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Type ‘A’ and ‘B’ recovery revisited: The role of field-edge habitats for Collembola and macroarthropod community recovery after insecticide treatment

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Collembola recolonisation differs among species; effectiveness of unsprayed crop edges as sources of arthropod recolonisation may depend on adjacent habitat.

Abstract

Previous work has identified two patterns of arthropod recovery after insecticide applications to arable crops: dispersal-mediated recolonisation from untreated areas (Type A) and recolonisation within treated areas assisted by reduced predation (Type B). Connectivity between field-edge habitats was manipulated using barriers to investigate whether a crop edge and adjacent hedgerow influence recolonisation of an insecticide-treated crop by surface-active Collembola and other arthropods. Collembola recovery patterns differed among closely-related taxa. Epigeic collembolan and macroarthropod communities were more diverse and abundant, and rates of artificial prey predation were higher, in sprayed crop areas connected to both hedgerow and unsprayed crop edge than in sprayed areas connected to the unsprayed edge alone. These findings indicate that effectiveness of unsprayed crop edges as sources of field recolonisation may depend on adjoining field margin habitats. An assumption in risk assessment that unsprayed crop edges assist population recovery within treated areas is not supported.

Keywords: Ecological effectiveness; Predation; Principal response curves; Recolonisation; Unsprayed crop edges

1. Introduction

Collembola (springtails) are among the most abundant arthropods in agroecosystems and are preyed upon by a wide range of specialist and generalist predators (Hopkin, 1997). Many generalist predators of Collembola (e.g. Carabidae, Staphylinidae and Linyphiidae) are also natural enemies of crop pests. Collembola could be an important prey resource for sustaining such beneficial predator populations (e.g. Agusti et al., 2003). Surface-active (epigeic) Collembola are highly sensitive to organophosphorus (OP) insecticides, with counts in sprayed areas often reduced locally to zero (Frampton, 2002). Colonisation of cultivated fields by epigeic Collembola can be influenced strongly by an adjacent hedgerow (Alvarez et al., 2000), but no studies have investigated whether hedgerows or unsprayed crop edges contribute to Collembola recolonisation after pesticide applications. The only detailed spatial information on recovery dynamics suggests that predatory arthropods recolonise sprayed areas slowly from

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unsprayed refuges ('Type A' recovery), whereas Collembola and other prey groups recolonise from within sprayed areas ('Type B' recovery). Type B recovery may reflect a temporary reduction of predation pressure within sprayed areas (Duffield and Baker, 1989; Duffield and Aebischer, 1994).

Broad-spectrum insecticides may be prohibited from the edges (outermost 6 m) of arable crops as a statutory practice to protect non-target arthropods (Campbell, 1995). Such pesticide exclusion has been assumed not only to protect populations within crop edges but also to assist recovery of populations in adjacent sprayed areas (Forster and Rothert, 1998). Seven previous studies have investigated the effects of crop-edge pesticide exclusion on arthropods within adjacent sprayed areas (Hald et al., 1988; Hassall et al., 1992; Hawthorne, 1994; Moreby, 1995; de Snoo and de Leeuw, 1996; Holland et al., 2000; Tones et al., 2000). Due to a lack of effects, or lack of replication of the pesticide treatments, these studies do not provide evidence that effects of pesticide exclusion (or selective use) extend beyond crop edges. Other detailed studies of arthropod recolonisation dynamics have been carried out but these did not involve crop edges (Duffield and Baker, 1989; Jepson and Thacker, 1990; Thomas et al., 1990; Thacker and Jepson, 1993; Duffield and Aebischer, 1994; Duffield et al., 1996; Dunger et al., 2002). Overall, mainly due to limited research, there appears to be no convincing evidence that unsprayed edges assist recovery of populations within sprayed areas.

In this work, the connectivity between field-edge habitats was manipulated using barriers to investigate whether an unsprayed crop edge and adjacent hedgerow contribute to recolonisation of an insecticide-treated crop by surface-active Collembola and other arthropods.

2. Materials and methods

2.1. Study site

The study was carried out during 2001 in a 35-ha rectangular field of winter wheat *Triticum aestivum* cv. Maris Widgeon on a commercial farm in Hampshire, southern England (51°7′ N, 1°2′ W). Soil type was a light loam over chalk (Andover Series, pH 7.6) comprising 8.4% organic matter, 8.9% clay, 30% silt, 18.3% fine sand and 10.5% coarse sand. The field was surrounded by hedgerows of uniform structure, had been cropped under cereals in the preceding 10 years and was known to contain a diverse arthropod fauna. Two homogeneous hedgerows were chosen for study (Fig. 1). These were approximately 1.8 m in height and 0.8–1.0 m wide with the woody species dominated by hawthorn *Crataegus monogyna*. Hedgerow bases were dominated by the grasses *Poa trivialis* and *Dactylis glomerata* and contained up to 17 species of annual arable flora and grasses; the composition and structure of the field boundary flora was similar in each of the experimental study areas. Adjacent habitats were a field of herbage seed *Lolium perenne* cv. Ronja adjoining Hedgerow 1 and a mature apple orchard (*Malus domestica*) adjoining Hedgerow 2.

2.2. Study design

An experimental approach using barriers to manipulate connectivity between the hedgerow, crop edge and sprayed field area was used to investigate

