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Hazard/Risk Assessment

CEREAL APHID AND PARASITOID SURVIVAL IN A LOGARITHMICALLY DILUTED DELTAMETHRIN SPRAY TRANSECT IN WINTER WHEAT: FIELD-BASED RISK ASSESSMENT

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Abstract—Dose rates of the pyrethroid insecticide deltamethrin were optimized for aphid control and the conservation of beneficial parasitoids in winter wheat. A logarithmic dose sprayer was used to apply concentrations ranging from twice the recommended field rate to a concentration representing one-fiftieth of the field rate. Volumetric analysis of colored dye deposits quantified the partitioning of pesticide through the crop canopy and was used to calculate direct exposure rates of aphid colonies and residue concentration on different plant structures contacted by foraging parasitoids. Aphid parasitoids, from the genus *Aphidius,* were found to be more at risk from exposure to insecticide residues than were their aphid hosts under the given bioassay conditions. However, the toxicity of deltamethrin residues on flag leaves was found to dissipate over a 5-d period after application. Deltamethrin provided significant aphid control at dose rates greater than 1 g a.i./ha (or at approximately one-sixth of the recommended field rate). At low concentrations of deltamethrin, aphids survived in the lower crop strata within low toxicity refuges. The implications of these refugia and the spatial redistribution of prey and host populations following spray application for the success of biological control agents are discussed.

Keywords—Cereal aphids *Aphidius rhopalosiphi* Deltamethrin

INTRODUCTION

Several authors have drawn attention to the possibility of increasing the selectivity of pesticides in a range of cropping systems by reducing dose rates [1–5]. In cereal systems, reduced insecticide dose rates offer a more economic means of aphid control in addition to having potential environmental benefits [6–8]. Reducing the concentration of aphicide may permit a greater survival rate of natural enemies and also maintain a residual population of aphids as food for the conserved natural enemy fauna. Natural enemies may then remain in the crop and prevent any further pest resurgence [6].

Estimates of the efficiency of current insecticide application methods suggest that only a small percentage of the applied active ingredient reaches the target pest [4]. This is partly because spray application technology is not designed to target the spray effectively and partly because the crop canopy filters the spray, leaving some areas uncontaminated by nonsystemic products. In the case of cereals, the attenuation of spray through the canopy provides for relatively uncontaminated areas under leaves and near the ground [9]. By using reduced dose-rate applications of, for example, the pyrethroid insecticide deltamethrin, which is a contact insecticide with no systemic action, relatively static aphid colonies may survive in these refuges. This phenomenon has been reported by Poehling [10,11], who recorded an elimination of *Sitobion avenae* (F.) from wheat ears when using reduced dose rates of fenvalerate, but persistence of *Metopolophium dirhodum* (Wlk.) under flag leaves, in areas not covered by insecticide residues.

Although considerable information is available about the fine-scale distribution patterns of certain aphid populations on plants [12–15], very little is known about the spatial distribution of aphid colonies on insecticide-treated plants. Information of this kind is important for the understanding of where residual populations may remain after application of reduced dosages, and how soon depleted populations may recover. Also, with the reported systematic search of plants by parasitoids potentially altered by the presence of insecticide residues [16,17], parasitism risk for aphids may fall if their distribution patterns change.

In these experiments we assessed the efficiency of deltamethrin as a summer-applied cereal aphicide at a range of different concentrations. Records of the spatial distribution of aphids on winter wheat plants and the resulting survival/redistribution of populations over the following days after insecticide application were made. The stratification of spray deposition through the crop canopy was measured to determine the degree of direct exposure of aphid colonies to spray and to measure the levels of residues that may be subsequently contacted by foraging parasitoids and predators. The residual toxicities of deltamethrin on foliage were assessed by exposing aphid parasitoids, *Aphidius* spp., to flag leaves on subsequent days after treatment.

MATERIALS AND METHODS

Experimental design and spray application

Experiments during June and July 1994 were conducted in a winter wheat crop, cv. Brigadier, growth stage 73 [18], with a mean density of 470 tillers/m², on the Manydown Estate, near Basingstoke, UK. Four 20 × 1-m plots were marked out with 8-m-wide unsprayed buffer zones between them to avoid cross-contamination when spraying. Two treatments were applied: a water control, and the pyrethroid insecticide, delta-

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methrin (Decis, Hoechst, UK, 2.5% emulsifiable concentration). Daily rainfall and hourly temperature records were made for the duration of the study on open ground in an adjacent field using a Delta-T electronic data logger (Delta-T Devices, Cambridge, UK).

