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Recovery responses of soil surface Collembola after spatial and temporal changes in long-term regimes of pesticide use

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Summary

Counts of several Collembola species in a rotation of grass and wheat cropping were consistently lower under a conventional regime of pesticide use than under a reduced-input regime. During a six-year period (1991–1996), counts of *Entomobrya nicoleti* remained at or close to zero under the conventional regime. This raised the question of how long recovery would take if conventional pesticide inputs ceased. To answer this question, and confirm effects of the pesticide regimes on patchily-distributed species, the two pesticide regimes were reversed spatially: from 1997 to 1999 the area formerly under conventional inputs subsequently received the reduced-input regime and *vice versa*. This paper presents results up to summer 1998 to show the effect on collembolan counts of reversing the pesticide regimes. Responses varied among species: after conversion of the conventional regime to reduced inputs, counts of *E. nicoleti* remained at or close to zero whereas counts of *Isotoma viridis* were the highest recorded during the study. Data from a rotation of cereals and break crops show that reversal of treatments can aid interpretation of pesticide effects for species with a patchy temporal distribution; treatment reversal improved confidence in the interpretation of pesticide effects for species of Collembola which were not present during the pre-treatment sampling phase of a long-term study.

Key words: Side-effects, experimental scale, recovery, replication, SCARAB Project

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Introduction

Relatively few field studies of pesticide side-effects have investigated beneficial arthropods' population recovery responses (Van Straalen & Van Rijn 1998), though recovery may be ecologically more important than the initial effect (Kelly & Harwell 1990). Detection of long-term effects and the subsequent recovery of populations, communities or ecosystems depends on adequate temporal scales of study. This is because effects of repeated applications of pesticides may develop slowly (Ogilvy et al. 1996) or persist over more than one season (Burn 1992; Frampton et al. 1992; Frampton 1997), whilst sporadically-occurring species, rare events or cyclic phenomena could be missed in a short-term study (Woiwod 1991). Even a single pesticide application may lead to ecological changes over several years, e.g. in the abundance of microarthropods (Krogh 1991). Such 'transient dynamics' are difficult to foresee and endorse the need for long-term ecological studies (Tilman 1988).

Long-term studies require realistic spatial scales because, at least among predatory arthropods, recovery rate is inversely related to the area treated with pesticide (Jepson & Thacker 1990; Thomas et al. 1990; Duffield & Aebischer 1994). Spatial replication of experimental treatments is usually necessary for unequivocal confirmation of treatment effects using statistical hypothesis testing (Hurlbert 1984) but is impractical where pesticide treatments are applied at large scales, e.g. to whole fields (e.g. Smart et al. 1989) or blocks of fields (Greig-Smith & Hardy 1992). Instead, large-scale studies may employ a 'quasi-experimental' design (Parker 1988) where confidence in the interpretation of treatment effects is obtained from experimental manipulation without formal statistical testing. In the Boxworth Project (Vickerman 1992) and SCARAB Project (Frampton 1997), for example, effects of pesticide regimes on arthropod communities were inferred from comparisons of arthropod counts obtained before and after the regimes were applied, together with comparisons of counts from experimental areas which had received different regimes. Effects of pesticide regimes in these studies were clearly detectable because broad-spectrum organophosphorus insecticides were used in most seasons (Frampton 2000). In a grass and wheat rotation of the SCARAB Project, counts of some Collembola, e.g. *Entomobrya nicoleti* (Lubbock), *Isotoma viridis* Bourlet and *Lepidocyrtus* spp., were consistently lower under conventional pesticide use than under a regime of reduced inputs for a six-year period (1991–1996) (Frampton 1997, 2000). This raised the question of how quickly collembolan abundance would increase, i.e. what the rate of recovery would be, if conventional pesticide inputs ceased. To answer this question, the pesticide regimes were reversed spatially; the area formerly treated with the conventional regime subsequently received the reduced-input regime (1997–1999) and *vice versa*.

In this paper I report the initial effect on collembolan counts (up to summer 1998) of reversing the pesticide regimes in the grass and wheat rotation. Spatial reversal of unreplicated treatments may also be useful for improving interpretation of pesticide effects upon patchily-distributed species. This is illustrated with data from another crop rotation of the SCARAB Project (cereals and break crops) in which potential effects of pesticide regimes were difficult to interpret because species of interest were not present during the pre-treatment sampling period.

