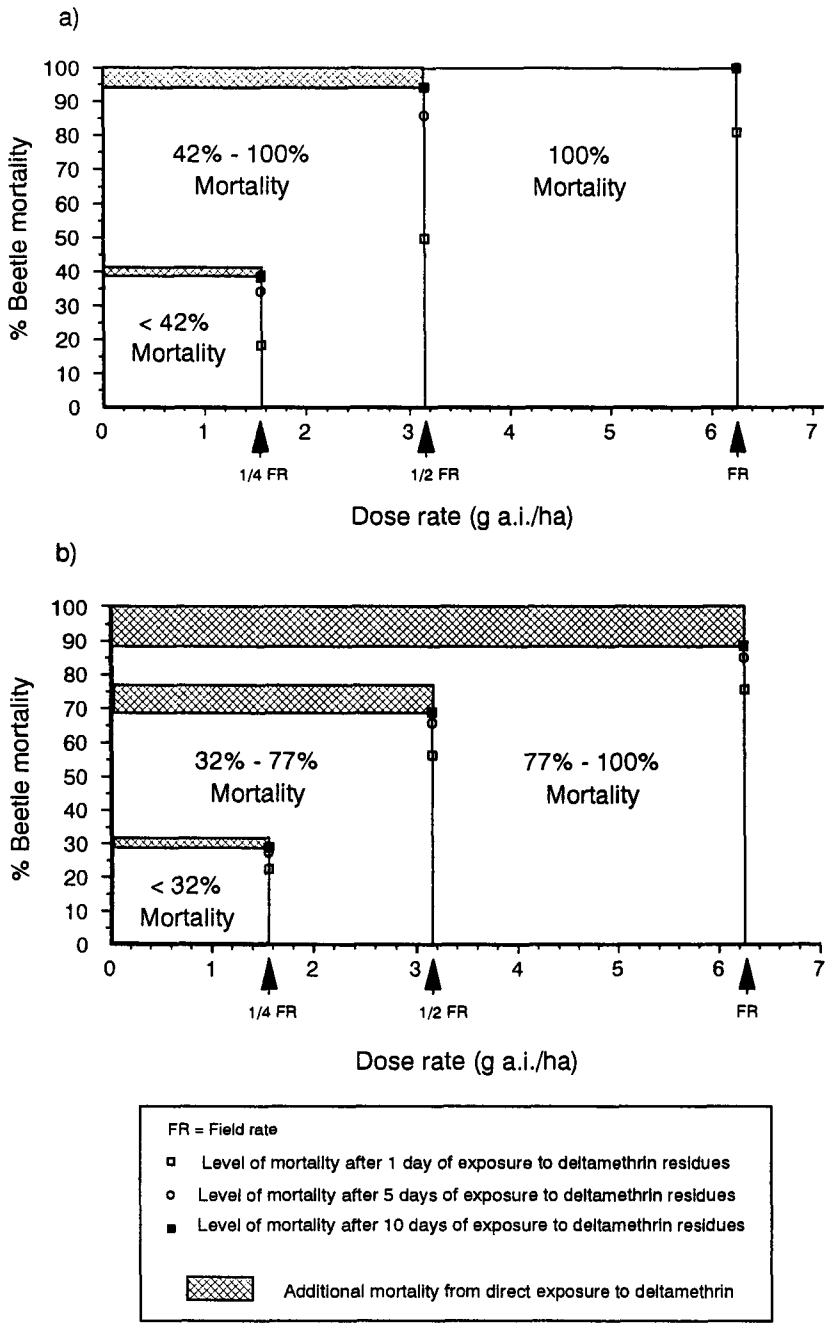


Fig. 7. Dose-response predictions for adult *C. septempunctata* a) exposed directly to deltamethrin spray and continuously to deltamethrin residues on flag leaves or b) exposed directly to deltamethrin spray and to deltamethrin residues on flag leaves for 24 h before being transferred to treated soil.

with pesticide drops during spray application. Coccinellid beetles are often found at the apex of plants because they are positively phototactic and negatively geotactic (Honek, 1973). They may have also occurred at the apex because aphids were present on the ears and flag leaves and therefore contact with prey and honeydew may have provided an arrestant stimulus for the coccinellid predators on these strata (Carter & Dixon, 1984). The beetle distributions found in the cage agree with those observed by Ferran *et al.* (1991) in an open

wheat crop in June, who found that adults and larvae of *C. septempunctata* spent a significant proportion of time, 68 and 65% respectively, on the flag leaf, first leaf and ear in close association with their aphid prey.

