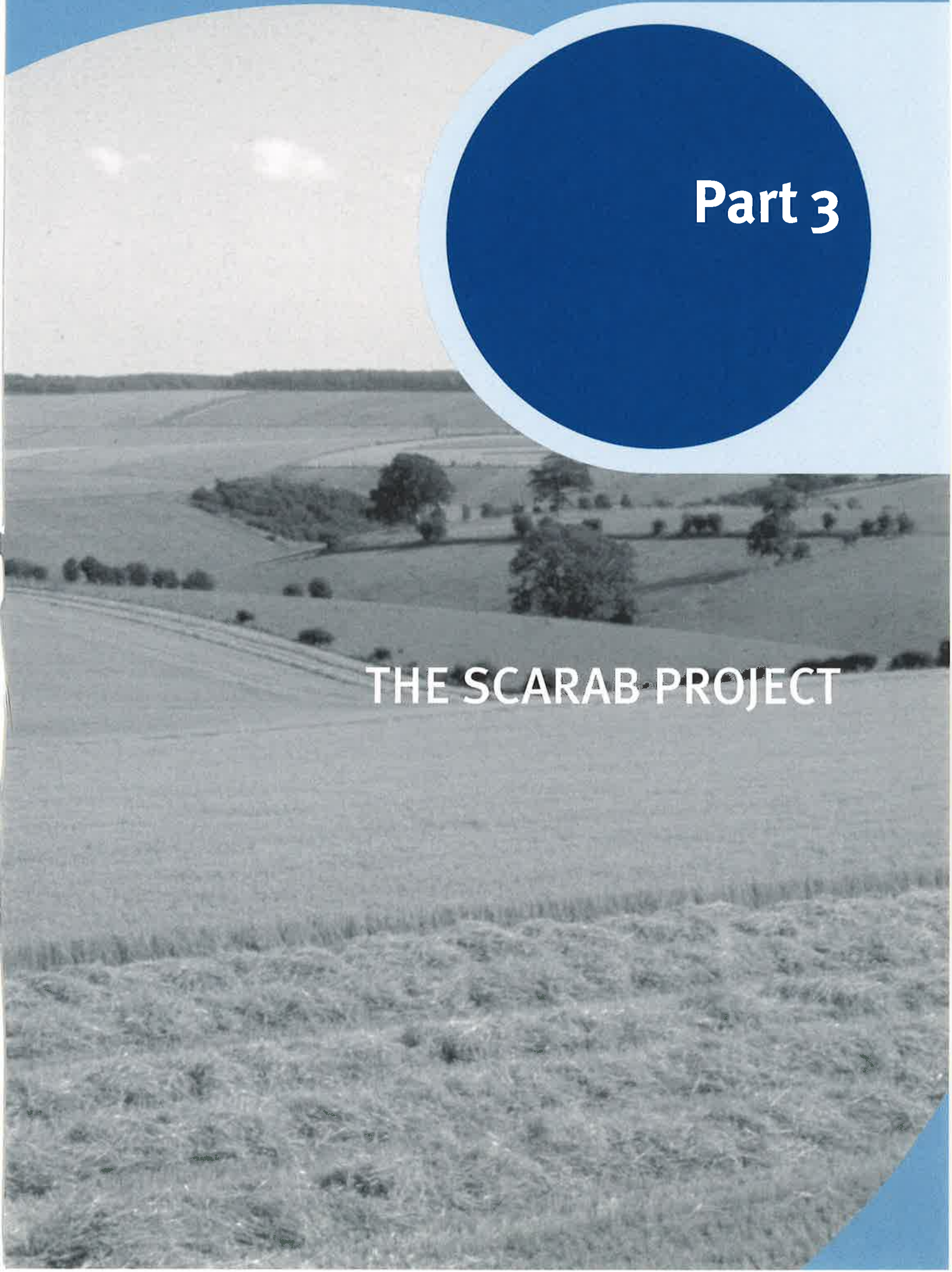
Part 3

THE SCARAB PROJECT



EXPERIMENT DESIGN, TREATMENTS, MONITORING AND PESTICIDE USE

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Design of SCARAB

The SCARAB Project was a multi-site, field-scale and long-term investigation of the ecological effects of two contrasting pesticide regimes in arable farming rotations (Cooper, 1990). SCARAB was designed to determine whether the environmental effects seen in the Boxworth Project (1981–88), particularly those on arthropod populations associated with intensive cereals (Greig-Smith *et al.*, 1992), were likely to occur under current commercial pesticide use, on different crops and in different locations. Information was also required on the long-term effect of current pesticide use on soil microbial biomass, earthworms, weeds, crop pests and diseases.

Experience gained during the course of the Boxworth Project helped to identify the major advantages and disadvantages of small and large plots for studies of farmland ecology. On the one hand, it is important to have large treatment areas, to reveal the effects on mobile species, or those for which there are large edge-effects at field margins. However, this restricts opportunities for replication, both for resource reasons and because it is more difficult to eliminate confounding factors (e.g. differences in soil type or drainage) when plots are larger.

