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Chapter 5

Large-Scale Monitoring of Non-Target Pesticide Effects on Farmland Arthropods in England: The Compromise between Replication and Realism of Scale

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Replication of experimental treatments is necessary for the unambiguous interpretation of pesticide effects on wildlife using statistical hypothesis testing but is incompatible with the large temporal and spatial scales required for a fully realistic field study. In this paper I consider the pros and cons of some large-scale experimental approaches used during the last two decades in England to investigate long-term effects of pesticide use on arthropods and other farmland wildlife. I present a potential solution to the trade-off between scale and replication in long-term studies which may be particularly appropriate for patchily-distributed species. Advantages of the recently-developed multivariate analysis method Principal Response Curves (PRC) for interpreting long-term effects of pesticides on arthropods at the community level are discussed.

Historical Perspective

During the 1970s, pesticide use on arable farmland in the UK increased rapidly [*1, 2*]. The number of active ingredients used, frequency of applications per season and incidence of the use of pesticide mixtures all increased at a time when the abundance of several taxa of non-target farmland arthropods was found to be in decline in southern England [*3*]. Most studies of the effects of pesticides on arthropods were single-season short-term investigations of individual pesticide applications. These provided valuable information on the risks posed by certain pesticides but could not detect long-term cumulative effects of repeated applications or effects of complex tank mixes. In 1979 a report to the UK Government by the Royal Commission on Environmental Pollution expressed concern "about the scale of pesticide use" and "the possibility of unforeseen and unforeseeable effects". The report gave a number of recommendations as to how pesticide effects research should progress to address these issues and proposed that reducing pesticide usage to the minimum consistent with agricultural objectives should be Government policy [*1*]. The report lent support to the concept of a large-scale study to examine the potential long-term effects of overall regimes of pesticide use on farmland wildlife which had been originally proposed in the mid-1970s [*4*]. Following a period of consultation to develop the best methodological approach, the Boxworth Project was initiated in 1981 under funding from the UK Ministry of Agriculture, Fisheries and Food (MAFF) [*4*].

Boxworth: a 1980s Farm-Scale Approach

The design of the Boxworth Project has been reported previously [*5*] and compared with those of other farming systems studies in western Europe [*6*] so here I refer only to aspects of the design which have a bearing on interpretation of pesticide effects. During the 'treatment phase' (1983-88), effects of three regimes of pesticide use were investigated upon birds, small mammals, invertebrates and plants. Each regime was applied to a discrete block of contiguous fields on a commercial winter wheat farm in eastern England. Two of the pesticide regimes ('Supervised', SUP and 'Integrated', INT) had managed inputs, applied in response to pest, weed or disease thresholds, whilst the third regime ('Full Insurance', FI) comprised prophylactic insurance use of pesticides, intended to mimic high-input commercial farming practice; FI had substantially higher pesticide inputs than SUP or INT [*7*]. The grouping of fields together under SUP (three fields, total 45.7 ha), INT (three fields, total 22.6 ha) and FI (four fields, total 53.2 ha) was necessary for realism of scale but precluded orthodox replication of the treatments [*7*]. A two-year 'baseline' period of pre-treatment monitoring (1981-82) was included in the Project to allow assessment of existing populations and permit the detection of any substantial changes in wildlife abundance at the start of the contrasting regimes.

The Project's design was geared towards detecting gross overall effects of pesticide use on wildlife in the long term rather than statistical testing of specific hypotheses concerning the pesticide regimes [*7*]. It was assumed that, given the large scale of the study, any substantial effects of pesticide use on wildlife would be detectable through intensive monitoring.