Sprays were applied with a Chesterford Miniature Logarithmic Sprayer (MDM Engineering, Portsmouth, UK) operating at 2 bar, and giving at swath width of 1 m. Walking speed was adjusted to give a precise volume application rate of 200 L/ha following individual calibration of the nozzles. The logarithmic dilution principle of the sprayer involves the chemical concentrate being forced out of a pressurized vessel at a constant rate and being replaced at an equivalent rate by a diluent (water) that is intimately mixed with it. This causes the concentration of the chemical to decrease exponentially. During application, if the operators walking speed is constant, the chemical dosage rate is proportional to both time and distance.

Calibration of the sprayer was achieved by applying a red dye solution (Kenacid Scarlet, 1%, w/v) to 9-cm-diameter filter discs placed at 1-m intervals along a flat 20-m transect. The deposition of dye on each filter paper was measured colorimetrically (see method below). The dose of concentrate halved every 3 m along the transect with a constant walking speed of 1 m/s.

Solutions of deltamethrin made up initially at double the recommended field concentration (i.e., equivalent to 2 × 6.25 g a.i./ha in 200 L of water) were applied along three 20-m transects. Walking commenced, and was maintained at a constant speed of 1 m/s, immediately when the spray emerged from the nozzles. The sprayer was set up to logarithmically dilute the initial concentrate to a final concentration of one-one hundredth of the original over the 20-m transect. The dose rates of deltamethrin applied therefore ranged from double to one-fiftieth of field concentration along the transect (i.e., 12.50–0.125 g a.i./ha). The fourth transect was sprayed with water as a control.

Spray deposition measurements

Direct measurements of the volume of spray solution landing on different parts of the plant at the time of spray application were made using the red dye solution (1%, w/v). The solution was placed in both the concentrate and diluent bottles to maintain constant dye strength and was applied to a separate 10-m^2 (10 ×1-m) area of wheat. Twenty-five strips of white paper (3.25 × 1 cm) were positioned at five different levels throughout the crop canopy. The papers were pinned vertically along the length of wheat ears, and horizontally along the central adaxial and abaxial sections of flag leaves and first leaves. Separate plants were selected randomly for each paper/position combination. After the spray solution had dried (approximately 30 min) the pieces of paper were individually removed with fine forceps and transferred to dry, labelled tubes and stored in dark conditions until analysis. A sample of the spray formulation in the tank mix was taken immediately after spraying and stored in identical conditions to the sample tubes. For the analysis, individual papers were placed in 6 ml of distilled water, left to soak for 20 min, then shaken for 1 min to ensure all the dye was washed off into the solution. The volume of dye in solution was determined by analysis in a colorimeter. To construct a calibration curve, enabling the amount of dye contained in the samples to be expressed as microliters of the original spray formulation, a range of volumes of the original tank mix were accurately micropipetted into 6 ml of distilled water and analyzed in the colorimeter. The volume of spray formulation in microliters was converted to estimated volume per cm^2 of foliage by division with the surface area of the paper (3.25 cm^2).

Aphid assessments

Twenty-four hours prior to spray application, groups of five randomly selected tillers at 1-m intervals along a 20-m insecticide-treatment transect were carefully cut at ground level. The number and location of aphids (*S. avenae* and *M. dirhodum*) on the plants were recorded. In addition, at each 1-m interval in another transect replicate, five wheat tillers supporting aphid colonies on ears and leaves were marked using labelled jewellers tags. Twenty tillers were marked in the control transect. Again, the number and location of aphids were recorded. Further aphid assessments on randomly selected plants and marked tillers were conducted at 1, 3, and 5 d after spraying.

Parasitoid bioassay

To obtain sufficient numbers of aphid primary parasitoids for the bioassays, D-vac suction sampling [19] was carried out in an adjacent crop. Live female parasitoids of the genus *Aphidius* (identified by their characteristic wing venation, see [20]) were collected and kept individually for 24 h prior to the experiments in 2 × 1.75-cm ventilated clip cages. They were fed with drops of 50% honey solution smeared over the mesh covering. After spray residues of water and deltamethrin had dried (approximately 1 h), 10 clip cages, each containing a single live *Aphidius* female, were positioned on randomly selected flag leaves at 1-m intervals along the third 20-m insecticide-sprayed transect. Ten individual parasitoids were clip-caged onto flag leaves in the control transect. Parasitoids were in contact with the adaxial leaf surface and fed with a 50% honey solution. The mean leaf area enclosed by these chambers was 3.1 cm^2. The weight of the clip cages drew the leaves down into the dense crop canopy, thus minimizing the likelihood of parasitoid mortality through desiccation. Parasitoid condition was assessed after 24 h and recorded as either dead/affected or live. The above procedure of exposing new parasitoids to foliage for 24 h was repeated on days 3 (72–96 h) and 5 (120–144 h) after spraying.