Materials and Methods

Study areas

The study comprised two fields, 'Field 5' (F5) and 'Bugdale' (BU) which were part of a long-term investigation of effects of conventional and reduced-input regimes of pesticide use on arthropods in arable farmland in England (the SCARAB Project) (Frampton 1997). These fields were, respectively, 8ha and 19ha in area and located at Drayton Research Centre in Warwickshire (52.2°N 1.8°W, calcareous clay) and at High Mowthorpe Research Centre in North Yorkshire (54.1°N 0.6°W, calcareous loam). Each field contained a rotation of crops typical of the locality where the field was sited; in F5 this was of grass and wheat whereas the rotation in BU was of cereals and break crops (Table 1).

Experimental design

Effects of two regimes of pesticide use on collembolan abundance were investigated in each field. These were a conventional regime (also known as 'current farm practice'; CFP) and a reduced-input approach (RIA) (Frampton 1997). The conventional regime reflected actual farming practice for each crop, as indicated by pesticide usage surveys (e.g. Thomas et al. 1997). The reduced input approach employed pesticides only where necessary to avoid excessive (>10 %) loss of crop yield or market value, either by use of reduced doses or by omitting applications altogether. A principal difference between the two pesticide regimes is that no insecticides were applied under the reduced-input regime (Table 1). No acaricides or molluscicides were used during the study (this reflected local crop management practice). Pesticide inputs under each regime differed between crop rotations, and hence between fields (Table 1), particularly with regard to the type and frequency of insecticide applications used in the conventional regime (Table 2).

A split-field approach was used for the experimental design (Cooper 1990). During 1990–1996, each pesticide regime was applied to one half of each field (Fig. 1). This followed an initial period of pre-treatment monitoring (PRE) in 1989–1990 (Fig. 1), during which pesticide inputs equivalent to conventional practice but excluding insecticides were applied to whole fields. The only agronomic variables which differed between the two halves of each field were the pesticide regimes (Fig. 1); cropping, cultivations and fertiliser applications were managed as whole-field operations.

Manipulation of treatments

At the end of the phase of contrasting treatments (1991–1996), the conventional and reduced-input regimes were reversed spatially (Fig. 1). The aim of this manipulation was to permit investigation of Collembola recovery rates in field F5 after the removal of conventional pesticide pressure. The pesticide regimes were also reversed in field BU to improve interpretation of long-term differences in collembolan abundance between the pesticide regimes; in this field a possible link between pesticide use and collembolan distribution could not be confirmed because species of interest were absent during the PRE phase of monitoring (see Results). The rationale of this approach was that the change from conventional to reduced inputs should permit arthropod recovery to be monitored in F5, while in BU if the observed collembolan distributions were caused by the pesticide regimes they would be expected to change spatially after the pesticide regimes were reversed (though not necessarily immediately if effects were indirect). An alternative approach would have been to manipulate only the conventional regime in F5 so that a permanent regime of reduced inputs could be used as a reference against which to judge collembolan recovery. This approach was rejected in favour of reversing both regimes, to avoid problems of interpretation caused by heterogeneous distribution of some species between the two halves of each field (see Discussion). Pesticide differences between the regimes