Direct exposure studies. The volumetric spray deposition data showed a pattern of spray stratification through the cereal crop canopy. Beetles present on the ear and adaxial flag leaf surface received the highest volumes of spray and those on the abaxial leaf surfaces received the lowest volumes of spray, probably because the foliage offered shelter from the spray drops. This was consistent with spray deposition patterns found on adult *C. septempunctata* in a cereal crop canopy at a range of crop growth stages by Çilgi & Jepson (1992). The predicted overall impact of a deltamethrin spray on adult *C. septempunctata* in a wheat crop (GS 70 to 73), based on the mean beetle crop distribution observed in the field cage study, suggested that relatively low levels of mortality (e.g. 19 ± 2% at the highest dose-rate tested (6.25 g a.i./ha)) would occur as a result of direct exposure.

Residual exposure bioassays. C. septempunctata suffered high levels of mortality in both the continuous flag leaf exposure bioassays and the soil transfer exposure bioassays at all three test dose-rates. Differences were evident between the toxic risk posed by deltamethrin residues on the flag leaf compared to the soil. Mortality levels increased very little over the exposure period for *C. septempunctata* transferred to the soil, probably because of rapid adsorption and loss of bioavailability of deltamethrin on the soil (Mullié & Everts, 1991; Unal & Jepson, 1991; Jagers op Akkerhuis & Hamers, 1992). Differences in the availability and toxicity of deltamethrin to predators inhabiting soil and foliage in cereals have been highlighted by Wiles & Jepson (1994a) who estimated that the bioavailable half-life of deltamethrin residues may be approximately two to three times greater on flag leaves than on the soil. The crop distribution of unconfined adult *C. septempunctata* is known to change after the beetles have picked up sublethal doses of deltamethrin (Wiles & Jepson, 1994b), with more beetles moving to the lower parts of the crop canopy and the ground. This may reduce the exposure of natural populations of beetles to spray deposits, however, deltamethrin remains toxic to predators on foliage for at least six days after application (Unal & Jepson, 1991; Wiles & Jepson, 1992b) and beetles will tend to return to the upper parts of the crop canopy to find food during this time.

Aphicidal efficacy of deltamethrin. Dose-rates of 6.25, 3.13 and 1.56 g a.i./ha caused reductions in mean aphid numbers by 95, 90 and 95% respectively from their pre-spray levels during the three days after spray application. These results agree with Turner (1994) who found similar reductions in aphid numbers in field plots of wheat sprayed with deltamethrin at 6.25, 2.08 and 1.25 g a.i. ha in 200 l water. The mean aphid numbers in the plots sprayed at 6.25 g a.i./ha remained lower than those in the other treatments during the post-spray period. The mean aphid numbers on the ears in the plots treated with 1.56 g a.i. ha began to increase four days after the spray application which mirrored an increase in the mean aphid numbers on the ears in the control plots over the same period. This suggests that the residual activity of deltamethrin applied at 1.56 g a.i./ha was of relatively short duration compared to the higher dose treatments.

An economic threshold for cereal aphids on wheat ears in the UK is 5 grain aphids/ear (George & Gair, 1979). The mean numbers of aphids in the plots treated with a quarter of the recommended field rate of deltamethrin (1.56 g a.i./ha) reached approximately 4 aphids/ear eight days after the spray application. This may indicate that a further aphid breakout was occurring. Such an outbreak in a cereal crop at this growth stage would be unlikely to result in significant economic damage (e.g. Watt *et al.*, 1984). However, if the reduced dose-rate applied enabled the preservation of a high proportion of predators in the crop, these may, in theory, remain in the crop and suppress the growth of the pest population. In addition to preserving natural enemies, dosage reduction may be economically attractive to farmers by significantly reducing variable costs. For example, Mann *et al.* (1991) applied full and reduced dose-rates of the carbamate insecticide, pirimicarb, and the pyrethroid insecticide, fenvalerate, to winter wheat over several seasons. They found that better economic returns could be achieved by applying reduced dose-rates under some circumstances, depending on factors such as the growth stage at which spraying took place and the size of the aphid populations.