Statistical analyses

The volumetric spray deposition data for each position in the crop were tested for homogeneity of variance using the Levene test [21]. Tukey's honestly significant difference multiple comparisons were calculated following one-way analysis of variance to identify means that differed significantly. A mean number of aphids on the five tagged plants at each location along the deltamethrin-treated transect was calculated. $\mathrm{Log}_{10}(n + 1)$ transformation was applied to all aphid data before the posttreatment transformed value for each group of tagged plants was subtracted from the pretreatment count of the same plants, to provide a log-difference value [22]. Probit analysis was performed on aphid mortality data, corrected for control effects using Abbott's formula [23], to obtain dose–response statistics [24]. This analysis was only conducted on data from the first posttreatment assessment as later ones would include reproduction, leading to changes not solely attributable to survival rate. Log-difference values were calculated separately for aphid numbers on individual plant structures (i.e., ear, flag leaf, and first leaf) to identify whether aphid survival/

Table 1. Deposition rate of spray tracer solution (μl/cm^2) on winter wheat. Data from Çilgi and Jepson [9] are given for comparison purposes (cv. Rendevous; growth stage 73; application rate 220 L/ha)

Canopy position	Volume of tracer (μl/cm^2 ± SE) (data from this study)[a]	Volume of tracer (μl/cm^2 ± SE) (data from Çilgi and Jepson [9])
Ear	0.27 (±0.019) a	0.23 (±0.01)
Flag leaf (adaxial surface)	0.43 (±0.054) b	0.305 (±0.02)
Flag leaf (abaxial surface)	0.03 (±0.0001) c	(adaxial and abaxial surfaces combined)
First leaf (adaxial surface)	0.19 (±0.024) a	0.298 (±0.02)
First leaf (abaxial surface)	0.04 (±0.0001) c	(adaxial and abaxial surfaces combined)

[a] Analysis of variance with additional Tukey's honestly significant difference test ($F= 8.02$; *d.f.* = 3, 7; $p < 0.001$). Different letters in the column indicate significant statistical separation ($p < 0.05$).

mortality varied significantly over the plant. Dose–response mortality trends were calculated for parasitoids on the days following insecticide treatment and probit analysis was performed on parasitoid mortality data obtained from the first posttreatment biossay.

RESULTS

Daily temperatures ranged from 8.4 to 30.2°C over the 7d of the experiment and no rainfall was measured.

Spray deposition

Statistical analysis of deposition rates of spray formulation on different plant surfaces revealed significant heterogeneity between positions in the canopy ($p < 0.001$) (Table 1). Deposition rates were significantly higher ($p < 0.05$) on the adaxial surface of flag leaves than any other plant surface. The ear received the next highest deposition rate, although not significantly different from the adaxial surface of the first leaves. Very low levels of spray formulation were found on abaxial leaf surfaces.

Aphid distribution over control plants

The mean number of aphids on tagged control plants over the four sample dates revealed similar numbers on ears and flag leaves, with fewer aphids colonizing the first leaves (Table 2). The abaxial leaf surfaces were the preferred location for aphid colonization. Numerical changes occurred in aphid colonies on each plant structure on each posttreatment sample date (Table 3). Numbers on ears and flag leaves decreased over the 5d after treatment, whereas numbers on the first leaves increased. Despite these redistributions of aphids around the plant, the overall changes in aphid numbers on plants as a whole showed little difference from the pretreatment numbers. A total of 123 aphid mummies were recorded over wheat plants in the control plot. The largest proportion of mummies were located on the ear, with awns and abaxial surfaces of flag leaves also harboring high numbers (Table 4).