The split-field design for SCARAB was chosen to provide the best compromise to meet the objectives of the experiment. Comparisons were made between paired plots, with each pair sited within a single field, chosen to be as uniform as possible in slope, soil type, field boundaries and other features. This was to eliminate the major problems caused by inherent field-to-field differences and to minimise any changes from one part of a field to another. Each pair of plots was located on a common boundary extending 150 m into the centre of the field (**Fig. 3.1.1**). This was to allow patterns of inward migration of arthropods from the field boundary to be traced. To avoid influences of the opposite boundary, fields were between 250 and 300 m in length. Plot width was 84 m, with a buffer zone of 36 m between the pair, and the outer edge of the plot was between 30 and 50 m from the field boundary at the side. These dimensions were chosen on the basis of information on arthropod migration into fields but were also adjusted to fit the fields available.

There were eight pairs of plots distributed among the three experimental sites. The various pairs of plots could not be regarded as replicates for the purpose of conventional statistical testing (using ANOVA, for example) because the habitats varied, the pesticide regimes were not identical, and the conditions of crop development could not be kept uniform. Instead, effects could be assessed simply by using a statistical test based on the number of pairs in which the difference between the two main treatments was in a particular direction. Similarly, the lack of replication meant that differences observed between the two plots could not be accorded formal statistical significance. Nevertheless, repeated sampling across plots provided a measure of variability which helped to interpret the likelihood of the differences being due to pesticides. Data from the ecological studies were analysed in different ways relevant to the types of organisms being studied. Details of these analyses are presented in the individual chapters.

Reducing Agrochemical use on the Arable Farm: The TALISMAN and SCARAB Projects.

Young J E B, Griffin M J, Alford D V, Ogilvy S E. [*eds*] 2001. London: DEFRA.

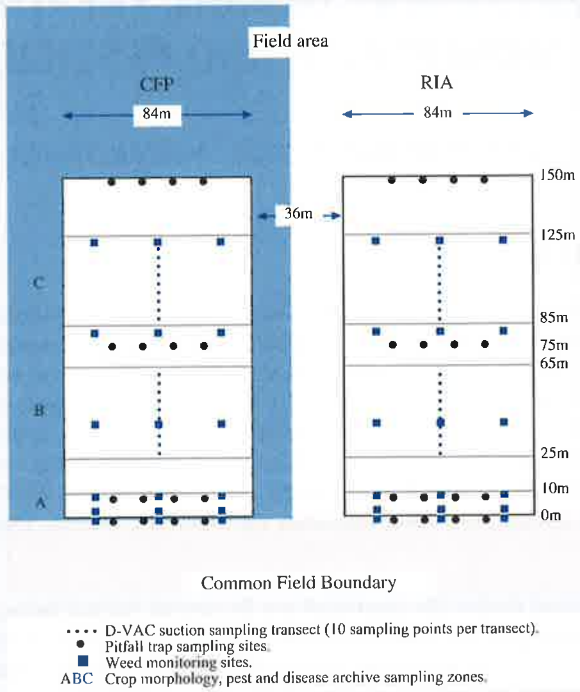

Figure 3.1.1. SCARAB site plan.

Duration

The SCARAB Project started with a baseline assessment in 1990, followed by six treatment comparison years, and the main project finished after harvest in autumn 1996. Additional studies to look at arthropod recovery rates continued in two project fields ('Field 5' at Drayton and 'Bugdale' at High Mowthorpe) in 1997, 1998, and finished after harvest in 1999.

Location of sites

The SCARAB project was sited on three ADAS research centres: Drayton in Warwickshire (now a MAFF centre); Gleadthorpe in Nottinghamshire; and High Mowthorpe in North Yorkshire (**Fig. 3.1.2**). The TALISMAN project was also located at Drayton and High Mowthorpe, which enabled complementary comparisons between the ecological and agronomic studies in both projects, and aided interpretation of the results seen at these particular sites. The three sites were chosen to provide soil type, cropping, geographical and climatical differences from the original Boxworth Project. Soil types ranged from a sandy loam at Gleadthorpe, through a shallow silty clay loam over chalk at High Mowthorpe, to a heavy clay at Drayton. Specific site details are given in **Table 3.1.1**.

Soil type influenced the cropping at each of the sites, with a wheat/grass rotation at Drayton, root and combinable crops at Gleadthorpe, and combinable crops at High Mowthorpe. Crops in the six-course rotations for each field at the three sites are shown in **Table 3.1.2**, and a summary of the number of crops grown is given in **Table 3.1.3**.