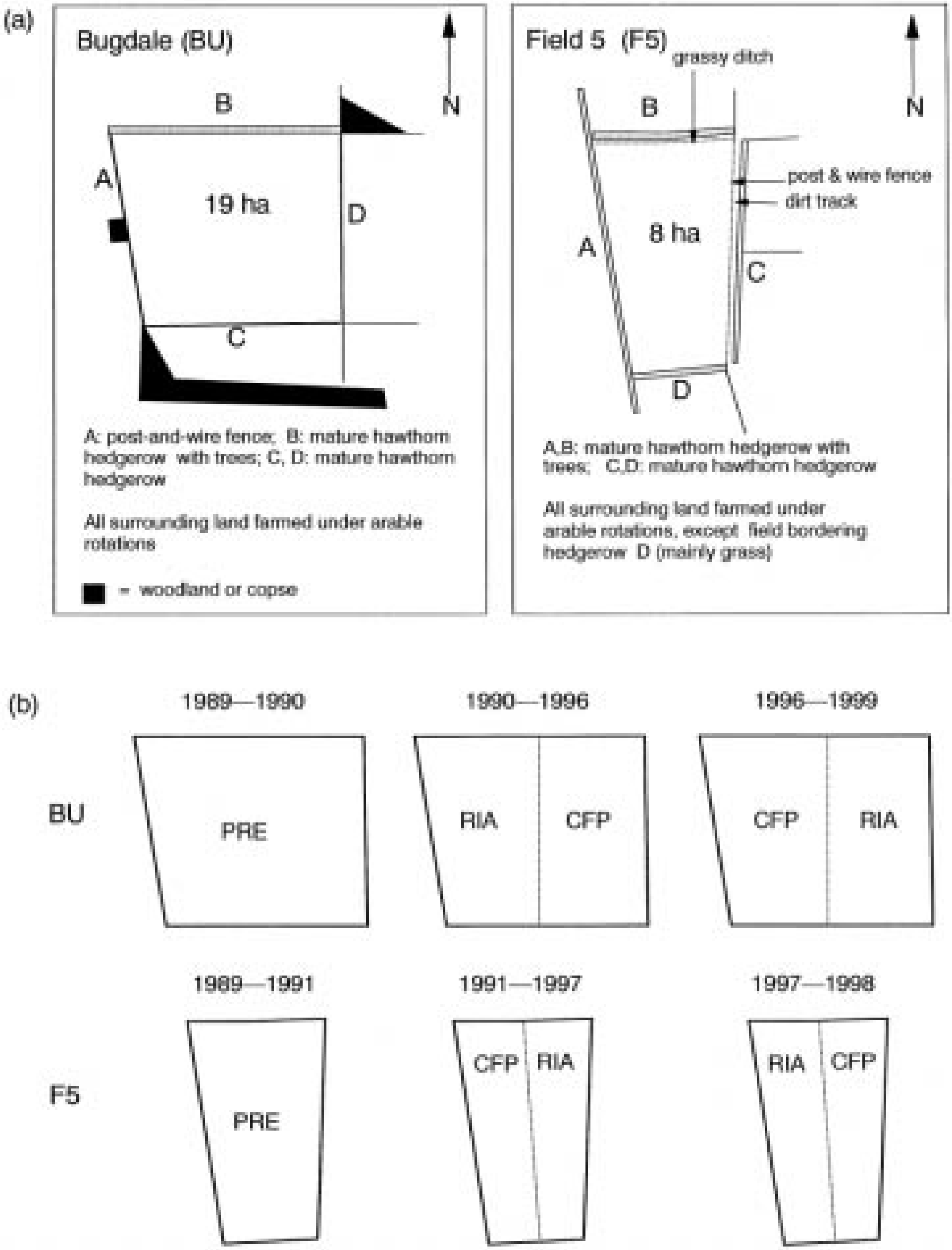


Fig. 1. Layout of fields BU and F5: (a) adjacent landscape features; (b) spatial orientation of pre-treatment (PRE), reduced-input approach (RIA) and conventional ('current farm practice', CFP) pesticide regimes, 1989–1999.

Table 1. Number of label-recommended-rate applications (excluding seed treatments) of herbicides (h), fungicides (f) and insecticides (i) in fields F5 and BU under conventional and (in parentheses) reduced-input regimes of pesticide use. The regimes were reversed spatially within each field after harvest 1996. Dates refer to crop-years (i.e. from sowing to harvest); asterisk denotes autumn 1995 application

	Field 5 (F5)				Bugdale (BU)			
year	crop	h	f	i	crop	h	f	i
1990–91	grass	0 (0)	0 (0)	1 (0)	winter rape	1 (0.5)	1 (0)	1 (0)
1991–92	winter wheat	3 (1.5)	2 (1)	1 (0)	winter wheat	1 (0.5)	3 (1)	1 (0)
1992–93	winter wheat	5 (2.5)	4 (2)	1 (0)	spring barley	1 (0.5)	1 (0.5)	1 (0)
1993–94	grass	0 (0)	0 (0)	1 (0)	spring beans	1 (0.5)	0 (0)	1 (0)
1994–95	grass	0 (0)	1 (0)	1 (0)	winter wheat	2 (1.5)	3 (1)	2 (0)
1995–96	grass	0 (0)	1 (0)	0 (0)	winter barley	2 (1.5)	3 (1)	1 (0)*
After regimes reversed:								
1996–97	grass	1 (1)	1 (0)	1 (0)	winter rape	1 (0)	3 (1)	1 (0)
1997–98	winter wheat	2 (1)	0 (0)	0 (0)	winter wheat	3 (1.5)	6 (2.5)	1 (0)

were maintained after the positions of the regimes (east or west half of a field) were reversed (Table 1; Fig. 1). Reversal of the regimes was in autumn 1996 in BU and in spring 1997 in F5, corresponding to the first differences in pesticide inputs between the regimes in the 1996–1997 season.