Aphid numbers on untagged deltamethrin-treated plants

Pretreatment aphid counts on randomly selected wheat plants showed a mean between 4 and 11 aphids per plant along the spray transect (Fig. 1). On day 1 after treatment, aphid numbers began to fall below the pretreatment values at dose rates greater than 1 g a.i./ha (approximately one-sixth of the recommended field concentration). At insecticide concentrations below this there were no visually detectable changes in aphid numbers over whole plants. Complete elimination occurred at dose rates equivalent to one-half the recommended field concentration (3.13 g a.i./ha) and above. Aphid numbers recorded on days 3 and 5 after treatment showed similar trends.

Aphid numbers on tagged deltamethrin-treated plants

The log-difference values, indicating changes in aphid numbers over whole tagged plants, indicated that the main population decreases occurred again at deltamethrin concentrations greater than 1 g a.i. of deltamethrin (Fig. 2). Very little change in numbers was observed between the sample dates. Probit regression analysis on estimated mortality rates gave a median lethal dose (LD50) of 1.33 g a.i. (≡1/5 of the recommended field concentration of deltamethrin) after 24 h posttreatment. The lethal dose, 10% (LD10) was calculated at 0.31 g a.i. (≡1/20 field concentration) and the lethal dose, 90% (LD90) at 5.62 g a.i. (≡1/1.1 field concentration). Aphid data for tagged plants, expressed as log-difference values for separate plant structures, indicated different degrees of numerical change in aphid populations over the plant (Fig. 3). On day 1 after treatment, aphids survived lower concentrations of deltamethrin to an equal extent on all plant structures (Fig. 3A). However, at the higher concentrations, causing $>60\%$ aphid mortality, the greatest rates of aphid decline occurred on ears and flag leaves, with lower mortality (i.e., greater survival)

Table 2. Mean number of aphids, over the four sample periods, on different plant positions on the tagged control wheat plants

Crop position	Mean number per plant (± SE)		Percentage of total
Ear		11.75 (±0.68)	38.5
Flag leaf			
Adaxial	2.13 (±0.16)	12.48 (±1.05)	
Abaxial	10.35 (±1.03)	(combined)	40.9
First leaf			
Adaxial	0.98 (±0.17)	6.28 (±0.75)	
Abaxial	5.30 (±0.65)	(combined)	20.6

Table 3. Calculated log-difference values for changes in aphid numbers on different plant structures on the tagged control wheat plants on days 1, 3, and 5 after treatment with water. Positive values indicate a decrease in aphid numbers compared to pretreatment numbers, a negative value indicates a numerical increase

Plant structure	Days after treatment 1	3	5
Ear	0.006	0.015	0.103
Flag leaf	0.076	0.182	0.127
First leaf	−0.040	−0.077	−0.089
Whole plant	0.019	0.068	0.053

Table 4. Number and location of mummified aphids found on wheat plants during the experimental period

Canopy position	Number of mummies	Percentage of total
Awn	15	12
Ear	53	43
Flag leaf (adaxial surface)	11	9
Flag leaf (abaxial surface)	22	18
First leaf (adaxial surface)	11	9
First leaf (abaxial surface)	11	9

occurring on the first leaves. At 3 and 5 d after treatment, the levels of aphid reduction remained high on ears and flag leaves on plants receiving the highest concentrations of deltamethrin (Fig. 3B and C). On plants sprayed with the lowest concentrations of insecticide, larger negative log-difference values, indicating numerical increases of aphids, relative to pretreatment densities, occurred at ear and first leaf positions.

Parasitoid survival

Percentage mortality of parasitoids in the control plot was very low (day 0, 0%; day 3, 10%; and day 5, 0%). Data from the insecticide treatments were corrected for control mortality using Abbott's correction. Percentage mortality trends of parasitoids exposed to deltamethrin residues on flag leaves, for the first 24 h after treatment (day 0), showed greater mortality at the highest insecticide concentrations (Fig. 4A). Subsequent exposure on days 3 and 5 revealed shallower trends in mortality, indicating that the highest concentrations of deltamethrin caused lower parasitoid mortality with increasing time after application (Fig. 4B and C). Probit regression analysis of mortality data from the first bioassay (0–24 h after treatment) estimated that an LD50 dose was 0.76 g a.i. (≡1/8 of the recommended field concentration of deltamethrin) (Fig. 4A). The LD10 was calculated at 0.18 g a.i. (≡1/33 field concentration) and the LD90 at 3.45 g a.i. (≡1/1.8 field concentration).