Field layout

At Drayton, a common hedge boundary separated 'Field 1' and 'Field 5', so that there was a pair of plots on each side of the hedge. At Gleadthorpe, all three pairs of plots were adjacent to different runs of hedge. 'South' and 'Balk' fields were next to each other, and a farm track ran on the other side of the hedge boundary for these two fields. 'Near Kingston' field was in a different part of the farm, and a conventional arable field was on the other side of the hedge. At High Mowthorpe, the pair of plots in 'Bugdale' was adjacent to a hedge, with a conventional arable field on the other side of the boundary. Two pairs of plots were situated in the large 30 ha 'Old Type' field. One pair was adjacent to the northern boundary of the farm which consisted of a mature wooded shelter belt; the second pair of plots, at the southern end of the field, was adjacent to a hedge with a permanent grass field on the other side. All the hedges in the study were composed predominantly of hawthorn (*Crataegus monogyna*).

Figure 3.1.2. Location of SCARAB sites.

Main treatments

The main treatment comparison in the SCARAB Project was between two contrasting pesticide regimes, conventional commercial use and a low input approach, termed Current Farm Practice (CFP) and Reduced Input Approach (RIA) respectively. The CFP pesticide regime was intended to be representative of pesticide use by a typical, technically competent, financially aware farmer in each site locality. Crop protection decisions were based on regular crop monitoring and each Site Manager's experience and knowledge of good agricultural practice, pest, disease and weed problems, together with the advice of a technical team of ADAS specialists (as detailed for TALISMAN in Chapter 2.1). If there was any doubt about whether a spray was justified, then a spray was applied. All pesticides applied to the CFP treatment were at label recommended rates and, where appropriate, the active ingredients chosen were those most commonly used on commercial farms, as defined by the most up to date Pesticide Usage Survey Report (PUSR) (Davis *et al.*, 1991; Davis *et al.*, 1993; Garthwaite *et al.*, 1995) during the course of the study. This was important as this study was meant to be representative of commercial pesticide use, so that the ecological effects seen at the three sites could be extrapolated to other arable farming situations.

The SCARAB CFP treatment was very similar to the TALISMAN Current Commercial Practice (CCP) pesticide treatment, with the exception that at least one insecticide was applied to each arable crop (excluding grass). This was to ensure that for the purposes of the ecological study, invertebrate populations were exposed to some of the insecticides that might be applied in commercial practice. In TALISMAN, insecticides were applied only when treatment thresholds were reached or a known pest problem was anticipated (see Chapter 2.1). The more prophylactic use of insecticides in SCARAB was to avoid the situation where no insecticides were applied throughout the six-year trial period because treatment thresholds were not reached. In the absence of damaging levels of a pest, a treatment was applied for the most commonly occurring pest for that crop in the site locality.

The RIA pesticide treatment was designed to be more benign than the CFP treatment on non-target arthropods. The objective was to apply no insecticides to the low-input-treatment plots. The same herbicides and fungicides as used on CFP were applied to RIA but at reduced rates, or omitted altogether depending on the risk of loss of crop yield or value. In situations where potential losses from lower inputs were expected to exceed 10%, full-rate treatments of herbicides or fungicides were applied. Conversely, if there was any doubt about whether a spray was justified, then it was not applied. Seed treatments containing insecticides were avoided, whereas fungicide seed treatments were considered on the same criteria as fungicide sprays. The overall intention was to apply a lower level of herbicides and fungicides in RIA than in CFP to each crop in the rotation, although it was recognised that this would not always be feasible in some crops (e.g. potatoes and sugar beet) without substantial crop losses. The philosophy behind the RIA treatment in SCARAB was ecologically driven and was therefore quite different to that of the LIA pesticide treatment in TALISMAN, which required a 50% or greater reduction in the use of pesticides in all groups, in order to examine the agronomic and economic effects of lower inputs (see Chapter 2.1).

Crisis management

Although a limited loss in yield and quality from omitting insecticides was considered acceptable in RIA plots, severe reductions in plant or shoot density were regarded as undesirable because the habitat and hence the abundance or activity of mobile predatory insects could differ between the paired plots. Extreme crop loss could also jeopardise the credibility of the experiment in the perception of some farming interests. As an alternative to using the same insecticide application as in CFP, the protocol permitted reduced rates or use of more specific insecticides (e.g. pirimicarb) in the event of a crop-threatening situation. Such events were very infrequent, as will be discussed later in this chapter.

Pesticide decision-making

Treatment decisions were taken by the Site Managers in consultation with a Technical Management Team (TMT) comprising various ADAS Consultants with specialist expertise. A telephone conference call was held at regular intervals to assist in the decision-making process.

At the start of each cropping season, a list of expected weed, pest and disease problems and likely treatments, including seed treatments, was reviewed as a basis for discussion with the TMT. This was to ensure that the most appropriate pesticide treatments were selected, that treatments were compared with survey results to ensure commercial relevance, and that the same pesticide was used for common problems at each site. Pesticide applications were then refined or omitted according to the incidence of weed, pest and disease problems recorded during routine crop monitoring and during conference-call discussions with the TMT.