Sampling technique

Arthropods were sampled in all years using a 'D-vac' suction sampler (sampling details in Frampton 1997) at matched sampling locations in each half of each study field (Fig. 1). 'D-vac' suction sampling is an efficient means of estimating collembolan abundance at the soil surface in arable land (Frampton 1989). The soil-surface cohort was sampled because surface-dwelling Collembola are both potentially at risk of direct exposure to sprayed pesticides and are an important component in the diet of aboveground predatory arthropods. Counts of all instars except eggs obtained using this method were added to give estimates of the abundance of surface-active species. Samples were usually taken at monthly intervals throughout the year (unless prevented by periods of cultivation or wet weather), but more frequently in summer. Sampling was only carried out when the crop and soil were dry. The pesticide regimes in each field were sampled simultaneously on each sampling date to minimise effects of abiotic variables on the catch. Immediately after collection, samples were stored in c. 70 % methylated spirit and subsequently sorted by hand. Collembola identification followed Fjellberg (1980) and Christiansen & Bellinger (1998). For brevity, the results presented here are for summer captures (May–July).

Table 2. Insecticides applied under conventional pesticide regimes in fields F5 and BU. Numbered applications refer to Fig. 2 (F5) and Fig. 3 (BU). All applications were sprays applied in 200 litres ha^{-1} water (except *: seed coating)

Field F5			Field BU		
Insecticide	Date	Rate (g.a.i. ha^{-1})	Insecticide	Date	Rate (g.a.i. ha^{-1})
1. chlorpyrifos	28 Jan 1991	720	1. gamma-HCH	20 Sep 1989	*
2. dimethoate	23 Jun 1992	336	2. triazophos	24 Jun 1991	420
3. dimethoate	23 Jun 1993	336	3. dimethoate	15 Jul 1992	340
4. chlorpyrifos	14 Jun 1994	720	4. dimethoate	30 Jun 1993	340
5. chlorpyrifos	22 Mar 1995	720	5. cypermethrin	02 Jun 1994	25
6. chlorpyrifos	02 Apr 1997	720	6. chlorpyrifos	28 Jun 1995	480
			7. dimethoate	15 Jul 1995	340
			8. cypermethrin	28 Oct 1995	25
			9. triazophos	17 Jun 1997	420
			10. dimethoate	03 Jul 1998	340