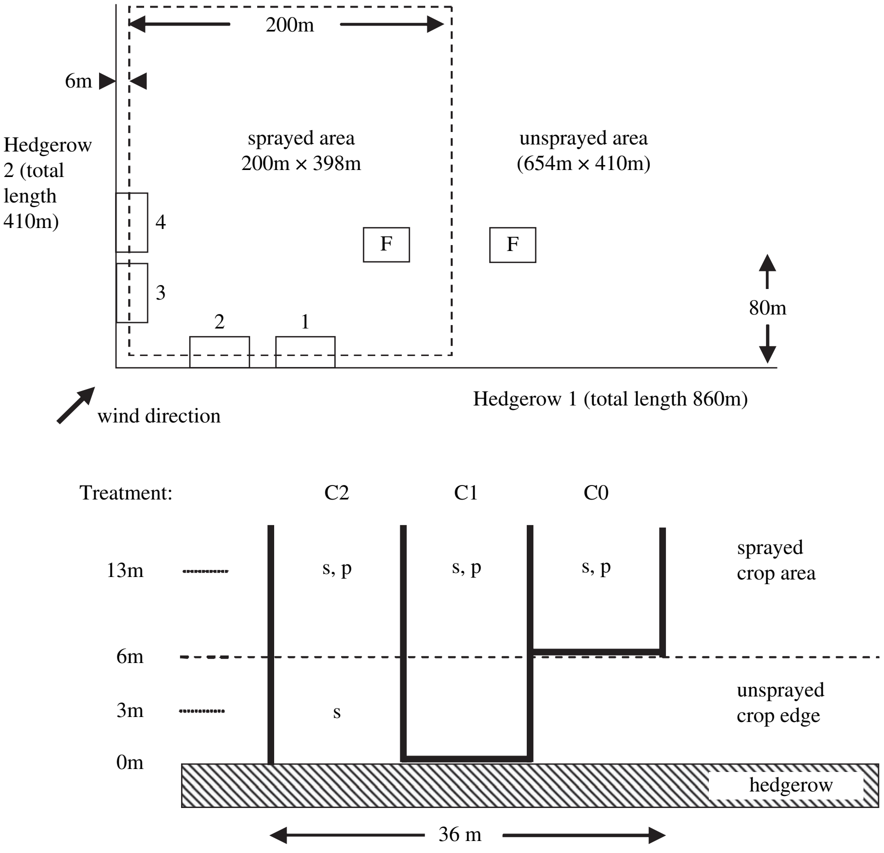

Fig. 1. (Top) The study site in a winter wheat field showing the locations of four blocks (1–4) of crop-edge experimental treatments and suction sampling positions in the field interior (F). (Bottom) Arrangement of the experimental connectivity treatments (C0, C1, C2) within one of the blocks, showing the positions of barriers (black lines) and the locations of suction (s) and pitfall (p) sampling.

the effect of a 6-m wide unsprayed crop edge and adjacent hedgerow on the abundance and species composition of epigeic Collembola in the sprayed field area. The barriers impede the movement of ground-active Collembola and other arthropods (e.g. Gravesen and Toft, 1987; Holland, 1998) and have some advantages over other possible experimental approaches (Section 4).

Three experimental connectivity treatments were created using polythene barriers supported using ropes and wooden stakes. The barriers were erected on 23 May, 12 days in advance of the insecticide application, and extended 0.7 m above and 0.3 m below ground. The experimental treatments were: C0, sprayed crop isolated from unsprayed crop edge and hedgerow; C1, sprayed crop connected to unsprayed edge but isolated from hedgerow; C2, sprayed crop connected to both unsprayed crop edge and hedgerow. These treatments were created, respectively, by placing 12-m-long barriers between the sprayed crop and unsprayed crop edge (C0), between the unsprayed crop edge and hedgerow (C1) or by using no barrier (C2) (Fig. 1). To prevent movement of ground-active arthropods between adjacent treatments, barriers were also installed perpendicular to the hedgerow, extending 18 m into the crop. The treatments were repeated in four blocks to give four replicates; two blocks were sited at each hedgerow (Fig. 1) at locations where field boundary structure and botanical composition were homogeneous. The spatial order of treatments within each block was chosen randomly.

2.3. Insecticide application

Chlorpyrifos (480 g litre^{-1} EC, 'Spannit'®; PBI) was applied in 200 L ha^{-1} water at 16:00 h BST on 5 June, 2001 during dry weather using a towed Chafer E-Series sprayer with low-drift 80° flat fan nozzles (Teejet® XR 80 03) at 0.5-m spacing. Boom height was 45 cm above the crop, operating pressure 2 bar and tractor speed 11 km h^{-1}. Wind speed was 8–10 km h^{-1} and the local screen temperature 18–19 °C. During the application, the wind direction (230°) was towards the field interior, away from the two study hedgerows (which were oriented 30°/210° and 120°/300°). An 8-ha area of the field was sprayed, excluding 6-m-wide crop edges (Fig. 1). No other pesticide applications were made during the study.

2.4. Insecticide deposition

Insecticide deposition was measured using 2.5 × 7.5 cm strips of Teejet water-and-oil sensitive paper, each laid horizontally, facing upwards, on a separate Petri dish lid to prevent contamination. Strips were placed at the crop edge (0 m), and at distances of 3, 5.5 and 13 m into the crop in each replicate of each experimental treatment. At each distance, strips were placed both on the ground surface and (supported on a wooden stake) at the top of the crop foliage. The strips were positioned in the field immediately before the insecticide application. After the application, they were wrapped individually in foil and kept in a dry environment prior to examination. Insecticide deposition on the strips was quantified in μl cm^{-2} by examining scanned images of the strips using computer image analysis software.

2.5. Arthropod sampling

Epigeic Collembola were sampled using a petrol-driven Ryobi suction sampler (MacLeod et al., 1994) with an 11.5-cm-diameter nozzle containing a muslin net (mesh < 100 μm). Each sample was obtained by placing the sampler nozzle on the ground surface between crop plants for 10 s at each of five randomly-selected locations and pooling the catch. Samples (each 0.052 m^2) were taken 13 m into the crop in each experimental treatment (7 m from the unsprayed crop edge into the sprayed area). To provide an indication of arthropod abundance within the unsprayed crop edge, samples were also taken at 3 m from the hedgerow in the sections of unsprayed edge without any barriers (treatment C2); this was to avoid any possible influence the barriers might have on estimates of arthropod abundance in the unsprayed edge. Additional samples were taken from the interior of the field, 80 m from the field boundary and 30 m from the interface between sprayed and unsprayed areas (Fig. 1) to confirm the spatial extent of effects of the insecticide and to assist in the detection of any recovery that might commence in situ within the sprayed area. At each location, four samples were collected, at 2 m spacing, in a line parallel to the hedgerow. Samples were taken on 12 occasions, in dry weather, from 25 May (11 days before insecticide application) to 14 August (1 week before crop harvest; 70 days post application) and were preserved in methylated spirit immediately after collection. Collembola were identified using binocular and compound light microscopy (Hopkin, 2000). Due to the large number of Collembola obtained, *Isotoma viridis* Bourlet and *Isotoma anglicana* Lubbock were not identified separately and are recorded together as *Isotoma viridis* 'group'.