Standard field crop walking techniques were used in each split field area, not just in the designated plot sampling areas. Site Managers were provided with detailed guidelines of potential pest and disease problems, with likely timings and sampling techniques, to determine if treatment thresholds were reached. Weed numbers and species were assessed on the split field basis at critical timings for treatment decisions in the autumn and spring. When treatment thresholds were not available, CFP treatment decisions were governed by the experience and knowledge of the Site Managers, together with the specialists on the TMT.

Once a decision was made to apply a pesticide to the CFP treatment, a parallel decision was taken to omit or apply an equivalent low- or full-rate application to the RIA. As discussed above, no insecticides were permitted in RIA, unless there was a crop-threatening crisis. In most situations, a lower rate of the CFP herbicide or fungicide treatment was applied to RIA, usually at 50% of the label rate and at the same time as the CFP treatment. Plant growth regulators (PGRs) were permitted where there was a high risk of lodging in wheat or barley crops. There was no planned differential approach to the use of PGRs in SCARAB, as it was considered important to maintain a comparable crop canopy structure between the two treatments to minimise crop effects on non-target invertebrates.

Full details of pesticide use in SCARAB are given later in this chapter and in **Appendix Tables 3.1.1 – 3.1.8**.

General agronomy

The plot sampling areas were superimposed onto conventionally drilled or planted farm crops. Crops were established perpendicular to the field boundary in most situations, except for the headland area which was drilled or planted parallel to the boundary. With the exception of the pesticide treatments, all the other choices, field operations and applications, including varieties, cultivations, previous crop residue disposal, drilling date, seed rate and fertiliser use were standard across the whole field, and were determined on the basis of routine site practice and the advice of the TMT. Pesticide treatments were applied to split-field areas with conventional farm equipment, using standard nozzles, pressure settings, water volumes, forward speeds, heights above crop etc., as recommended on the individual pesticide labels.

Field boundaries adjacent to both plot sampling areas were managed uniformly. Traffic along the boundary headland was limited to farm operations only, and kept to a minimum. Plots were accessed for sampling purposes from the mid-field end of the plot.

Monitoring

Crop morphology

Routine crop assessments covering plant population counts, fertile tillers or stems, crop growth and ground cover, pest, disease and weed incidence were assessed at the appropriate growth stages for each crop, in the three sampling zones (A, B, C) of each plot sampling area (**Fig. 3.1.1**). Yields were assessed on whole plot areas for combinable crops and from sub-samples of plots for potatoes, sugar beet and grass.

Weeds

Weeds were monitored at three timings in each crop, in each year: early crop establishment; crop established but before canopy closure; and pre-harvest (mid-July to early August). Assessments were done on three transects into the crop, at right angles to the field boundary (**Fig. 3.1.1**). One 0.1 m^2 quadrat was assessed at each sampling point, at the following distances into the crop from the field boundary on each transect: 2.5, 10, 40, 80 and 120 m. The number of plants in each species present was counted and the size of plants was recorded, based on the Zadoks growth stage (Tottman & Broad, 1987) or the BCPC code for broad-leaved weeds (Lutman & Tucker, 1987).

Arthropod monitoring

Arthropod species were sampled in all of the SCARAB test fields by two standard techniques, suction sampling using a Dietrick vacuum insect sampler (D-vac) (Dietrick, 1961) and pitfall trapping. The D-vac was used to estimate the density of pest species, predators, parasitoids and hyperparasitoids and other non-target arthropods. Samples were taken along a transect down the centre of each plot, perpendicular to the field boundary (**Fig. 3.1.1**), starting 25 m into the crop up to a distance of 125 m. Within each plot, and on each sampling occasion, four samples, each of five randomly placed sub-samples of 0.092 m^2 (D-vac nozzle sampling area), were taken. Samples were collected at intervals of approximately 14 days from the end of April until October, and with reduced frequency at other times of the year.

Pitfall traps were used to provide estimates of the numbers and activity of the carabid and staphylinid beetles, adult spiders and other ground-zone predators. White plastic beakers, 9 cm in diameter and 15 cm deep, were placed in plastic outer sleeves and were set into the soil so that the rim of the beaker was flush with the soil surface. Traps contained water and detergent, and were fitted with wire mesh inserts to prevent small mammals and birds falling into the traps. The traps were located along transects situated in the field boundary, in the headland (10 m) and at distances of 75 m and 150 m into the crop (**Fig. 3.1.1**). Four traps were placed along each transect, 12 m apart. Traps were operated one week in two, whenever possible. They were taken out at harvest and were replaced after the next crop was sown or after autumn cultivations for a spring-sown crop. Full details of the arthropod monitoring are given in Chapter 3.2.