Boxworth's Limitations and Lessons

When the Project concluded in 1988 it was evident that the most substantial effects of the pesticide regimes had been upon arthropods. Negative and also some positive effects of the FI regime on abundance of several arthropod species were detected [*8, 9*]. Counts of some species of Carabidae and Collembola had declined sharply in FI fields relative to SUP and INT when the FI regime was initiated and these remained close to zero for the remainder of the treatment phase [*9*]. This endorsed the suitability of the Project's contiguous-field design for detecting at least major effects of pesticides. But the Project was limited in its geographical and agricultural coverage, raising questions as to whether the observed pesticide effects would also occur in other arable crops at other locations. The realism of the relatively inflexible FI regime at the end of the Project was also questioned as it had not kept pace with changes in farming practice during the 1980s. Lessons that emerged from the Boxworth Project included: (1) Different experimental scales are necessary for the study of environmental and economic impacts of pesticide use [*10, 11*]; (2) 'Baseline' monitoring is essential in an unreplicated long-term study [*9*]; and (3) The arthropod species most vulnerable to FI pesticide use were those characterised as having poor dispersal ability [*8*].

Implementing the Lessons : SCARAB in the 1990s

From the Boxworth Project came a need to determine whether the negative effects of intensive pesticide use on arthropods in wheat in eastern England would be likely in other crops and locations. In line with UK Government policy objectives there was also a need to investigate the economic consequences of reducing pesticide use. These questions required different scales of study and were addressed by two different MAFF-funded long-term projects during the 1990s: SCARAB (Seeking Confirmation About Results At Boxworth) was an environmental study with subsidiary economic monitoring whilst TALISMAN (Towards A Low Input System Minimising Agrochemicals And Nitrogen) was primarily an economic study with limited environmental monitoring [*6, 10-12*]. The focus of SCARAB was on arthropods; this permitted the use of smaller experimental areas than those used in the Boxworth Project. From an agronomic perspective, realistic experimental units for studying arthropods would be individual fields. However, heterogeneity of arthropod populations among fields at Boxworth indicated that within-field comparison of treatments would be preferable in follow-up studies [*11*]. SCARAB accordingly used a split-field approach for comparing effects of two pesticide regimes on arthropods. The regimes were: current farm practice (CFP), representing conventional practice but flexible in response to changes in pesticide use as indicated by pesticide usage surveys; and a reduced input approach (RIA), in which insecticides were avoided and use of other pesticide types minimised where possible.

SCARAB comprised eight fields, sited at three locations in England (Table 1) (two of the fields, ON and OS, were adjacent, with identical cropping and pesticide inputs; some previous references to SCARAB consider these as one field). Cropping in each field followed a rotation typical of the locality (Table 1). During a 'baseline' pre-treatment monitoring year (1989-90), both halves of each field received identical pesticide inputs (which approximated the RIA regime) to permit comparison of arthropod abundance in each half of the field before the contrasting CFP and RIA regimes were initiated at the start of the 1990-91 crop season. Pesticide inputs varied between years and fields according to cropping but to ensure long-term continuity each regime was applied to the same half of each field every year during 1991-1996. Arthropods were monitored on up to four occasions per month throughout the Project using pitfall trapping and suction sampling at matched locations in the CFP and RIA halves of each field; sampling details have been given previously [*13, 14*].

Table 1. Design of the SCARAB Project: during 1991-1996 each of the RIA and CFP pesticide regimes was applied consistently to one half of each field

Farm	Drayton		Gleadthorpe			High Mowthorpe		
	52.2°N 1.8°W calcareous clay		53.2°N 1.1°W stony sand			54.1°N 0.6°W calcareous loam		
Field (area)	F1 (11ha)	F5 (8ha)	BA (12ha)	NK (8ha)	SO (12ha)	BU (19ha)	ON (17ha)	OS (17ha)
Year:								
89-90	grass	grass	w-bar	beet	w-bar	w-bar	w-bar	w-bar
90-91	w-wht	grass	beet	s-bar	pots	rape	beans	beans
91-92	w-wht	w-wht	s-wht	w-bar	s-wht	w-wht	w-wht	w-wht
92-93	grass	w-wht	w-bar	beans	w-bar	s-bar	w-bar	w-bar
93-94	grass	grass	pots	w-wht	beet	beans	rape	rape
94-95	grass	grass	s-wht	w-barl	s-wht	w-wht	w-wht	w-wht
95-96	grass	grass	w-bar	beet	w-bar	w-bar	s-bar	s-bar

Note: w- = winter-sown; s- = spring-sown; wht = wheat; bar = barley; beet = sugar beet; pots = potatoes; beans = spring beans; rape = winter oilseed rape.