Results

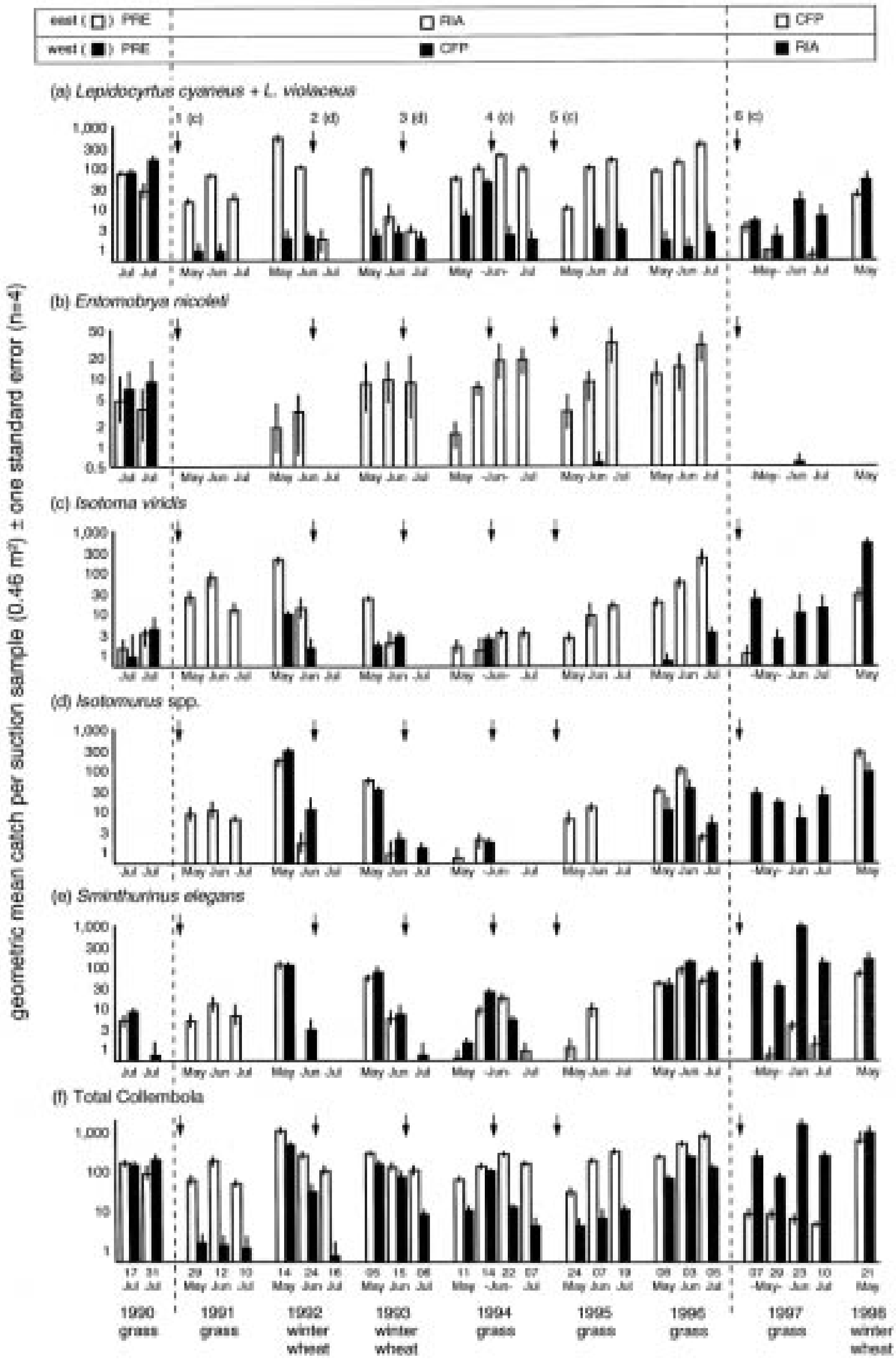
Long-term distributions of Collembola in the study fields (1991–1996)