Biomass monitoring

The effects of the CFP and RIA pesticide regimes on soil biomass were monitored only on selected fields: 'South' and 'Balk' fields at Gleadthorpe and 'Old Type North' and 'Old Type South' at High Mowthorpe. These fields were chosen because they provided contrasting soil types, with similar crop rotation systems. Soil sampling occasions were determined by the pesticide applications on the fields, with samples taken pre-treatment and seven days post-treatment. Six samples, each of 1 kg from 2 cm to 10 cm depth, were taken from the plot areas at intervals of 10 m on an oblong grid pattern. Full details of the biomass monitoring and assessments are given in Chapter 3.3.

Earthworm monitoring

Earthworm populations and biomass were not monitored from the outset, as this study was proposed after the start of the main project. Sampling commenced in spring 1993 and continued until spring 1996. All SCARAB fields were sampled twice a year, in the spring and autumn. On each sampling occasion, three sub-samples of 0.25 m^2 were taken at random from each field plot but outside of the designated plot sampling area, because of the destructive nature of the sampling technique. A combination technique of hand-digging and sorting to plough depth, followed by formalin drenching, was adopted. Full details of the earthworm monitoring and pesticide residue assessments are given in Chapter 3.4.

Pesticide use

As with TALISMAN (see Chapter 2.1), reference to general pesticide use includes applications of herbicides, fungicides and insecticides applied as sprays or granular applications. Seed treatments are dealt with separately, and plant growth regulators are not included in the general pesticide use data, as they were used infrequently, with no difference between CFP and RIA. In addition, the insecticide data include all applications of nematicides. No molluscicides were used in this study, as thresholds were not reached in the study phase. Pesticide use is quantified throughout by the use of 'pesticide units', where one unit equals one full-rate application of an active ingredient, as given on the product label for the specific use in question.

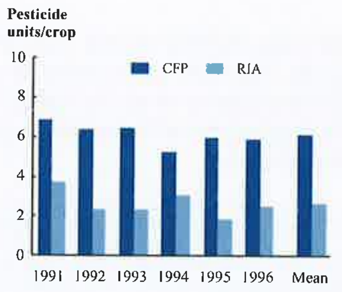

Figure 3.1.3. The effect of treatment regime on yearly pesticide use (all groups) on SCARAB crops. CFP: Current Farm Practice. RIA: Reduced Input Approach.

Unlike TALISMAN, there was no specific reduction target for pesticide use in SCARAB. However, no insecticides and low rates of herbicides and fungicides were to be used in RIA. Overall, 57.7% fewer pesticide units were applied to RIA compared with CFP. The average yearly pesticide use in CFP ranged from 5.2 to 6.8 units per crop (**Fig. 3.1.3**). Yearly reductions in use in RIA ranged from 42.3 to 69.5%. The smallest reductions occurred in 1991 and 1994, when sugar beet and potatoes were grown at Gleadthorpe.

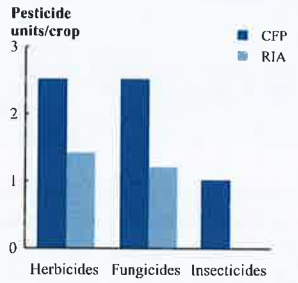

Figure 3.1.4. The effect of treatment regime on pesticide use by group on SCARAB crops. CFP: Current Farm Practice, RIA: Reduced Input Approach.

No insecticide sprays or granular applications were used in RIA, and herbicide and fungicide sprays were reduced by 43% and 52% respectively (**Fig. 3.1.4**). Average pesticide use per crop varied between the sites, with least being used on the grass-dominated rotation at Drayton, and most on the root and combinable crop rotation at Gleadthorpe (**Fig. 3.1.5**). Greater reductions were achieved in the use of fungicides than herbicides at all sites. Insecticide use in CFP averaged just over one unit per crop at Gleadthorpe and High Mowthorpe. However, less than one unit was used at Drayton, because not every grass crop was treated with an insecticide.

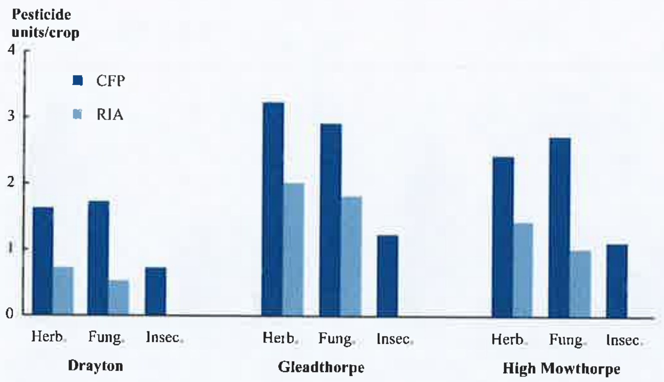

Figure 3.1.5. The effect of site and treatment regime on pesticide use by group in SCARAB crops. CFP: Current Farm Practice. RIA: Reduced Input Approach.