A comparison of dose–response statistics (between LD10 and LD90) for aphids and parasitoids indicated that for a given deltamethrin concentration, parasitoids exhibited greater mortality than their hosts, under the given bioassay conditions (Fig. 5). For comparison, LD50 values of 1.33 g a.i. of deltamethrin (≡1/5 field concentration) for aphids and 0.76 g a.i. (≡1/8 field concentration) for parasitoids were estimated.

DISCUSSION

Aphid colonies were unevenly distributed over the different plant structures of winter wheat, with greatest numbers on ears and flag leaves. These are the most preferred feeding sites for *S. avenae* and *M. dirhodum* [25]. Overall, only small changes in distribution were recorded on the control tagged plants over the 6-d experimental period. These changes may have resulted from disturbance by predators or parasitoids, and restlessness, leading to wandering and falling off the plant [26]. The action of plants brushing together and rainfall have also been implicated in dislodging aphids [27]; however, no precipitation was recorded during the experimental period.

The current recommended rate of deltamethrin (6.25 g a.i./ha) in cereals resulted in a very high aphid mortality (approximately 90% of the aphid population). This therefore proves useful for eliminating populations of the virus-spreading *Rhopalosiphum padi* (L.) during autumn spraying. However, during a summer spray campaign, the insecticide concentration may be reduced, allowing the survival of small residual aphid populations in the crop.

High levels of aphid mortality occurred over the whole plant with concentrations of deltamethrin exceeding 1 g a.i./ha in 200 L of water (≡1/6 of the recommended field concentration). These results agree with those of Turner [28] and Wiles and Jepson [29] who found similar reductions in aphid numbers in field plots of wheat sprayed with deltamethrin at reduced dose rates of 1.25 g and 1.56 g a.i./ha in 200 L water, respectively. These results highlight the potential for using reduced dose rates of deltamethrin in cereals, and suggest that future research effort should be concerned with dose reductions as low as one-sixth of the current recommended field concentration.

Little indication was given of any recovery of aphid numbers on either tagged or untagged plants at the highest dose

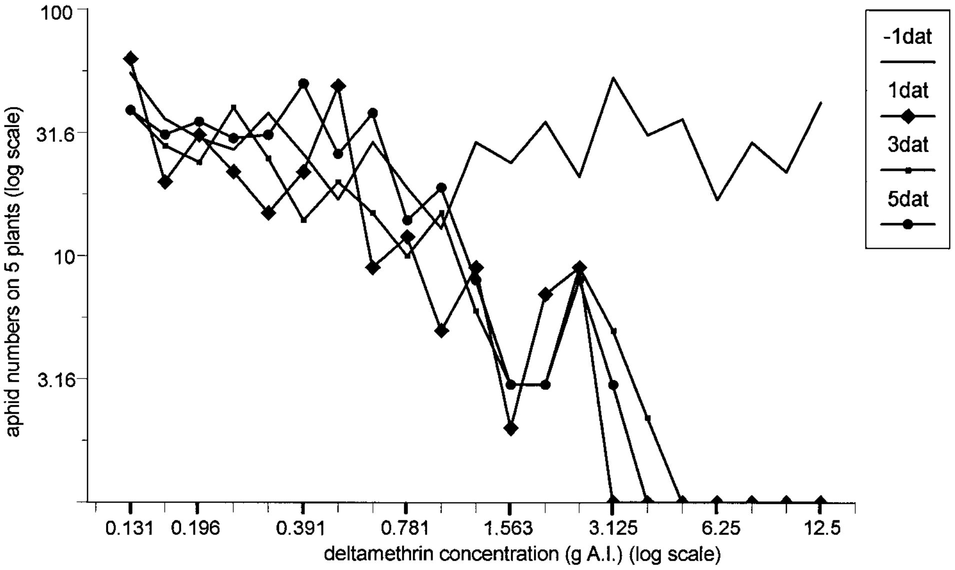

Fig. 1. Number of aphids on untagged wheat plants along the deltamethrin-treated transect, showing pretreatment numbers (−1) and numbers on 1, 3, and 5 d after treatment (dat). Treatment data points are linked by lines to emphasise trends.