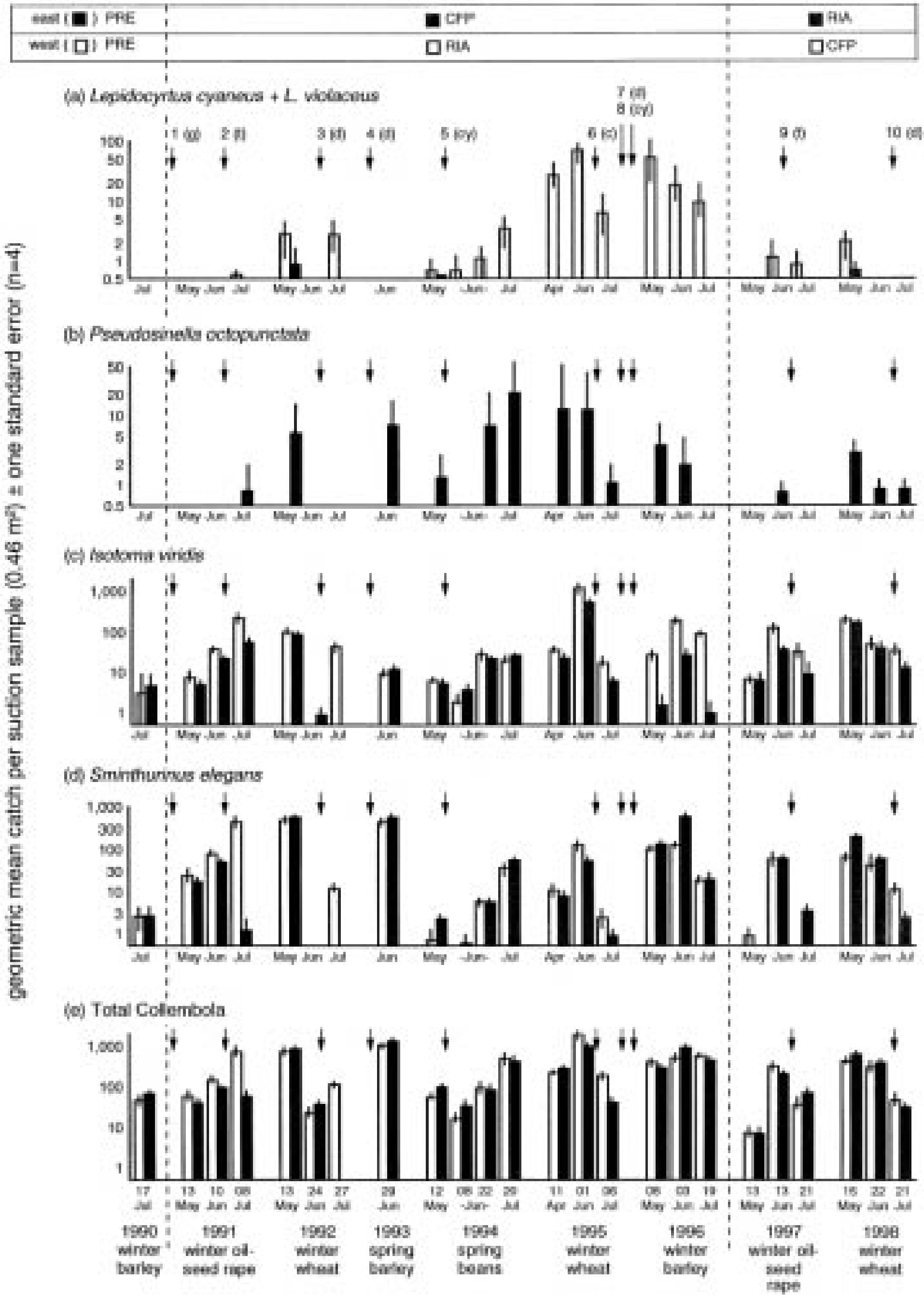
During 1991–1996, long-term differences in collembolan abundance between the half-field units under conventional and reduced-input pesticide regimes were evident both in field F5 (Fig. 2) and in BU (Fig. 3). In F5, distributions of several Collembola species between the east and west halves of the field were obviously related to the pesticide regimes because the pattern of catches differed markedly between the pre-treatment (1990) and treatment contrast (1991–1996) years of the study (Fig. 2). Counts of *E. nicoleti*, *I. viridis* and *Lepidocyrtus* spp. (mainly comprising *L. cyaneus* Tullberg and *L. violaceus* Lubbock), were initially similar in both halves of the field during summer 1990 but became considerably lower in the conventional (west) than the reduced-input regime (east) half of the field during 1991–1996 when the conventional regime was applied (Fig. 2). This pattern was especially clear for *E. nicoleti*, which was rarely encountered in the west half of F5 while the conventional regime was applied to it (Fig. 3).

In field BU, two species of Collembola exhibited long-term differences in abundance between the half-field areas under conventional pesticide inputs (east) and reduced inputs (west) (Fig. 3). Counts of *Lepidocyrtus* spp. (principally *L. cyaneus* and

▶

Fig. 2. Collembola counts in suction samples in the east (□) and west (■) areas of field F5 under pre-treatment (PRE), reduced-input approach (RIA) and conventional (CFP) regimes of pesticide use. The RIA and CFP regimes were reversed spatially in spring 1997. Numbered arrows refer to Table 2 and show chlorpyrifos (c) and dimethoate (d) insecticides (applied only under the CFP regime)


east ( ) PRE
RIA
CFP
west ( ) PRE
CFP
RIA
(a) Lepidocyrtus cyaneus + L. violaceus
(b) Entomobrya nicoleti
(c) Isotoma viridis
(d) Isotomurus spp.
(e) Sminthurinus elegans
(f) Total Collembola
geometric mean catch per suction sample (0.46 m²) ± one standard error (n=4)
1990 grass
1991 grass
1992 winter wheat
1993 winter wheat
1994 grass
1995 grass
1996 grass
1997 grass
1998 winter wheat


east (■) PRE
west (□) PRE
■ CFP
□ RIA
■ RIA
□ CFP
geometric mean catch per suction sample (0.46 m²) ± one standard error (n=4)
(a) Lepidocyrtus cyaneus + L. violaceus
(b) Pseudosinella octopunctata
(c) Isotoma viridis
(d) Sminthurinus elegans
(e) Total Collembola
1990 winter barley
1991 winter oil-seed rape
1992 winter wheat
1993 spring barley
1994 spring beans
1995 winter wheat
1996 winter barley
1997 winter oil-seed rape
1998 winter wheat

L. violaceus) and *Pseudosinella octopunctata* Börner suggested mutually exclusive distributions within the field; the former species were encountered almost exclusively in the west half of the field (Fig. 3a), whilst *P. octopunctata* was found only in the east half (Fig. 3b). Unlike the situation in field F5 however, these species were not present during the pre-treatment monitoring period (1990), so the possibility that these patterns of abundance might have been caused by the pesticide regimes could not be confirmed.