As a contingency in case wet weather precluded suction sampling, pitfall traps were installed in each experimental treatment 13 m into the crop (Fig. 1). In each treatment, five traps (9 cm diameter, 13 cm depth) were placed at 1 m spacing in a line parallel to the hedgerow. The traps were half-filled with water and a drop of detergent to break the surface tension so that captured arthropods could not escape. Traps were operated for 7-day periods on 10 occasions after the insecticide application. After collection, the trap contents were rinsed with water (sieve mesh 150 μm) and preserved in methylated spirit.

2.6. Predation assessment

Recolonisation patterns of predatory arthropods may affect rates of predation in insecticide-treated fields (Duffield et al., 1996). It was not feasible to monitor individual predator–prey interactions in the current work which involved many predator and prey groups. Instead, an indication of the overall predation pressure was obtained using *Drosophila* pupae (Diptera: Drosophilidae) as indicator prey baits, in a similar approach to that of Duffield et al. (1996). Freeze-killed pupae were obtained from laboratory cultures and attached at regular spacing to 14 × 12 cm sections of waterproof card (medium-grade abrasive paper) using flour and water paste. Pupal baits were used on nine occasions (from 14 to 71 days after insecticide application), with 30 pupae per card on the first two dates and subsequently 15 per card. On each sampling occasion three cards of pupae were placed in each replicate of each treatment (C0, C1, C2), with each card sited 0.5 m from a pitfall trap (Fig. 1). The cards were placed with the pupae uppermost, to prevent pupae falling off, and were shielded from rainfall by 15-cm^2 metal covers supported ca. 3 cm above the ground on narrow legs to permit easy access of arthropods. On each sampling occasion the bait cards remained in the field for 24-h periods, after which the number of damaged and removed pupae were counted, excluding cards that had been visited by slugs.

2.7. Data analysis

As macroarthropod catches appeared to differ between the experimental treatments, pitfall catches of macroarthropods as well as suction catches of Collembola were analysed. The null hypothesis tested (H_0) is that the experimental treatments did not influence arthropod abundance (i.e. $\mathrm{C0} = \mathrm{C1} = \mathrm{C2}$). Rejection of H_0 would indicate that recolonisation occurred from the unsprayed crop edge (Type A recovery) if $\mathrm{C2} \geq \mathrm{C1} > \mathrm{C0}$. Acceptance of H_0 would indicate that the unsprayed crop edge did not on balance contribute to arthropod recovery in the sprayed area. If recovery is promoted by low predator abundance (Type B recovery), the result could be either $\mathrm{C0} = \mathrm{C1} = \mathrm{C2}$ (caused by generally low predator abundance in the sprayed area without any influence of experimental treatments) or $\mathrm{C0} > \mathrm{C1} \geq \mathrm{C2}$ (caused by treatment-specific differences in predator recolonisation from the unsprayed edge and hedgerow). If H_0 is accepted, comparisons of arthropod abundance in the sprayed and unsprayed areas of the field and between the sprayed area and unsprayed crop edge can help to identify Type B recovery.

Univariate analysis of variance (treatment fixed, block random; treatment × block interactions included) was used to test H_0 for individual arthropod taxa and also the null hypothesis that rates of predation assessed with bait cards were independent of the connectivity treatment. Analyses were performed on normalised data (log $(x + 1)$ of arthropod counts x, and arcsine-transformed proportions of pupae removed per bait card).

The community response to the experimental treatments was investigated using principal response curves (PRC) analysis. PRC analysis is a multivariate technique derived from redundancy analysis (RDA) that focuses on the proportion of the variance in the data set that is explained by treatment and time. For each species k the response T_{dtk} is modelled as a multiple (the species weight,

b_k) of one basic response pattern, c_{dt}, i.e. $T_{dtk} = b_k \times c_{dt}$ (van den Brink and Ter Braak, 1999). By plotting values of c_{dt}, for each treatment t and time d, a PRC diagram is obtained that shows the temporal change in community composition (the 'principal response') in each treatment relative to a reference treatment. Species weights indicate the affinity of each individual taxon with the overall community response. The choice of reference treatment in PRC analysis ($c_{dt} = 0$) is arbitrary; for present purposes the zero-connectivity treatment (C0) is used. PRC analysis was performed using the software program CANOCO 4 (Ter Braak and Šmilauer, 1998). For each analysis the null hypothesis that the PRC diagram does not display the treatment variance ($T_{dtk} = 0$ for all t, d, k) was tested using an F-type statistic obtained by permuting whole time series in the partial RDA from which the PRC was obtained (Ter Braak and Šmilauer, 1998). Permutation tests within sampling dates were also used to test the null hypothesis that the principal response c_{dt} did not differ between treatments (van den Brink and Ter Braak, 1999).

3. Results

3.1. Insecticide deposition

Very little insecticide reached the unsprayed crop edges, and none penetrated within 3 m of the hedgerow. Mean deposition 5.5 m into the unsprayed edge (i.e. 0.5 m from the sprayed crop) was less than 0.1 μl cm^{-2}. In the sprayed area, 13 m into the crop, mean chlorpyrifos deposition was 1.69 μl cm^{-2} at crop height, which was twice that at the ground surface (Fig. 2).

3.2. Collembola communities—suction sampling

Suction sampling yielded ca. 99,000 Collembola in total, representing 25 taxonomic groups (Appendix A). Of the total variance in the Collembola data set, 22% is explained by differences between blocks, 41% by sampling date and 37% by experimental barrier treatment. The PRC diagram (Fig. 3) summarises the overall community composition for the 25 taxa and displays a significant proportion of the treatment effects variance (85%; $p = 0.001$).

The overall community composition differed significantly ($p = 0.001$) between the unsprayed crop edge (3 m from the hedgerow) and the sprayed crop (13 m from the hedgerow) on all sampling dates, with consistently higher relative abundance in the unsprayed crop edge; this difference was apparent both before and after the field received chlorpyrifos but increased after the insecticide application. The majority of Collembola have high positive species weights, indicating higher abundance in the unsprayed crop edge than in the sprayed crop area. *Isotomurus* spp., however, show the opposite pattern (Fig. 3).