Results from SCARAB

During the period 1991-1996, overall RIA inputs of herbicides, fungicides and insecticides were, respectively, 48%, 53% and 100% lower than those of the CFP regime [*12*]. Abundance of several arthropod taxa, and the similarity of CFP and RIA arthropod communities, declined after individual CFP applications of broad-spectrum insecticides in most of the Project fields but recovery usually occurred within the same season [*15*]. Only Collembola exhibited persistent long-term differences between CFP and RIA regimes. This occurred in only two of the eight fields (BU and F5), where differences in abundance and species richness persisted from 1991 to the Project's end in 1996 (Figure 1; [*15*]).

In addition to effects of pesticides the project provided information on spatial and temporal distributions of arthropods (Table 2). For example, *Bembidion obtusum* Serville, *B. tetracolum* Say and *Pterostichus cupreus* (L.) (Carabidae) were absent from some fields, reflecting these species' preferences for different soil types, whilst *Pseudosinella octopunctata* Börner (Collembola) occurred only in one field (BU) throughout the Project (Table 2). These patterns of distribution are important for the interpretation and prediction of pesticide effects (see below).

Table 2. Summer occurrence of *Bembidion obtusum* (A), *B. tetracolum* (B), *Pterostichus cupreus* (C) (Carabidae) and *Pseudosinella octopunctata* (D) (Collembola) in the SCARAB project (May-July inclusive)

Field	F1	F5	BA	NK	SO	BU	ON	OS
Year:								
89-90	A C	A C	B	B	B	A	A	A
90-91	A C	A C	B	B	B	A D	A	A
91-92	A C	A C	B	B	B	A D	A	A
92-93	A C	A	B C	B	B	A D	A	A
93-94	A C	A C	B	B	B	A D	A	A
94-95	A C	A C	A B	B	B	A D	A	
95-96	A C	A C		A		A D	A	A

Note: Data are overall summer presence-absence records from two 7-day pitfall trap catches per month for Carabidae (n=16 traps) or one suction sampling per month for Collembola (n=8 samples); species were absent unless indicated.

Interpreting the SCARAB Findings

The long-term differences in the abundance of Collembola under the CFP and RIA halves of fields BU and F5 (Figure 1) at first appear consistent with long-term effects of the pesticide regimes. In F5, a link with pesticide use is evident when pre-treatment and treatment-phase data are compared (Figure 1a, 1b). Differences in collembolan abundance between the regimes in F5 were largest in years when the broad-spectrum OP insecticide chlorpyrifos was applied in winter or early spring under the CFP regime [*15*]. Patterns in the catches of individual collembolan species suggested that the repeated application of OP insecticides in consecutive seasons impeded recovery of some species [*14*]. In BU field however, long-term differences in collembolan distribution are less easily interpreted because the species which exhibited differences in abundance between the CFP and RIA halves of the field were not present in pre-treatment samples (Figure 1c, 1d). Furthermore, unlike the situation in F5, relatively few broad-spectrum OP insecticides were applied to BU under the CFP regime [*14*]. Obvious links between collembolan distribution and use of individual pesticides in BU were therefore lacking. At the end of the treatment phase of SCARAB in 1996, the possible influence of pesticide use on the spatial distributions of *Lepidocyrtus* spp. (Figure 1c) and *P. octopunctata* (Figure 1d) in field BU thus could nether be confirmed nor discounted.

Beyond SCARAB: the Recovery Study

In response to the results outlined above, the SCARAB project was continued in a modified form, the Recovery Study, to address two questions: (1) were the CFP and RIA pesticide regimes responsible for the long-term patterns of collembolan abundance observed in BU; and (2) how long would recovery take for species negatively affected by CFP pesticide use in F5, if the pesticide inputs were reduced ?