Estimating optimum dose-rates for C. septempunctata. The mortality predictions indicated that *C. septempunctata* exposed to spray residues in a cereal crop in the 10 days after spray application may suffer high levels of mortality from continuous exposure to deltamethrin residues sprayed at dose-rates of between 3.13 and 6.15 g a.i./ha. Dosage reductions of between half and three quarters of the recommended field rate

of deltamethrin may be required to preserve between 23 and 68% of the population depending upon the substrate they are exposed to. The combined direct and residual mortality predictions suggested firstly, that exposure to residues may be a more important route of pesticide uptake for *C. septempunctata* than direct exposure to spray and secondly, that the recommended field rate of deltamethrin in the UK (6.25 g a.i./ha) may need to be reduced by as much as three quarters to preserve approximately 60% of the adult coccinellid population present in the crop at the time of spraying and the following 10 days.

If these predictions are to be of value for pest management purposes the predictions require validation in the field with natural predator populations to ascertain a) if predators are preserved by these reduced dose-rates, b) if the surviving predators remain in the sprayed crop after spraying and c) if the predators are capable of suppressing any residual populations of aphids that remain in the crop after the spray application. The predictions presented here also only consider the impact of sprays on adult life-stages. Little information is available on the toxicity of deltamethrin to egg and pupal stages of coccinellids. It is likely that eggs will be offered protection from spray as they are often laid on the underside of foliage, on weeds under the cereal crop canopy or even on the ground (Ferran *et al.*, 1989). The pupae, which are often located towards the top of the crop canopy, may be more exposed to direct contact with spray, however, the thick hardened cuticle may offer protection against chemical penetration. The impact of deltamethrin sprays on coccinellid larvae, however, is likely to be high given that they are more susceptible to deltamethrin than adults (Wiles & Jepson, 1992a, 1994a) and have a similar distribution in the cereal crop (Ferran *et al.*, 1991).

In this study the timing of spray application (GS 70 to 73) represents a fairly late spray in UK cereals (Oakley & Walters, 1994). The usual spray window for controlling summer outbreaks of cereal aphids in wheat in the UK is between GS 61 and 73, spraying only being necessary when pest densities reach $\geq$ 5 *S. avenae*/ear (equating approximately to 66% of ears infested) or $\geq$ 30 *M. dirhodum*/flag leaf and increasing (Anonymous, 1988). However, aphicide sprays in cereals may take place as early as GS 41 to 45 in a tank mix with fungicides (Carter *et al.*, 1989; Oakley & Walters, 1994). The risk of direct contact of *C. septempunctata* by spray deposits may differ between early and late season. For example, Ferran *et al.* (1991) found that early in the season (April and May) adults and larvae spend a large proportion of time on the ground (64 and 49% respectively). Beetles present on the ground may be more sheltered from spray drops when the crop is at an earlier growth stage because the crop canopy may be more dense (Çilgi & Jepson, 1992; Jepson, 1993). However, if beetles are carrying out thermoregulatory 'basking' (Honek, 1985) or mating in open tractor wheelings, they may be at a greater risk of exposure to spray drops.

Overall, this paper outlines a general method for estimating optimum dose-rates thay may preserve key predators in a crop after spraying. The methodology may be suitable for use in many different crops with a range of appropriate natural enemies. However, when interpreting the predicted impacts of given dose-rates it is necessary to consider the main assumptions that they are based upon. Firstly, predictions of direct contact mortality are based upon laboratory intrinsic susceptibility data. Many factors, such as temperature and humidity, will influence susceptibility and therefore test conditions in the laboratory should approximate to realistic field conditions. Secondly, the use of *in situ* bioassays enforces the exposure of insects of spray residues, reflecting a worst-case effect. For example, in unconfined situations behavioural changes, caused by exposure to sublethal doses, may modify the exposure of predators to treated surfaces, e.g. by repellency or changes in crop distribution. Thirdly, toxic effects of doses received from different routes of exposure are additive. Experimental evidence (e.g. Mullié & Everts, 1991) and toxicological theory suggest that this is true, however, it may not be true of all situations; and fourthly, the predictions only take account of two routes of exposure, exposure to spray drops and contact with spray residues. Although these are likely to be the main routes of exposure for many predators, other routes of exposure, such as consumption of contaminated prey may also be important for certain species.

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