Effects on Collembola of reversing pesticide regimes (1997 - 1998)

Spatial reversal of the conventional and reduced-input pesticide regimes in field F5 in spring 1997 had a clear effect on the abundance of Collembola (Fig. 2). Catches of *Lepidocyrtus* spp. (Fig. 2a), *I. viridis* (Fig. 2c) and the total Collembola (Fig. 2f) were consistently highest under the reduced-input regime, both when it was applied to the east half of the field during 1991–1996 (white bars in Fig. 2), and when it was applied to the west half of the field during 1997–1998 (black bars in Fig. 2). This pattern confirms the negative impact of the conventional regime on collembolan abundance. Rates of increase in counts after the conventional regime was switched to a reduced input regime in spring 1997 (black bars in Fig. 2) varied among species. Counts of *I. viridis* under the reduced-input regime of F5 during May 1998 were the highest recorded in the study (Fig. 2c), indicating that this species was capable of recovering from negative effects of the previous conventional pesticide regime. For *E. nicoleti*, however, the pattern of catches suggests that virtually no recovery had occurred up to May 1998 (Fig. 2b). There are, however, limitations to the interpretation of collembolan recovery using these data, which are considered below (see Discussion).

In contrast to the situation in field F5, reversal of the pesticide regimes in BU in autumn 1997 did not result in obvious changes in the distribution of Collembola (Fig. 3). *Lepidocyrtus* spp. remained consistently most abundant in the west half of the field (Fig. 3a) whilst *P. octopunctata* remained most abundant in the east half (Fig. 3b). Counts of total Collembola provided no evidence for a response to the pesticide regimes, either when the regimes were first applied after harvest in 1990, or when they were spatially reversed after harvest in 1996 (Fig. 3e).

Effects of individual insecticides on collembolan abundance

The study was designed to investigate effects on arthropods of overall regimes of pesticide use rather than specific pesticide applications. Nevertheless, some effects of individual insecticide applications within the conventional regime were evident. In F5, large differences in counts of several species between the regimes occurred follo-

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Fig. 3. Collembola counts in suction samples in the east (■) and west (□) areas of field BU under pre-treatment (PRE), reduced-input approach (RIA) and conventional (CFP) regimes of pesticide use. The RIA and CFP regimes were reversed spatially in autumn 1996. Numbered arrows refer to Table 2 and show chlorpyrifos (c), cypermethrin (cy), dimethoate (d), gamma-HCH (g), and triazophos (t) insecticides (applied only under the CFP regime)

wing use of chlorpyrifos in January 1991, June 1994, March 1995 and April 1997 (Table 2; Fig. 2). These patterns are consistent with the known broad-spectrum toxicity of chlorpyrifos to Collembola (Van Straalen & Van Rijn 1998). Among *I. viridis*, *Isotomurus* spp. and *Sminthurinus elegans* (Fitch), differences between the pesticide regimes were larger following winter or spring applications of insecticides (1991, 1995, 1997) than those in summer (1992, 1993, 1994) (Fig. 2; Table 2). In field BU, markedly higher catches under the reduced-input regime were evident briefly for *S. elegans* when triazophos was applied under the conventional regime in June 1991 and for *I. viridis*, *S. elegans* and the total Collembola when dimethoate was applied in July 1992 (Fig. 3; Table 2). Transient negative effects of the conventional pesticide regime in BU thus occurred, even though the regime was apparently not detrimental to Collembola in the long term.