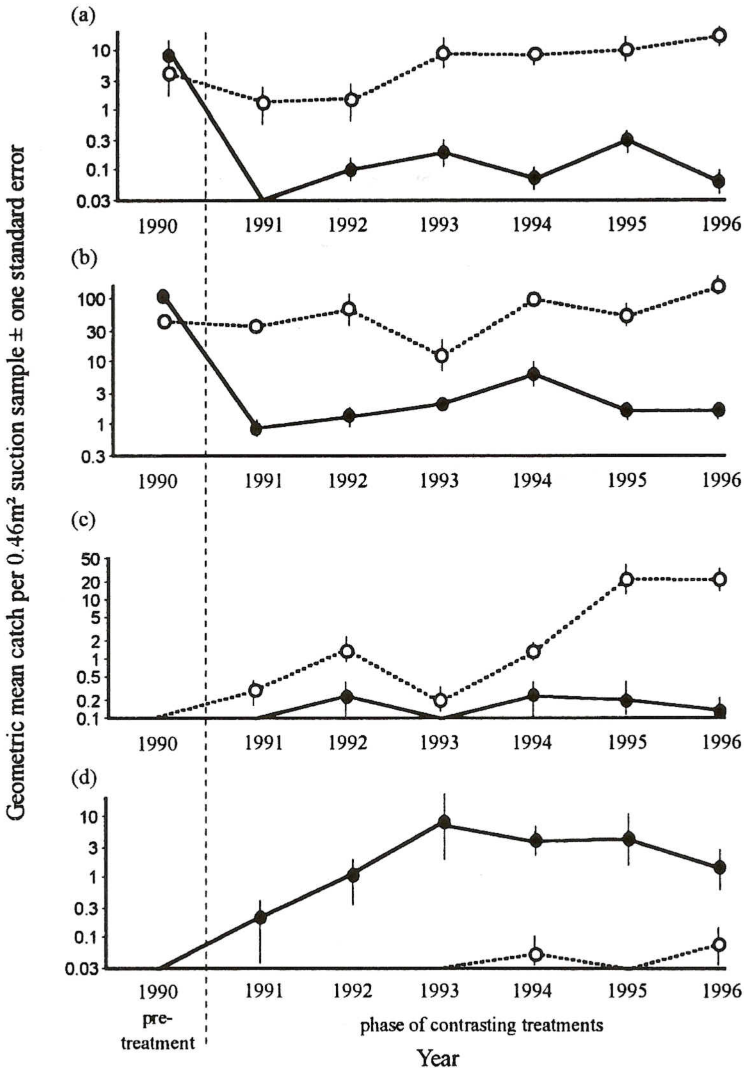

Figure 1. Collembola counts under CFP (•) and RIA (○) pesticide regimes in two SCARAB Project fields in summer (May-July inclusive), 1990-1996: (a) Entomobrya nicoleti in F5; (b) Lepidocyrtus spp. in F5; (c) Lepidocyrtus spp. in BU; (d) Pseudosinella octopunctata in BU (data from 8 to 24 samples per year).

An experimental approach to answer these questions commenced in autumn 1996. This involved spatial reversal of the CFP and RIA pesticide regimes in BU and F5 such that the half of each field formerly under CFP was switched to RIA pesticide inputs and *vice versa*. The rationale was that if the distributions of Collembola in BU (Figure 1c, 1d) resulted from pesticide use, changing the spatial arrangement of the pesticide regimes would cause changes in the collembolan distributions, though not necessarily immediately if effects were indirect. In F5, collembolan recovery would be expected when CFP pesticide inputs were replaced with the lower RIA inputs; results from SCARAB had raised the hypothesis that recovery rates would differ among species [*14*]. The Recovery Study ended in autumn 1999, allowing three years in which to detect any changes in arthropod distributions following reversal of the pesticide regimes. Here I report the latest results from the ongoing data analysis.