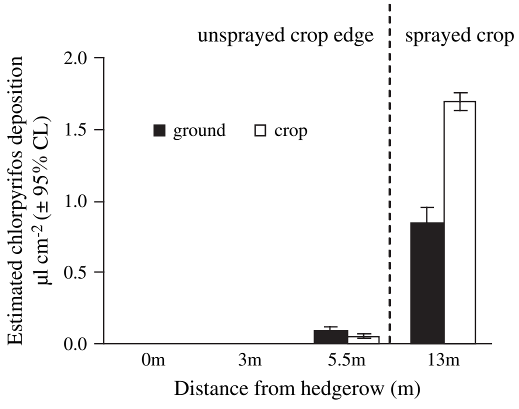

Fig. 2. Mean deposition (μl cm^{-2} ± geometric 95% CL; $n = 16$) of chlorpyrifos estimated using water and oil sensitive paper at different locations in the study field.

Differences in the fitted relative abundance (c_{dt}) between the experimental connectivity treatments were relatively small compared to the differences between the unsprayed crop edge and sprayed crop area. However, the highest relative abundance was consistently in the full-connectivity treatment (C2) on 10 of the 12 sampling dates (Fig. 3). The null hypothesis that c_{dt} was similar for each connectivity treatment was rejected for 7 of the 12 sampling dates. Fitted relative abundance for treatment C2 was significantly higher than for C0 and C1 on six and four dates, respectively, whereas a significant difference between treatments C0 and C1 occurred on one date (Fig. 3).

Total collembolan abundance (Fig. 4a) and taxonomic richness (Fig. 4b) reflect the overall pattern shown by the PRC diagram, being higher in the unsprayed crop edge than in the experimental barrier treatments in the sprayed area. Where a difference occurred between the experimental treatments, total collembolan abundance and taxonomic richness were consistently higher in C2 than C0 or C1 but there was no consistent difference between C0 and C1 (Fig. 4).

The overall collembolan community response reflects those of the most abundant Collembola taxa, *Lepidocyrtus* spp. (Fig. 5a) and *Isotoma viridis* 'group' (Fig. 5b).These were consistently more abundant in C2 than C1 on several sampling occasions during July but did not exhibit consistent differences between C0 and C1. A less abundant species, *Orchesella villosa*, also had clearly higher abundance in C2 than either C0 or C1 at the end of the sampling period (Fig. 5c).

Negative effects of chlorpyrifos on *Lepidocyrtus* spp. and *Isotoma viridis* 'group' occurred close to the unsprayed field edge and also at 80 m into the crop, with counts in the sprayed area remaining close to zero throughout the sampling period (Fig. 6a,b). However, *Pseudosinella* spp. and *Isotomurus* spp. exhibited a different pattern, with the highest counts in the field interior being in the sprayed area (Fig. 6c,d). These latter taxa had relatively high spatial and temporal heterogeneity of abundance with no consistent differences between the connectivity treatments (data not shown; 95% confidence limit (CL) overlapped for C0, C1 and C2 on all sampling dates).

3.3. Macroarthropod communities—pitfall sampling

Pitfall sampling yielded 16,000 macroarthropods (i.e. excluding Collembola) in total, representing 54 taxonomic groups (Appendix A). Of the total variance in the data set, 70% is explained by differences between blocks, 26% by sampling date and 4% by experimental barrier treatment. The PRC diagram (Fig. 7) summarises the overall community composition and displays a significant proportion of the

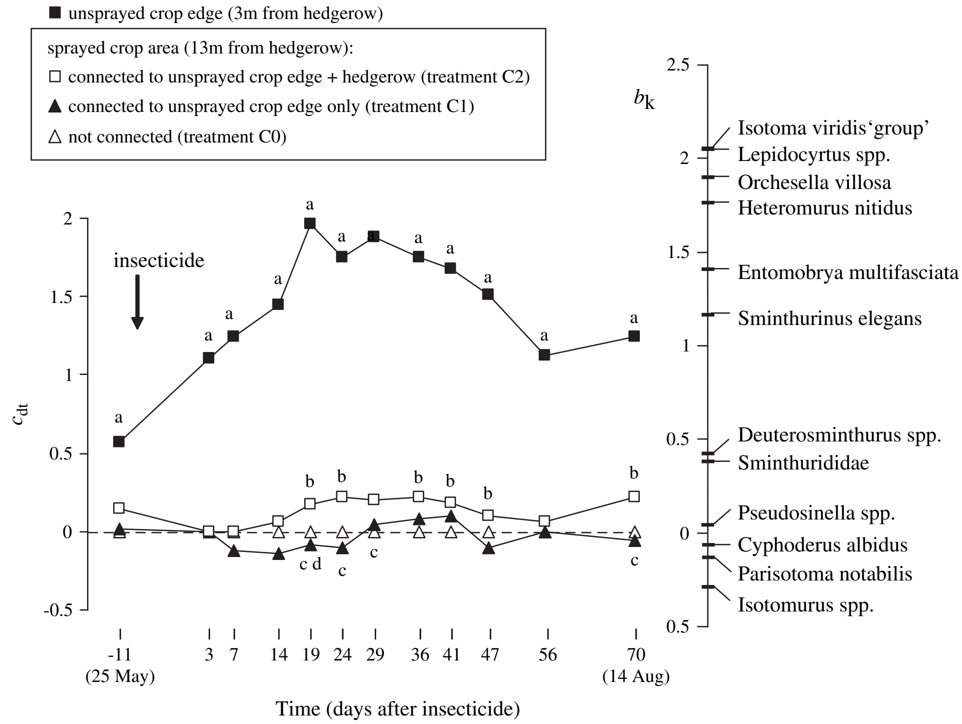

Fig. 3. PRC diagram showing the principal response (c_{dt}) and species weights (b_k) for a suction-sampled Collembola community (25 taxa) in an unsprayed crop edge and at three locations (C0, C1, C2) in the sprayed crop differing in connectivity with the unsprayed edge and hedgerow. Treatment C0 is nominated as the reference ($c_{dt} = 0$). Letter codes indicate significant differences in values of c_{dt} ($p = 0.001$): a, between the unsprayed crop edge and all other treatments; b, between C0 and C2; c, between C1 and C2; d, between C0 and C1. For clarity, taxa with b_k values close to zero are not shown.