Discussion

The clear response of the collembolan fauna to spatial manipulation of the pesticide regimes in F5 shows that this method might be suitable for increasing confidence in the interpretation of pesticide effects where replication of treatments is not feasible. Before the pesticide regimes in BU were reversed, it was not possible to determine whether long-term differences in abundance of *Lepidocyrtus* spp. and *P. octopunctata* between the east and west half of the field were caused by the different pesticide regimes applied to these areas, as these species were not encountered during pre-treatment monitoring. The fact that distributions of *Lepidocyrtus* spp., *P. octopunctata* and the total Collembola were unaffected by reversal of the regimes in BU indicates that substantial effects of the conventional regime like those seen in field F5 were lacking, even though BU received more insecticides than F5 (Table 2). Possible explanations for the lack of long-term effects of conventional pesticide use in the cereals and break crops rotation of BU are: (1) All applications of broad-spectrum insecticides in this field were in summer or autumn. Data from F5 (see Results) suggest that winter or spring applications of insecticides may be more harmful, perhaps because less vegetation cover is available to moderate exposure of soil surface species to sprayed applications. (2) Cypermethrin, one of the insecticides applied under the conventional regime in BU, is not harmful to Collembola (Wiles & Frampton 1996; Frampton 1999). (3) Some species vulnerable to insecticides, for example *E. nicoleti*, were not present in the field. (4) In comparison with F5, a lower application rate of chlorpyrifos was used in BU (Table 2) (this reflects different chlorpyrifos label recommendations for control of grass and wheat pests).

Although the discussion here has focused on effects of insecticides, inputs of herbicides and fungicides also differed between the pesticide regimes. Some widely-used fungicides are harmful to Collembola (Frampton & Wratten 1999), including propiconazole which was applied to F5 on several occasions at higher rates under the conventional than the reduced-input regime; fungicide use might have contributed to the overall negative impact on Collembola counts of the conventional regime in F5. However, fungicide use also differed between the pesticide regimes in BU (Table 1), where no obvious long-term effects of the regimes were evident.

Experimental design

The point at which recovery occurs may be difficult to define, or even impossible if irreversible ecosystem 'evolution' occurs within the duration of a study or if background variation is high. It may be difficult therefore to decide what is acceptable as reference against which to measure recovery.

A possible experimental approach for investigating collembolan recovery which was considered initially would have been to keep the reduced-input regime in the same half of the field throughout the study as a reference treatment against which to judge recovery after the conventional regime was manipulated. This approach would have been inappropriate however because pesticide regime would be confounded with other variables which differed between the half-field areas; these included field boundary vegetation (Fig. 1) and collembolan counts, which for some species varied spatially within a field before the pesticide regimes were applied (G.K. Frampton, unpublished data). Spatial reversal of the pesticide regimes was chosen to overcome this problem, but the reversal approach does not provide a 'reference' treatment against which to gauge recovery following the change from conventional to reduced inputs. Instead, the data obtained under the reduced-input regime during 1991–1996 were used as an indication of likely variation in collembolan counts in the crop rotation, against which abundance after the conversion of the conventional regime to reduced inputs could be compared.

Collembolan recovery

It is clear that negative effects of the conventional regime upon *I. viridis* did not persist beyond one year after removal of the regime, as counts under the reduced-input regime in field F5 in 1998 (i.e. after conversion from the conventional regime) were the highest recorded for this species during the nine years of the study. Recovery of *I. viridis* in the west half of the field can be seen as a gradual increase in counts (black bars in Fig. 2c) in each season during 1995 to 1998. Perhaps it is significant that that no insecticides were applied in F5 under the conventional regime in 1996, which is when counts of *I. viridis* began to increase. In contrast, counts of *E. nicoleti* showed no evidence of increase when the conventional pesticide regime was changed to reduced inputs (Fig. 2b). It is worth noting however that in summer 1991, *E. nicoleti* was not encountered at all in field F5, suggesting that occurrence of this species may be temporally unpredictable. These results clearly endorse the need for long-term monitoring. Sampling will continue in F5 following reversal of the regimes (1997–1999) to clarify the temporal dynamics observed for *E. nicoleti* and other species. The ecological reasons for the inter-specific variation in recovery responses are not known at present and warrant further investigation.

Previous sampling of arthropods during the SCARAB Project (1990–1996), of which fields BU and F5 were part, showed that *E. nicoleti* and *P. octopunctata* each occurred in only one of eight fields which were monitored (Frampton 2000). For such spatially restricted species, within-field manipulation of the pesticide regimes as employed here would be the only feasible means of investigating their responses to the pesticide regimes.

Conclusions

Spatial reversal of pesticide regimes within individual arable fields is a potentially useful manipulative approach for confirming effects of pesticides on Collembola where replication of experimental treatments is not feasible. This method could be particularly useful where species of interest have restricted temporal or spatial distributions. Collembolan responses to reversal of conventional and reduced-input pesticide regimes in a grass and wheat rotation differed among species but the ecological reasons for this are not known and warrant further investigation. The fact that spatial distributions of some collembolan species were restricted within fields has implications for the design of field studies in which treatment comparisons are made at a subfield scale.

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