Manipulation of the pesticide regimes in F5 led to changes in the distribution of Collembola. When the RIA regime (no insecticides) was replaced with the higher inputs of CFP (which included insecticides), counts of several species declined (e.g. Figure 2a, 2b; [*16*]). Replacement of the former CFP regime with reduced inputs (RIA) led to little change in the abundance of *Entomobrya nicoleti* (Lubbock), indicating no discernible recovery by summer 1998 (cf. Figures 1a, 2a). However, recovery was evident for *Lepidocyrtus* spp. (cf. Figures 1b, 2b) and other species [*16*].

In field BU, counts of *Lepidocyrtus* spp. and *P. octopunctata* were generally low after 1996 but the previous distributions of these species (Figure 1c, 1d) did not exhibit any obvious change in response to spatial reversal of the pesticide regimes in autumn 1996 (Figure 2c, 2d). Highest counts of these species in BU were consistently in the same half of the field during 1991-1998, irrespective of which pesticide regime was applied to it. On the evidence of this preliminary data, the restricted spatial distributions of *Lepidocyrtus* spp. and *P. octopunctata* in BU thus appear to be independent of pesticide use.

Community Analysis: Principal Response Curves

The foregoing discussion has centred on the responses of individual species or genera to pesticide use but it would be helpful to know whether such lower taxa are important for the response of the arthropod community as a whole. Measures of species richness, similarity, diversity, trophic composition and total arthropod abundance differed between the CFP and RIA regimes of F5 [*15*] but such indices hide the relative contribution of individual species.

Multivariate analysis methods such as Redundancy Analysis (RDA) provide a means of summarising complex data sets and the resulting ordination diagrams show the relative contributions of species to the overall variance in the data [*17*]. However, changes in the size of treatment effects can be difficult to follow in an ordination diagram [*15*]. Principal Response Curves (PRC) analysis, which is based on RDA, has been developed recently to optimally display temporal changes in invertebrate communities in aquatic microcosm and mesocosm tests [*18-20*]. As the experimental design of the SCARAB Project was appropriate for PRC analysis, this technique was used to elucidate the response of the terrestrial arthropod communities to the CFP and RIA pesticide regimes. A full description of the PRC methodology is not possible here but is available in the literature [*18-20*].