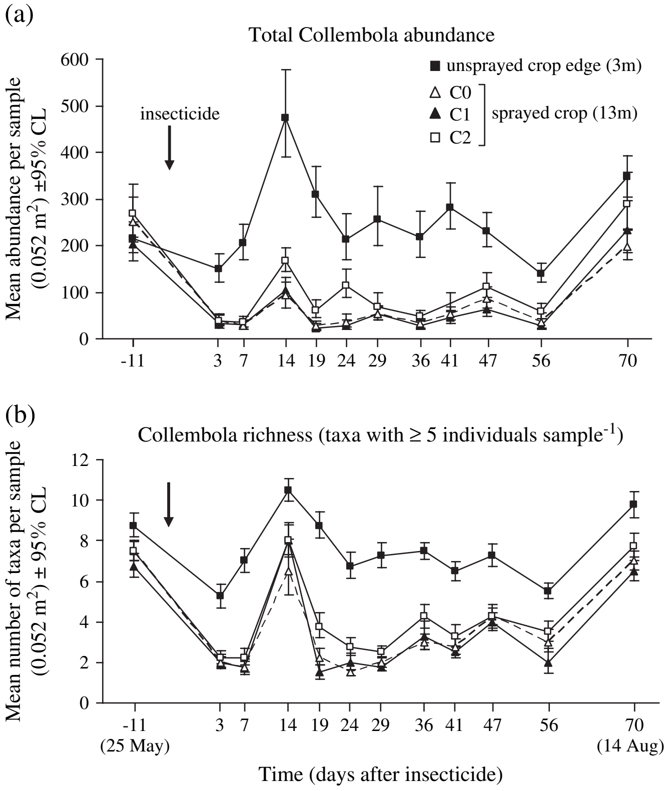

Fig. 4. Mean (±geometric 95% CL; $n = 16$) abundance (a) and taxonomic richness (b) of suction-sampled Collembola in an unsprayed crop edge and at three locations (C0, C1, C2) in the sprayed crop differing in connectivity with the unsprayed edge and hedgerow (connectivity details are as in Fig. 3).

treatment effects variance (22%; $p = 0.004$). Despite the relatively high heterogeneity of the data set compared to suction sampling, the fitted relative catch for the pitfall-sampled community was consistently higher in treatment C2 than C0 or C1 on most sampling dates, with differences between treatments significant on three dates (Fig. 7). Three individual species of Carabdae (*Agonum dorsale, Harpalus rufipes* and *Pterostichus madidus*) as well as the total Carabidae and total macroarthropod catch were affected significantly by the experimental treatments, but effects were transient and limited to individual sampling dates. In all cases the direction of treatment effects was consistent (C2 > C1 and/or C2 > C0) (Table 1). Accumulated total catches of three coleopteran taxa also differed significantly between the connectivity treatments, in all cases with higher catches in treatment C2 than C0 or C1 (Table 2).

3.4. Predation

Predation rates indicated by the proportion of prey baits removed were initially similar in treatments C0, C1, and C2 but heterogeneity among the treatments increased with time. The proportion of prey removed was significantly higher in C2 than in C0 on two occasions at the end of the sampling period but no other differences between treatments were statistically significant (Fig. 8). Higher predation pressure in C2 would be consistent with the higher overall abundance of predatory arthropods in this treatment.

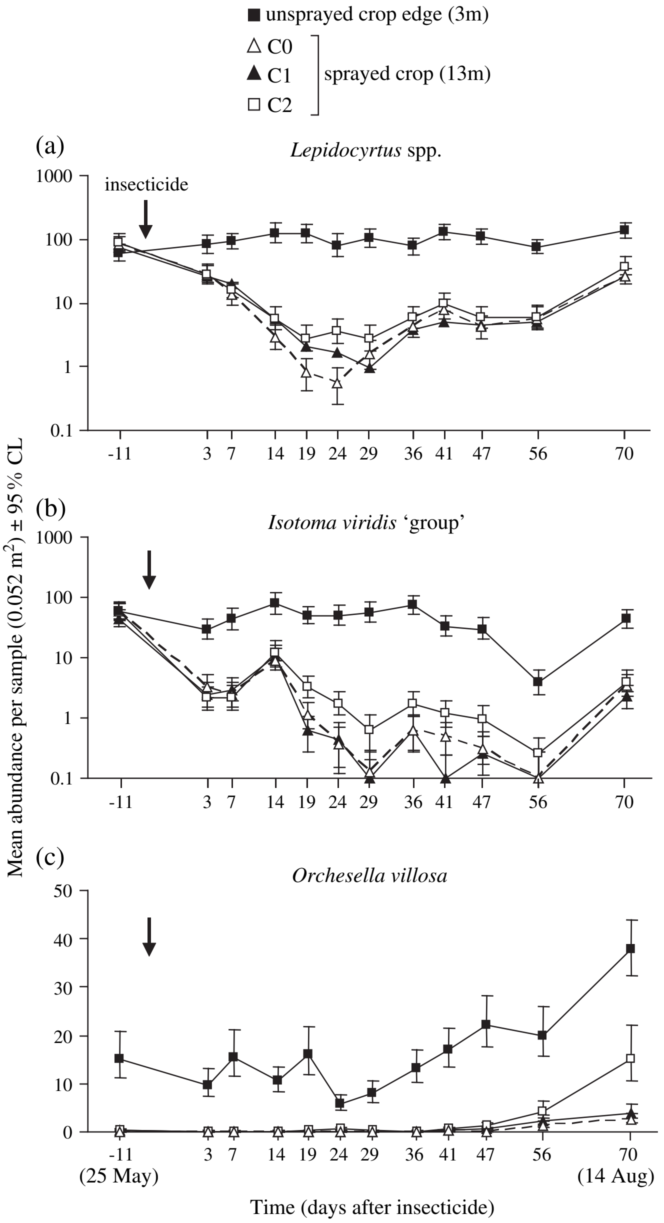

Fig. 5. Mean (±geometric 95% CL; $n = 16$) abundance of three Collembola taxa (a–c) in an unsprayed crop edge and at three locations (C0, C1, C2) in the sprayed crop differing in connectivity with the unsprayed edge and hedgerow (connectivity details and sampling dates are as in Fig. 3). Note that in (a) the CL of treatment C1 are omitted for clarity; on all dates they overlapped the CL for treatments C1 and C2.