Effect of crop type on pesticide use

Cereals

CFP pesticide use was greatest on the wheat crops at Drayton and least on the barley/wheat crops at Gleadthorpe (**Fig. 3.1.6**). The average number of units applied to winter wheat was 8.3 per crop on CFP, the highest for all the cereal crops, with a 63.9% reduction in RIA (**Table 3.1.4**). The highest insecticide use of 1.5 units per crop was on the spring wheat crops at Gleadthorpe.

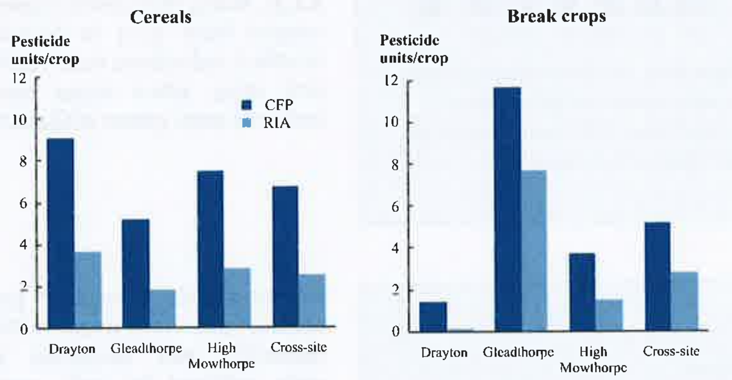

Figure 3.1.6. The effect of site and treatment regime on pesticide use (all groups) in SCARAB cereals and break crops. CFP: Current Farm Practice. RIA: Reduced Input Approach.

When overall pesticide use on cereals in SCARAB was compared with commercial use in the 1990 and 1996 PUSRs (Davis *et al*., 1991; Thomas *et al*., 1997), the CFP use was closer to the lower 1990 results (**Fig. 3.1.7**). Commercial use of herbicides and fungicides has increased over the period of the project, whereas use of insecticides has declined. SCARAB CFP insecticide use was higher than commercial usage in both survey years, reflecting the moderately prophylactic use of at least one insecticide per cereal crop in the study. Herbicide use was lower than commercial practice, whereas fungicide use was comparable with 1990 but lower than 1996 commercial use. The intensive monitoring and use of up-to-date specialist advice would suggest that inputs to CFP in SCARAB were more appropriately tailored to crop requirements than commercial practice.

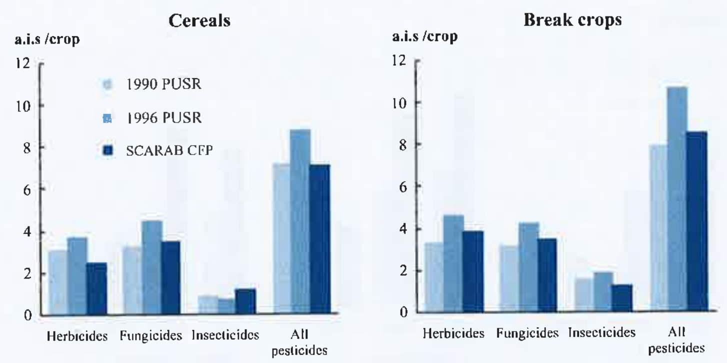

Figure 3.1.7. The average number of active ingredients (including repeat applications of the same a.i.) applied to cereal and break crops in SCARAB Current Farm Practice (CFP), compared with MAFF Pesticide Usage Survey Report (PUSR) data for equivalent cereal and break crops.

Break crops

Use of pesticides on break crops was dominated by the crops grown on each site, from the very low use on the grass leys at Drayton, moderate use on the winter oilseed rape and spring bean crops at High Mowthorpe, to the relatively heavy use on the potato and sugar beet crops at Gleadthorpe (**Fig. 3.1.6**). An average of 14.9 units, which were mostly fungicides for potato blight (*Phytophthora infestans*) control, was applied to the CFP potato crops, with only an 18.8% reduction in RIA (**Table 3.1.5**). The sugar beet crops received an average of 11.7 units per crop, which mostly comprised repeated low-dose herbicide treatments. (Each low-dose herbicide application was regarded as one pesticide unit for the purposes of this study, as this gave comparative data to the PUSRs, which record the number of active substances applied to crops including repeat applications of the same active substance.) Pesticide use on RIA sugar beet crops was 44.4% lower than CFP. Greater reductions in pesticide use of 60.0, 65.2 and 92.9% were achieved on the spring bean, winter oilseed rape and grass crops respectively.

Data in **Figure 3.1.7** are presented for the arable break crops only, and exclude the grass crops. Average herbicide and fungicide use on the CFP winter oilseed rape, spring bean, potato and sugar beet crops was in between the comparative data for these crops for the 1990 and 1996 PUSR years, whereas insecticide use on CFP was lower than survey use in both years.