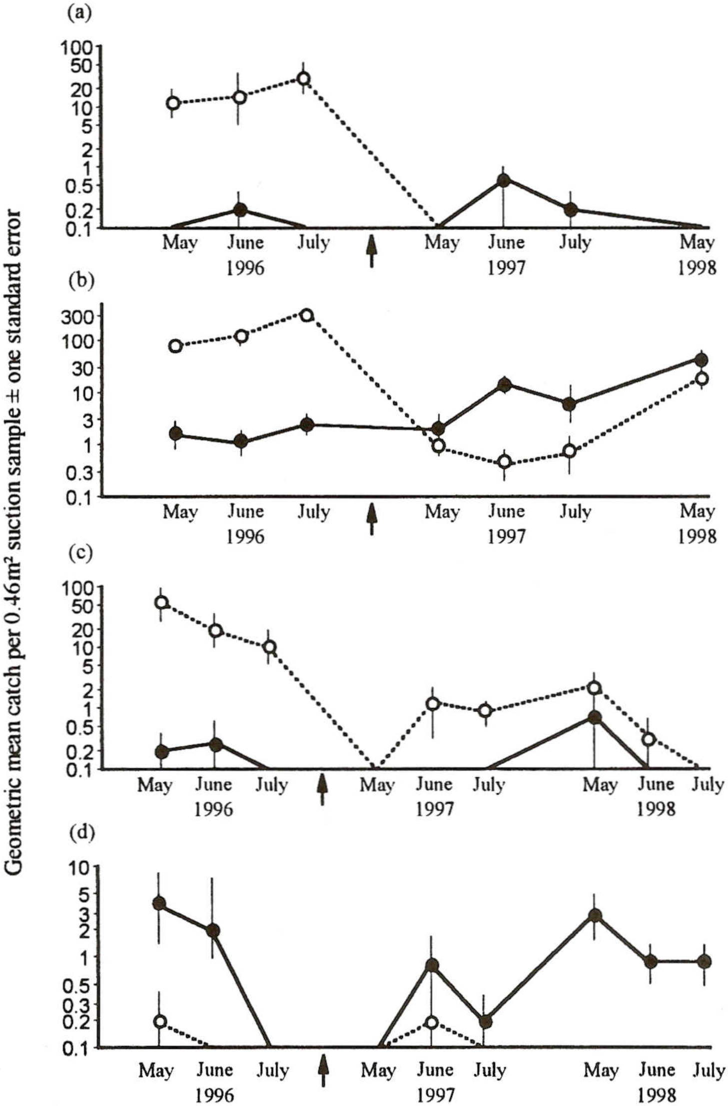

Figure 2. Collembola counts in two SCARAB Project fields under two patterns of pesticide inputs: CFP in 1991-1996 changed to RIA in 1997-1998 (•); RIA in 1991-1996 changed to CFP in 1997-1998 (○); arrows indicate timing of the changes. Species and fields (a)-(d) are the same as in Figure 1 (data are from 8 samples per month).

The model fitted by PRC analysis is: $y_{d(j)tk} = 0_{tk} + b_k \cdot c_{dt} + e_{d(j)tk}$, where $y_{d(j)tk}$ is the log abundance of species k in sample j of treatment d at time t, 0_{tk} is the mean log abundance of species k in the control (d=0), c_{dt} is the score of the d^{th} treatment at time t, b_k is the weight of the k^{th} species and $e_{d(j)tk}$ is an error term with mean zero and variance $\acute{o}_k^2$. For the SCARAB Project data, the RIA pesticide regime was nominated as the control treatment. By definition, $c_{0t} = 0$ for every t, i.e. the abundance counts are modelled as a count in the control plus a deviation, which is calculated for each treatment level at each sampling date. The time course of the deviations from the control forms the PRC for each level of treatment. The weight of a species b_k indicates how closely the actual abundance of a species relative to the control treatment resembles the fitted relative abundance predicted by the PRC diagram. In more formal ordination terms, a PRC diagram displays the first principal component (canonical coefficient) of treatment effects (c_{dt}) obtained algebraically from a partial RDA (*18-20*). By plotting each treatment d against sampling date t, temporal changes in the overall arthropod community response to experimental treatments are displayed. With PRC analysis the contribution of individual species to the overall community response may be interpreted numerically using the species weights obtained from the analysis [*18-20*].

After ln(2x+1)-transformation of suction-sampled arthropod counts x [*21*], PRC analyses were performed using the software program CANOCO 4 [*18*]. Means of transformed counts for May, June and July in each year were used. PRC diagrams are included here for three data sets obtained by suction sampling in F5: (1) all arthropods; (2) Collembola only; and (3) arthropods excluding Collembola (Figure 3). The PRC diagrams show that Collembola made an important contribution to the overall community response; negative values of c_{dt} for the CFP pesticide regime indicate an overall negative effect of the regime on arthropod abundance relative to the RIA regime, which was nominated as the reference treatment. For brevity, no attempt is made here to numerically interpret the contribution of individual taxa to the treatment effects displayed in Figure 3 (hence, species weights b_k are not given); PRC diagrams (Figure 3) are included here to illustrate the value of the PRC method in concisely summarising temporal changes in arthropod responses to the pesticide regimes, for which purpose the values of c_{dt} may be interpreted simply as indicating the deviation in relative abundance between CFP and RIA pesticide regimes. With Collembola data omitted (Figure 3b), the effects of the CFP regime were not persistent, indicating recovery had occurred following individual OP insecticide applications in each year.