4. Discussion

There seems to be no robust evidence that leaving crop edges unsprayed assists recovery of arthropod populations in adjacent pesticide-treated crop areas. This reflects a lack of reliable information rather than clear evidence for a lack of effects. In this work, the unsprayed crop edge alone did not appear to act as a source of arthropod recovery for the sprayed crop area, as physically isolating it from the sprayed crop made no difference to arthropod abundance or diversity in the sprayed area. The influence of connectivity between the sprayed area and hedgerow suggests that the effectiveness of an unsprayed crop edge as a source of recolonisation may depend on the presence of suitable field boundary habitat.

Most of the Collembola taxa that were present in the unsprayed crop edges are affected adversely by chlorpyrifos (Frampton, 1999, 2002). An in situ protective effect of excluding the insecticide is supported by the persistence of relatively high Collembola densities (up to 9000 m^{-2}) in the unsprayed crop edges. However, counts in the sprayed area at 13 m and 80 m from the hedgerow remained relatively low, with no evidence that recovery reached the interior of the sprayed area during the 70-day duration of the study. An exception is the increase in counts of *Isotomurus* spp. and *Pseudosinella* spp. in the sprayed area of the field interior whereas counts of these taxa in the unsprayed area remained low. This pattern would be consistent with a resurgence of abundance following release from predation or other density-limiting biotic interactions. Although data are scarce, there is evidence that *Isotomurus* spp. and *Pseudosinella* spp. may in some situations be less adversely affected than other Collembola by chlorpyrifos (Wiles and Frampton, 1996; Frampton, 1999). (In other situations, *Isotomurus* spp. as a group may appear highly susceptible to chlorpyrifos (G.K. Frampton, unpublished data), perhaps reflecting different susceptibilities of individual *Isotomurus* species.) Although the mechanism underlying the increased catches of *Isotomurus* and *Pseudosinella* is not proven, Collembola recolonisation patterns following an insecticide application clearly differ among taxa, meaning that recovery patterns may not be interpreted appropriately if the taxonomic resolution of monitoring is too coarse.

Some Collembola (e.g. *Lepidocyrtus* spp. and *Orchesella villosa*) appear to be capable of dispersing over relatively large distances (at least tens of metres) by active locomotion (Dunger et al., 2002). These taxa, together with *Isotoma viridis* 'group', may have originated from the hedgerow, indicated by higher catches in treatment C2 than C0 or C1. Such a pattern would be consistent with dispersal-mediated (Type A) recovery (Duffield and Aebischer, 1994). Although hedgerow connectivity clearly had an impact on Collembola abundance and species composition in the sprayed crop area, it is difficult to determine its general importance for recovery, as individual taxa exhibited different response patterns. Hedgerow connectivity appears to have been more important for *O. villosa* than for *I. viridis* 'group' and *Lepidocyrtus* spp., as abundance of *O. villosa* progressively increased in treatment C2 whereas for the other taxa the difference in abundance between treatments did not persist to the end of the study. However, as *O. villosa* was not present outside the crop edge prior to the insecticide application, population recovery in the sprayed area is difficult to define.

The lower frequency of statistically significant treatment effects on predators compared to Collembola is not surprising, as the spatial scale of the study would have been inadequate for detecting effects of the experimental treatments on mobile