Commercial use of pesticides on grass (less than five years old) averaged 0.1 insecticide, 0.3 fungicide and 2.3 herbicide applications in the 1993 PUSR (Thomas & Garthwaite, 1994) whereas for CFP in SCARAB, more insecticide was used (0.5 units), more fungicide (0.6 units) and less herbicide (0.3 units) (**Table 3.1.5**).

Seed treatments

The number of seed treatments used in CFP and RIA is detailed in **Table 3.1.6**, and the active ingredients used are listed in **Appendix Table 3.1.8**. Fungicides were the most common seed treatment used, and tended to be applied to both CFP and RIA crops, with the exception of the RIA potato crops at Gleadthorpe. The fungicide seed treatment was also omitted from RIA on one wheat crop at Drayton, and on one oilseed rape crop at High Mowthorpe.

An insecticide seed treatment was used on one spring wheat crop (CFP only) and three CFP oilseed rape crops. The RIA oilseed rape seed in 'Old Type' field, north and south, in 1994, was also treated with an insecticide, to prevent a crop-threatening attack of flea beetle (*Phyllotreta* spp.)at establishment. This was the only insecticide treatment to have been used on any RIA crop throughout the study, and was within the treatment rules of the project (see *Crisis management*, earlier in this chapter).

Herbicide and fungicide use

Full details of the herbicide and fungicide active ingredients used in SCARAB are given in **Appendix Tables 3.1.1 – 3.1.8.** For these two groups of pesticides, choice of active ingredient was primarily determined by the weed species present at each site and the presence or expected threat of a particular disease respectively, rather than choice of the most commonly used active ingredient from survey data.

Insecticide and nematicide use

Specific details are given in this section on the individual active ingredients used for this group of pesticides because of the importance of their effects on non-target invertebrates – the main theme of this study, as highlighted by the results of the Boxworth Project (Greig-Smith *et al.*, 1992). The scientific names for all invertebrate pest species mentioned in the following section are listed in **Tables 3.1.7 – 3.1.9**. In most situations, excluding grass, only one insecticide was applied per crop per year (**Tables 3.1.7 – 3.1.9**).

Cereals

The most common treatment for winter wheat in SCARAB was dimethoate for summer aphid control; pirimicarb was also used on one crop at Gleadthorpe for the same reason. Two wheat crops at Drayton received autumn applications of deltamethrin to control aphid vectors of barley yellow dwarf virus (BYDV), and one crop at High Mowthorpe was treated with chlorpyrifos to control orange wheat blossom midge. The spring wheat crops at Gleadthorpe generally received more than one insecticide treatment because of the high risk of wheat bulb fly damage at this site, plus problems with orange wheat blossom midge or aphids in summer.

All the winter barley crops were treated conventionally with cypermethrin in the autumn to prevent aphids spreading BYDV. Two spring barley crops were treated with dimethoate to control summer aphids, and one received chlorpyrifos in the spring to control wheat bulb fly.

Break crops

Winter oilseed rape seed in CFP at High Mowthorpe was treated with gamma-HCH to prevent flea beetle damage (one RIA crop was also treated to prevent crop loss); triazophos was applied to crops post-flowering to control cabbage seed weevil and brassica pod midge. Spring beans were either treated with cypermethrin to control pea and bean weevil or pirimicarb to control black bean aphid. Potato crops at Gleadthorpe were treated with pirimicarb to prevent feeding damage by summer aphids. All the sugar beet crops received a granular application of aldicarb to control migratory nematodes; one crop was also sprayed with pirimicarb to control aphids, and in 1996, cypermethrin was used on one crop following an attack of silver y moth larvae.

Insecticide use on grass at Drayton was less frequent than for the arable crops because, in Great Britain, less than 5% of the total grass area under five years old is treated commercially with insecticides (Thomas & Garthwaite, 1994). Chlorpyrifos was applied to an established grass ley in 'Field 5' to control an above-threshold population of leatherjackets. When grass was re-established in this field after two wheat crops, chlorpyrifos was used again in 1994 and 1995 for the same target pest, and also to see if the effects on non-target arthropods seen after the 1991 application would be repeated (see Chapter 3.2). Only one insecticide, omethoate, was applied to the newly established grass ley in 'Field 1' in 1993 to prevent frit fly damage.

Commercial use

When compared with commercial use of insecticides detailed in the PUSRs (Davis *et al.*, 1991; Davis *et al.*, 1993; Thomas & Garthwaite, 1994; Garthwaite *et al.*, 1995; Thomas *et al.*, 1997; Garthwaite *et al.*, 1999) (**Table 3.1.10**), the insecticides used in SCARAB were among those most commonly used on farm crops. Some of the newer insecticides, such as lambda-cyhalothrin and esfenvalerate, were not used in the study, although their treated area on commercial crops increased rapidly up to 1996 (Thomas *et al.*, 1997). Commercial use of some insecticides fluctuated greatly between survey years, indicating the seasonal response to control of specific pests, e.g. the use of chlorpyrifos in 1994 increased nearly seven-fold from 1992 because of a resurgence of orange wheat blossom midge incidence in winter wheat in that year.