Discussion

Three key findings from the Boxworth and SCARAB projects are: (1) Collembola are more vulnerable than other arthropods to effects of pesticide use in the long term; (2) spatial and temporal distributions of species may not be properly represented in small-scale studies; and (3) the most harmful type of pesticide use for arthropods is repeated application of organophosphorus insecticides in consecutive seasons

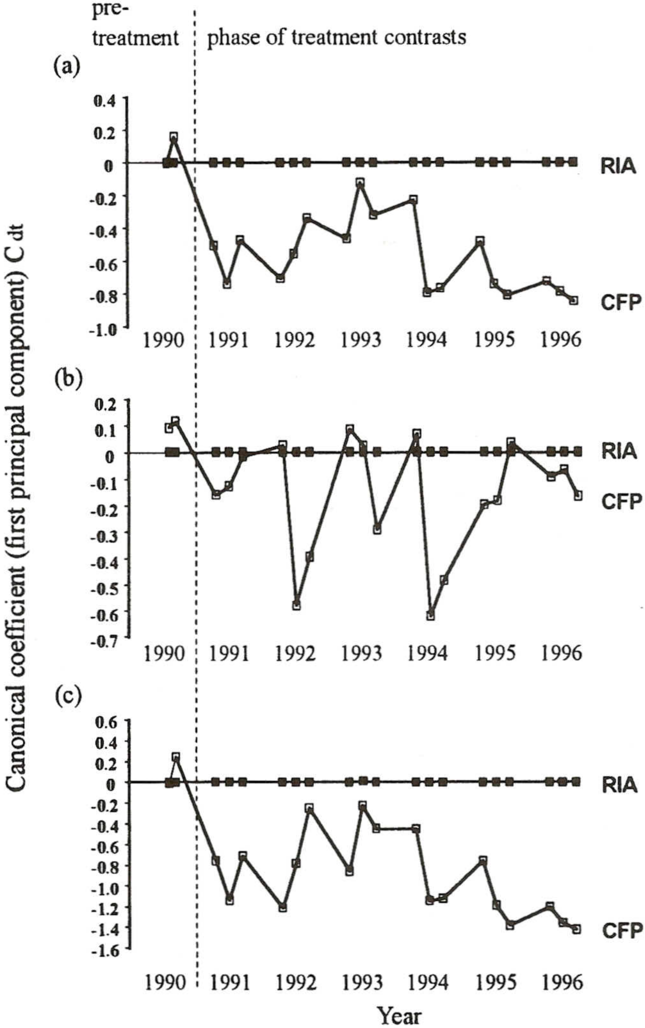

Figure 3. Principal Response Curves (PRC) diagrams summarising the response of arthropod communities in field F5 to Reduced Input Approach (RIA, reference treatment) and Current Farm Practice (CFP) pesticide regimes: (a) all arthropods; (b) arthropods excluding Collembola; (c) Collembola only. Values of C_{dt} *indicate the magnitude of the impact of CFP on abundance relative to RIA.*

Vulnerability of Collembola

The extensive literature on terrestrial arthropod responses to non-target effects of pesticides is biased heavily towards predatory species. Until recently hardly any work in Britain had investigated effects on Collembola of the most widely used insecticides [*22*] and fungicides [*23*]. Interpretation of pesticide effects on Collembola is difficult because, even though they may be the most abundant arthropods in temperate farmland, the ecology of many species is poorly known [*24*]. So, while the seasonal migration of carabid beetles into arable fields is a known to be major determinant of exposure and recovery, and hence vulnerability [*8, 9*], such information is lacking for Collembola. Only recently has the possibility that they may migrate seasonally into arable fields from non-crop habitats been addressed [*25*].

Recovery plays an important part in determining the significance of overall pesticide effects [*26*]; among predatory arthropods, rates of recovery depend upon species' dispersal ability and may be related inversely to the spatial scale of the experimental treatments [*27-29*], as well as other factors such as the distribution of source habitats for recolonisation and refugia from exposure [*30*]. Hypotheses to explain the slow recovery after long-term CFP pesticide inputs, e.g. of *E. nicoleti,* (Figure 2a) have yet to be tested but include: (1) poor dispersal ability at a field scale, resulting in slow recolonisation; (2) lack of a suitable source of recolonists in the vicinity; (3) low physiological potential for recovery once a population is depleted (e.g. low fecundity, either inherently or as an indirect result of pesticide use); or (4) indirect effects of pesticide use on collembolan interactions with other biota. Variation among species in recovery rates [*31*] could also reflect inter-specific variation in initial exposure to pesticide residues [*14*]. In this respect, the timing of applications appears to be important, as species with different temporal patterns of seasonal abundance may receive a different degree of exposure to a particular pesticide [*14*]. It has been established for predatory arthropods that dispersal ability and reproductive potential are important factors influencing recovery rates [*8, 9*] but such information is lacking for Collembola.