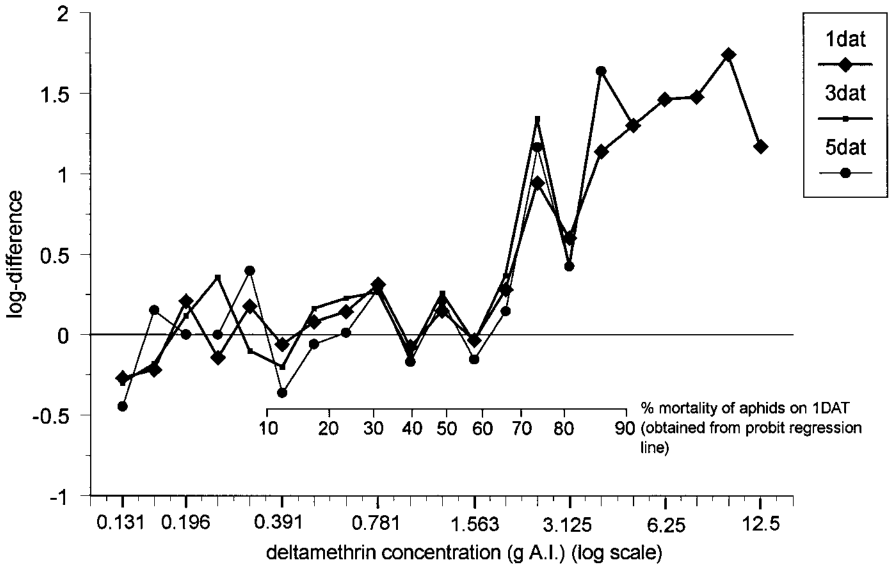

Fig. 2. Changes in aphid numbers (expressed as log-difference values, see text for details) on tagged wheat plants, on 1, 3, and 5 d after treatment (dat). Percentage mortality estimates for aphids on 1 dat are given, based on probit equation ($y = -0.248 + 1.778x$; goodness of fit $\chi^2 = 3.721$, *d.f.* = 13, not significant). Treatment data points are linked by lines to emphasise trends.

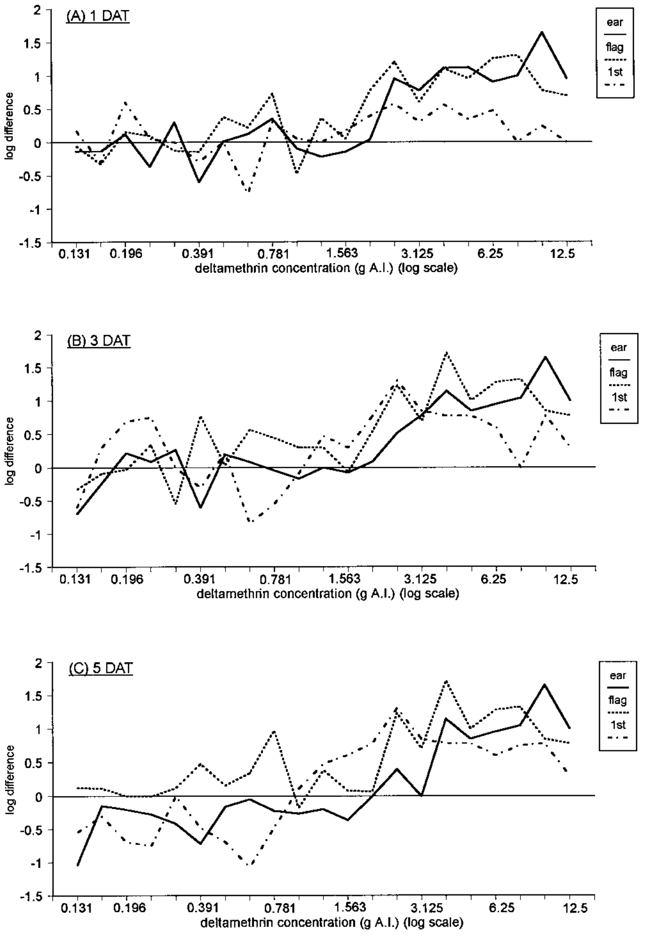

Fig. 3. Changes in aphid numbers (expressed as log-difference values, see text for details) on different plant structures on tagged wheat plants, on (**A**) 1, (**B**) 3, and (**C**) 5 d after treatment (DAT). Treatment data points are linked by lines to emphasise trends.

rates over the experimental period. However, percentage mortality estimates for parasitoids exposed to deltamethrin residues on flag leaves declined over time. This may suggest that the residual activity of deltamethrin was of relatively short duration under the given conditions of high daily temperatures. Further bioassays are needed to consider the residual activity under a wide range of different conditions. The decline in bioavailability of a pesticide on foliage has been shown to be determined by crop type [30], crop growth stage [31], and climatic conditions [32]. The trend for a decay in the toxic effect of deltamethrin residues on flag leaves with time provides a basic guide to the probability of harm to parasitoids invading the treated area at different times following spray application. This will have important consequences for the rate of reinvasion, mediated by diffusion processes, which determines the rate of population recovery [33].