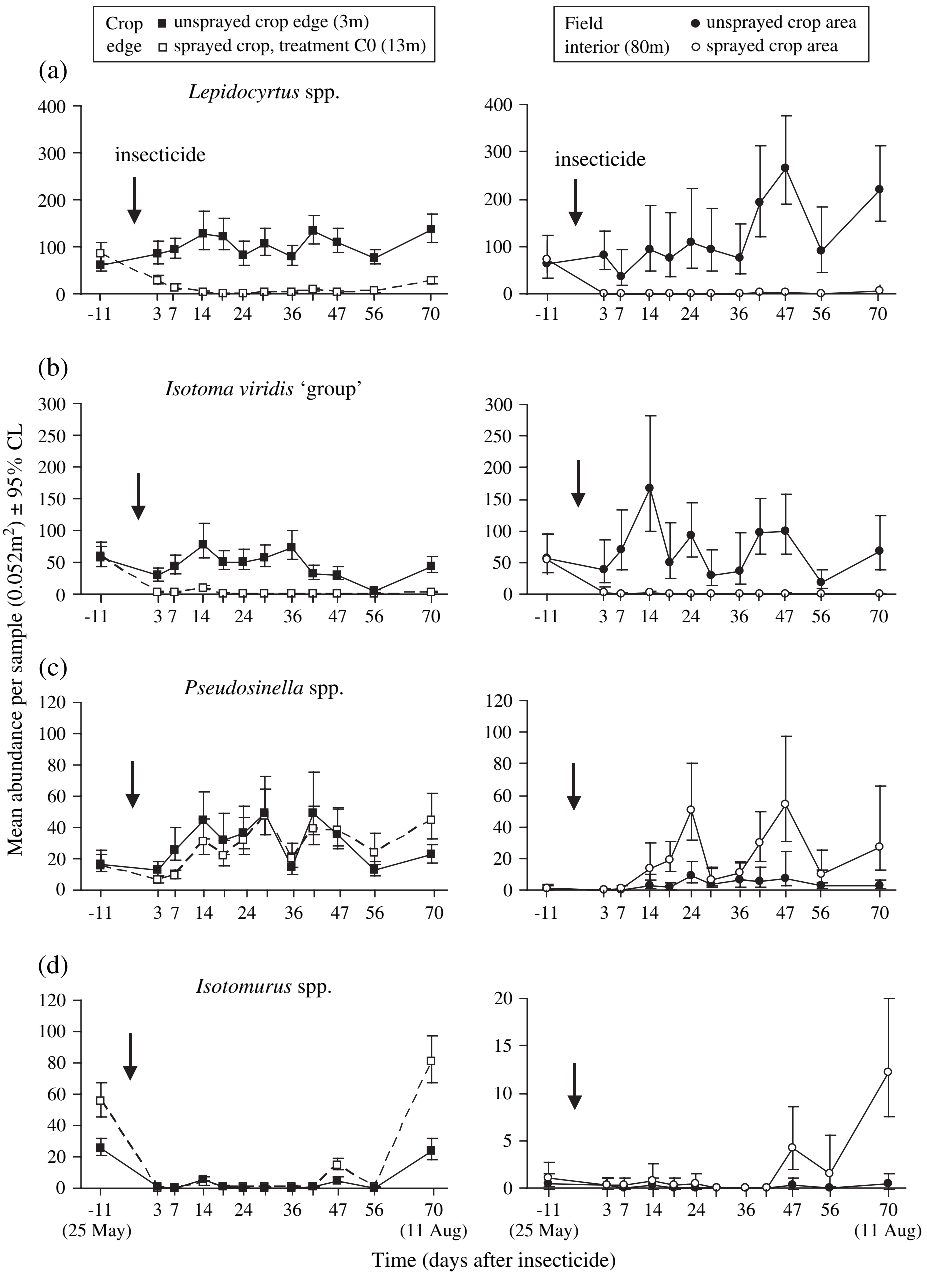

Fig. 6. Mean (±geometric 95% CL) abundance of four Collembola taxa (a–d) in sprayed and unsprayed areas of crop at the field edge (3 m and 16 m from the hedgerow; $n = 16$) and in the field interior (80 m from the hedgerow; $n = 4$). Sampling dates are as in Fig. 3. Note differing y-axis scales in (d).

predatory arthropods such as Carabidae, Staphylinidae and Linyphiidae, some of which disperse aerially. The transient significant effect of the treatments on *Agonum dorsale* (Table 1) would be consistent with barriers in C0 and C1 interrupting the annual spring dispersal of this species from the field boundary into the crop (Jensen et al., 1989). The findings are also consistent with previous work demonstrating that *Harpalus rufipes* may disperse from aggregations in crop edges (Thomas et al., 2001) whilst *Pterostichus madidus* is able to disperse between fields across field boundaries (Holland et al., 2004).

Predation assessment using prey baits can only detect predation by arthropods that forage upon immobile prey. A limitation is that many predators of Collembola (e.g. Linyphiidae, some Carabidae and some Staphylinidae) only hunt active prey, so it is unlikely that the predation rate estimated using bait cards would reflect the predation pressure upon Collembola. However, the significantly lower predation pressure in treatment C0 than in C2 suggests that the overall biocontrol potential of arthropods (for example as antagonists of pests such as aphids) might be influenced by the type of field margin habitat where the unsprayed crop edge is sited.

To ensure that barriers did not influence the estimates of arthropod abundance in the unsprayed crop edge, sampling in the crop edge was carried out in treatment C2. This

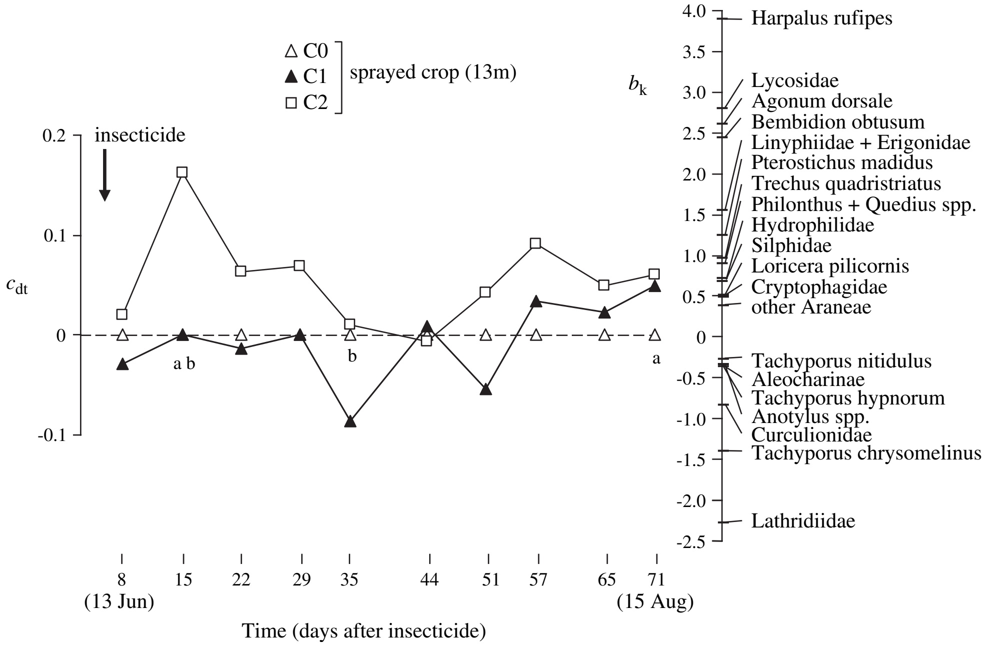

Fig. 7. PRC diagram showing the principal response (c_{dt}) and species weights (b_k) for a pitfall-sampled macroarthropod community (54 taxa) at three locations in a sprayed crop (C0, C1, C2) differing in connectivity with the unsprayed crop edge and hedgerow (details are as in Fig. 3). Treatment C0 is nominated as the reference ($c_{dt} = 0$). Letter codes indicate significant differences in values of c_{dt} ($p < 0.005$): a, between C0 and C2; b, between C1 and C2. For clarity, taxa with b_k values close to zero are not shown.

correlation between sampling locations is unlikely to affect interpretation of the results, however, as differences in arthropod abundance between the unsprayed edge and the sprayed crop area were considerably larger than the effects of the connectivity manipulation treatments. Treatment C2 is an appropriate location for assessing abundance in the unsprayed crop edge, as the connectivity between the hedgerow and sprayed crop is realistic, whilst close proximity to the other treatments should minimise background spatial heterogeneity of arthropod abundance.