Importance of Species Distributions in Space and Time

The spatial and temporal distributions of species directly influence the interpretation of pesticide effects observed in the field. It seems to be a paradigm that species particularly vulnerable to effects of pesticide use are patchily distributed in farmland. The carabid beetle *Bembidion obtusum* is vulnerable to broad-spectrum insecticides [*8, 32*] but has a fragmented spatial distribution in Britain [*33*] and was absent from some fields in the SCARAB project (Table 2). *Pterostichus cupreus* is used as a bioindicator species in regulatory testing with pesticides [*34*] but is also patchily distributed in Britain [*33*] and was absent from most of the SCARAB project fields (Table 2). The collembolan *E. nicoleti* was vulnerable to the CFP regime of pesticide use in SCARAB but occurred almost exclusively in one field (F5). If vulnerable species are absent from a study site [*22*], effects of pesticides on the wider environment may be underestimated. Conversely, effects may be overestimated if vulnerable species present at a study site are not actually widespread in farmland and so would not normally be exposed to particular scenarios of pesticide usage. It is difficult to design field studies which encompass all the possible spatial and temporal distributions of potentially important species; even contiguous fields which shared the same cropping history, soil type and agrochemical inputs differed in their collembolan species composition [*22*].

In the SCARAB Project the absence of two species of interest during the pre-treatment period of monitoring in field BU (Figure 1c, 1d) suggests that a longer period of pre-treatment monitoring would have been desirable. However, the temporal unpredictability of some arthropods makes it difficult to know *a priori* when certain species will occur in a field. For instance, in field NK, *Entomobrya multifasciata* (Tullberg) quickly became abundant in samples during 1995 and 1996 after several years of absence [*14*]. To include a pre-treatment sampling period long enough in duration that such temporally unpredictable species are likely to be present would be impractical in most field studies where site availability and technical resources are at a premium. From an anthropocentric standpoint, availability of funding and the need for researchers to publish research papers do not weigh in favour of long-term studies [*35*], despite the need for such studies in ecology, as illustrated by the results from Boxworth, SCARAB and other projects [*3, 36, 37*].

Conclusions

Results from the SCARAB Project and Recovery Study show that spatial manipulation of pesticide regimes within a single field can provide valuable information on the responses of arthropods to pesticide use. This experimental approach was the only available means of confirming or refuting potential effects of the pesticide regimes on *P. octopunctata,* given that the species was not present during pre-treatment monitoring in the only SCARAB Project field in which it occurred. The manipulative approach as outlined here thus has potential value as a means of confirming effects of experimental treatments upon species which are highly restricted in spatial distribution.

The importance of Collembola in determining the response of the overall arthropod community to pesticide use was shown clearly using PRC analysis. This method has been used mainly in aquatic ecotoxicological studies to date but is also appropriate for summarising the long-term responses of terrestrial arthropods to effects of pesticide use. The next step in the analysis of the SCARAB Project and Recovery Study data will be to apply the PRC method to investigate how spatial reversal of the pesticide regimes affected the overall arthropod community. PRC analysis is well suited to the study of recovery because changes in the size of treatment effects over time are easily discerned from a PRC diagram (*18-20*).

Repeated use of OP insecticides in most years was the only scenario of pesticide use which had a long-term negative effect on arthropods, as a result of effects on Collembola, the most abundant taxon. This probably represents a worst-case scenario of pesticide use in Britain [15] but has direct relevance to cropping systems worldwide in which high usage of OP insecticides occurs.

Acknowledgements

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