Invertebrate exposure to insecticides is determined by a number of biological factors, including the seasonal phenology of the organism and its temporal and spatial distribution in the treated area. A comparison of the dose–response statistics for aphids and parasitoids indicated that for a given concentration of deltamethrin, the natural enemy will suffer greater mortality under the given conditions. This is undesirable from the point of view of integrated pest management and suggests that physiologic selectivity in favor of the parasitoid through dose reductions is unlikely to be achieved. However, mortality estimates were based upon bioassay results for the parasitoid with an intrinsically high degree of exposure. Compared to aphids, which are relatively nonmobile and mainly exposed to nonsystemic insecticides via direct contact during spray application, parasitoids are highly mobile and may be exposed to insecticides through direct, residual, and dietary routes. The contribution of these different routes of exposure to overall toxicity were not quantified in the present study. However, the parasitoid bioassays can be taken to represent a worst-case scenario, with confinement likely to expose insects in an unrealistic way. Incorporation of more realistic features into laboratory and semifield bioassays (i.e., exposing parasitoids to insecticide residues for different durations of time and of dif-

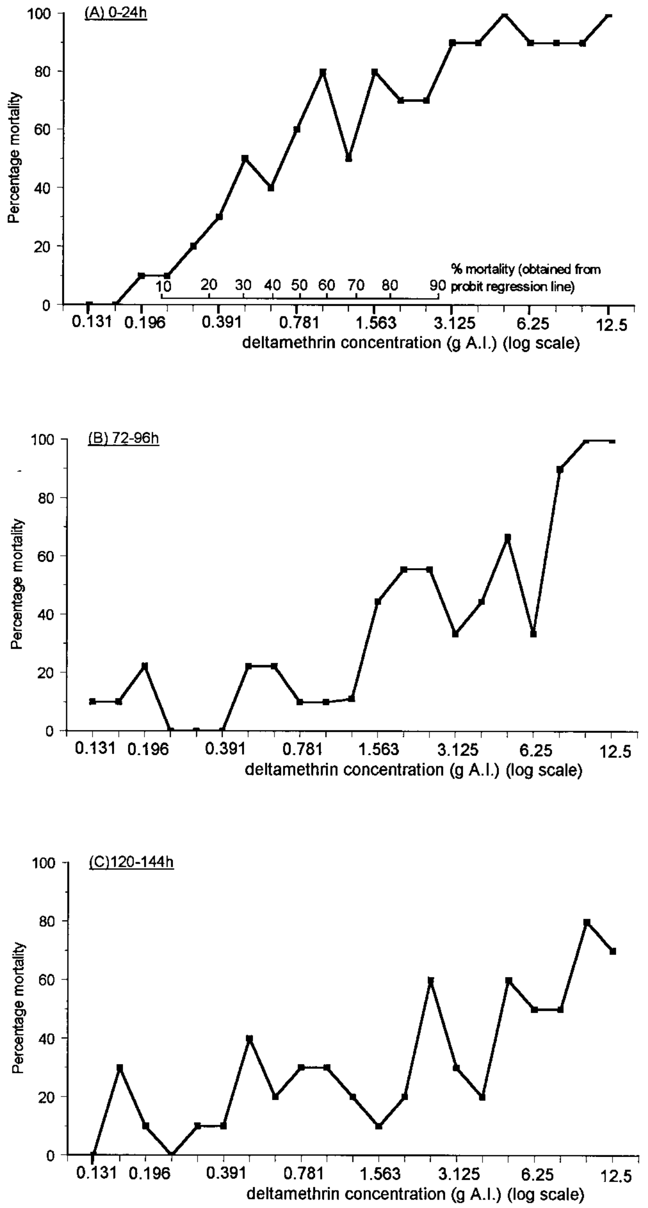

Fig. 4. Percentage mortality of parasitoids, corrected for control changes using Abbott's formula, exposed to deltamethrin residues on flag leaves on (**A**) 0 to 24 h, (**B**) 72 to 96 h, and (**C**) 120 to 144 h after spray application. Percentage mortality estimates are given for parasitoids during the 0- to 24- h bioassay (**A**), based on the probit regression equation ($y = 0.189 + 2.024\,x$; goodness of fit $\chi^2 = 9.028$, $d.f. = 14$, not significant).