The use of barrier treatments to manipulate connectivity between the sprayed crop, unsprayed crop edge and hedgerow permitted this study to be carried out at a relatively small spatial scale. Advantages of this approach are: (i) the area sprayed with chlorpyrifos could be kept to a minimum; (ii) spraying of crop edges was avoided; and (iii) the work could be carried out within homogeneous areas of crop and hedgerow. These were important considerations as the study was carried out on a commercial farm employing bird conservation management, which would be incompatible with wide-scale use of broad-spectrum insecticides on crop edges. Organophosphorus insecticides and Collembola provide a useful model ecotoxicological system because the insecticides cause clear and repeatable differences of abundance and diversity between treated and untreated areas (e.g. Frampton, 1999, 2002). However, it is unlikely that results could be generalised to different insecticide modes of action. Studies using broad-spectrum organophosphate insecticides might underestimate recovery that is assisted by reduced predation because they have a broad activity against both predators and prey, whereas the more widely-used synthetic pyrethroid insecticides appear to be more harmful to

Table 1
Significant effects of the experimental treatments (C0, C1, C2) on pitfall catches of macroarthropods on individual sampling occasions

Days after insecticide	*Agonum dorsale*	*Harpalus rufipes*	*Pterostichus madidus*	Total Carabidae	Total macro-arthropods
15	$F_{2,48} = 50.15$ $p < 0.001$ C2 > C0 = C1	n.s.	n.s.	$F_{2,48} = 9.67$ $p = 0.013$ C2 > C1	n.s.
22	n.s.	$F_{2,48} = 50.15$ $p = 0.017$ C2 > C0 = C1	n.s.	n.s.	n.s.
71	n.s.	n.s.	$F_{2,48} = 50.15$ $p = 0.035$ C2 > C0 = C1	$F_{2,48} = 10.90$ $p = 0.01$ C2 > C0 = C1	$F_{2,48} = 19.17$ $p = 0.002$ C2 = C1 > C0

Each sampling occasion refers to the end of a 7-day trapping period. Effects were only statistically significant on those dates included in the table. Treatment effects were independent of location (in all cases treatment × block $p > 0.05$). n.s., treatment effect not significant ($p > 0.05$).

Table 2
Mean catches of Coleoptera per pitfall trap per 7 days averaged over 10 sampling dates

	C0	C1	C2	$F_{2,48}$	p
Pterostichus madidus	1.9 a	1.9 a	3.2 b	7.71	0.005
Total Carabidae	14.3 a	15.7 a	21.1 b	16.43	0.004
Total Coleoptera	32.5 a	33.7 a	40.9 b	5.93	0.038

Treatments (C0, C1, C2) sharing the same letter (a, b) did not differ significantly (Tukey multiple range test). Treatment effects were independent of location (in all cases treatment × block $p > 0.05$).

predators than to Collembola (Frampton, 1999). Clarification of arthropod recovery dynamics for other chemicals would be prudent, given the widespread use of insecticides. It is also important that the role of unsprayed crop edges is clarified with regard to whether they can be generally assumed to influence arthropod recovery in sprayed areas (Forster and Rothert, 1998).

5. Conclusions

Unsprayed crop edges can provide in situ protection of arthropod populations from effects of insecticides but their effectiveness as sources for arthropod recolonisation of adjacent sprayed crops has not been adequately proven. Unless more research is carried out to confirm the ecological function of unsprayed crop edges as source habitats, the assumption that unsprayed crop edges assist recovery of populations within sprayed areas cannot be supported. Accordingly, in regulatory risk assessment, the protection goal of unsprayed crop edges should be clearly stated as being restricted to those populations that occur in situ within the crop edge. The taxonomic variation in recovery responses observed in this study also advises against grouping Collembola taxa together as a single response unit in ecotoxicological studies.

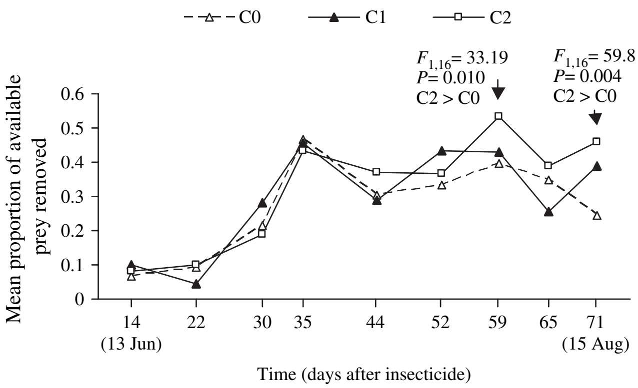

Fig. 8. Predation rate (mean proportion of artificial prey removed) at three locations (C0, C1, C2) in the sprayed crop differing in connectivity with the unsprayed edge and hedgerow (connectivity details and sampling dates are as in Fig. 3). Treatment effects were independent of location (in all cases treatment × block $p > 0.05$).

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Appendix A

Arthropod taxonomic groups identified in suction and pitfall samples

Sampling method	Arthropod group	Number and identity of taxa monitored	
Suction	Collembola: Arthropleona		
	Isotomidae	4	*Isotoma viridis* ‘group’, *Parisotoma notabilis*, *Isotomurus* spp., other Isotomidae
	Hypogastruridae	1	Total Hypogastruridae
	Entomobryidae	11	*Pseudosinella* spp. (2), *Lepidocyrtus* spp. (3), *Entomobrya multifasciata*, *Heteromurus nitidus*, *Orchesella* spp. (2), *Tomocerus* spp., other Entomobryidae
	Other Arthropleona	1	Total other Arthropleona
	Collembola: Symphypleona		
	Sminthuridae	6	*Bourletiella hortensis*, *Deuterosminthurus* spp., *Sminthurinus* spp. (2), *Sminthurus viridis*, other Sminthuridae
	Sminthurididae	1	Total Sminthurididae
	Other Symphypleona	1	Total other Symphypleona
Pitfall	Coleoptera		
	Carabidae	24	*Amara* spp., *Agonum* spp. (2), *Asaphidion flavipes*, *Badister bipustulatus*, *Bembidion* spp. (3), *Calathus fuscipes*, *Carabus violaceus*, *Demetrias atricapillus*, *Harpalus* spp. (4), *Leistus* spp. (2), *Loricera pilicornis*, *Nebria brevicollis*, *Notiophilus biguttatus*, *Pterostichus* spp. (2), *Trechus quadristriatus*, other Carabidae
	Staphylinidae	10	Aleocharinae, *Anotylus* spp., *Philonthus* + *Quedius* spp., *Tachyporus* spp. (5), Xantholininae, other Staphylinidae
	Other Coleoptera families	17	Cantharidae, Clambidae, Coccinellidae, Colydiidae, Chrysomelidae, Cryptophagidae, Curculionidae, Elateridae, Erotylidae, Histeridae, Hydrophilidae, Lathridiidae, Leiodidae, Nitidulidae, Oedemeridae, Phalacridae, Silphidae
	Araneae	3	Linyphiidae, Lycosidae, other Araneae

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