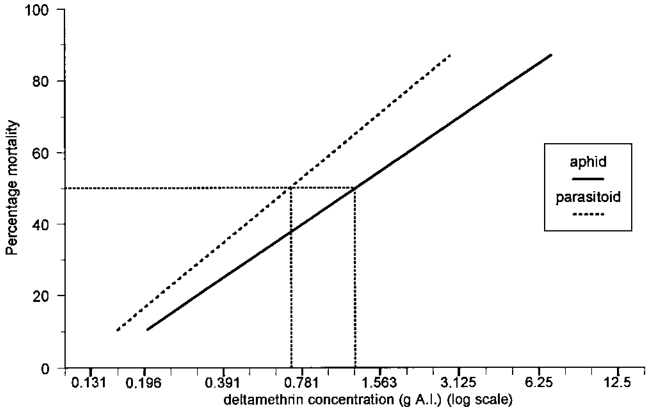

Fig. 5. Comparison of dose–response statistics for aphids and parasitoids obtained from data and probit equations given in Figures 2 and 4A, respectively.

ferent concentrations on the plant) have been proposed in order to increase the realism of risk predictions for parasitoid populations in the field [34].

The spray deposition trend showing an attenuation down through the crop canopy agreed with previous findings [35,36]. The deposition measurements were also in close agreement with those reported by Cilgi and Jepson [9] using a tractor-mounted sprayer in a winter wheat crop at the same growth stage (Table 1). Data of this kind are important for risk predictions because the hazard that an insecticide poses to a particular invertebrate species will be a function of the relative distributions of the target population and the pesticide throughout the crop canopy. Species that frequently inhabit the upper crop canopy (i.e., parasitoids and the majority of aphids on a wheat plant) are likely to be more at risk than species inhabiting the soil surface or lower leaves [37].

Certain regions of the wheat plant (i.e., the first leaves and, particularly, the abaxial leaf surfaces) received significantly less spray than other areas of the plant. With the application of reduced dose rates, these relatively uncontaminated plant parts acted as refuges for surviving aphid populations. The level of spray deposition within individual plant parts has been shown to vary with differences in the shape and curvature of leaves [38]. More detailed studies of aphid location upon individual leaves and spray deposition trends spanning all the phases of crop growth when sprays are applied may help in assessing the extent of aphid survival and their subsequent location by foraging parasitoids after spray application.

A parasitoid's residual exposure to pesticides is determined by the extent of searching activity, which is dependent upon prey density and distribution. Within an insecticide-treated environment, an aphid's food supply (the crop) remains unlimited, whereas, as demonstrated in this study, the parasitoid's food supply (the aphid) is often significantly reduced and/or its distribution changed in space. If the pesticide reduces pests/hosts to a large extent, beneficial predators and parasitoids may starve, emigrate, or have limited reproduction following spraying. This effect could theoretically be minimized by using reduced-dose insecticide applications. In this study, no assessment was made of the degree of foraging success of parasitoids searching for residual aphid populations on plants. The 11- to 15-d time delay between parasitoid oviposition and mummification [39] delays assessments of parasitism. However, aphid parasitoids have been demonstrated to search all parts of the wheat plant [17,40] and mummies are found on all plant structures including abaxial leaf surfaces (Table 4). Therefore, one could assume that these residual aphid colonies would be located by parasitoids, provided that residues of honeydew and insecticide posed minimal interference with a parasitoid's normal foraging pattern [17]. However, this hypothesis needs to be tested.

Overall, this study has demonstrated a general screening methodology for estimating dose rates of aphicides that may provide effective pest control yet leave residual aphid populations for parasitoid and predator populations. However, this study only investigated effects over a period of 5 d after treatment. A larger study incorporating multiple pesticide applications and differing spray intervals would prove more useful in determining the effects in the real world. Comparisons of different classes of insecticides would also prove interesting, because physiologic selectivity may be achieved by using systemic compounds, such as organophosphate insecticides. These would remove the pest refuge phenomenon demonstrated with contact insecticides and might therefore enable further reductions of insecticide active ingredient applied to crops. In addition, residues of the organophosphate insecticide dimethoate on foliage have been shown to dissipate more rapidly than deltamethrin over time [41], therefore posing less long-term risk to foraging parasitoids. Further studies are required to determine pesticide distribution on crops and the influence of environmental factors in altering toxicity over time.

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