Discussion

As outlined at the beginning of this chapter, the aim of SCARAB was to assess the ecological impact of two contrasting pesticide regimes on a range of crops in different locations, and to test whether the adverse effects on non-target invertebrates seen in the Boxworth Project (Greig-Smith *et al.*, 1992) were relevant under commercial practice in the 1990s. The SCARAB CFP treatment was comparable with the Boxworth Project Supervised treatment in terms of the number of pesticide units applied and the threshold-based approach to treatment. Although the Boxworth Project Supervised treatment had much lower inputs than the Full Insurance approach in the same project, it was difficult to assess the full ecological effects of the Supervised treatment, as insecticides and molluscicides were used when required (Greig-Smith *et al.*, 1992) (**Table 3.1.11**). The RIA treatment was designed to be more environmentally benign than the Boxworth Supervised treatment, by having no insecticides and lower levels of other pesticide inputs, whereas the Low Input Approach (LIA) treatment in TALISMAN was used to measure the agronomic and economic effects of lower inputs (Cooper, 1990; see also Chapter 2.1).

The omission of insecticides (with the exception of one seed treatment) and the substantially reduced inputs of fungicides and herbicides on 48 crops in RIA have provided a suitably different pesticide regime to the commercial practice CFP treatment, without producing substantially different crops. It is recognised, however, that the RIA treatment will have reduced the yield and gross margin potential of some of the crops (see Chapter 3.6).

The pesticides used in SCARAB were comparable with those used on commercial crops, as detailed in the PUSRs. However, pesticides were applied to the SCARAB CFP treatment at label recommended rates in contrast to commercial practice, where reduced dose rates, especially for fungicides and herbicides, are being increasingly used.

The key points relating to pesticide use in SCARAB are as follows:

- No insecticide sprays or granular applications were used in the RIA treatment, but one insecticidal seed treatment was used on oilseed rape to prevent a crop failure.
- Herbicide use was reduced by 44% over all crops.
- Fungicide use was reduced by 52% over all crops.
- Potatoes and sugar beet received the greatest number of active ingredient units in the CFP treatment (14.9 and 11.7 units respectively), followed by winter wheat at 8.3 units per crop.
- CFP pesticide use in SCARAB was lower than the Boxworth Project Insurance treatment for wheat, especially for insecticides (1.1 active ingredient units and 5.2 product units respectively), but was comparable with the Supervised treatment (0.8 product units).
- CFP pesticide use was comparable with Pesticide Usage Survey data in terms of the number of active ingredient applications used on crops, but it is recognised that dose rate was likely to be higher on CFP than in commercial use.

- Herbicide and fungicide product choices were more dependent on crop, target, soil type and local influences at each site but were still representative of commercial use.

- Insecticides used in CFP were in general those most commonly used by commercial farmers, e.g. cypermethrin for autumn aphids and dimethoate for summer aphids in wheat.

- The RIA treatment provided a sufficiently low pesticide regime to allow the ecological effects of commercial pesticide use to be assessed without the distortion of major crop effects that may have arisen from a nil pesticide regime.

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Table 3.1.1. SCARAB site details, pre-treatment soil analysis and previous cropping.

	Drayton		Gleadthorpe			High Mowthorpe	
Field name	Field 1	Field 5	Balk	Near Kingston	South	Bugdale	Old Type N & S
Soil series	Haselor/ Evesham	Haselor/ Drayton	Cuckney & Wick	Cuckney & Wick	Cuckney & Wick	Panholes	Panholes
Soil texture	Heavy clay		Loamy sand/sandy loam			Silty clay loam	
Drainage	Good		Very good			Very good	
Soil analysis (1990)							
pH	7.7	7.3	7.0	7.6	7.4	7.4	8.2
P index	0	1	3	3	2	3	3
K index	3	3	1	1	1	1	2
Mg index	4	5	2	3	3	1	1
Organic matter %	4.7	4.8	1.8	1.8	1.6	4.4	5.4
Previous cropping							
1990	Grass	Grass	W. barley	Su. beet	W. barley	W. barley	W. barley
1989	Grass	Grass	W. barley/ rye	W. wheat	W. wheat	W. wheat	W. barley
1988	Grass	Grass	W. barley	Potatoes	W. oilseed rape	W. oilseed rape	W. Wheat/ W. barley
1987	Grass	Grass	S. barley	S. barley	W. barley/ rye	W. barley	W. wheat
Field size (ha)	11.1	8.3	12.0	7.5	11.5	15.0	30.0

W, Winter; S, Spring; Su, Sugar.

Table 3.1.2. SCARAB crop rotations.

Site and year	Field name		
Drayton	**Field 1**	**Field 5**	
*1990**	*5th grass ley*	*4th grass ley*	
1991	W. wheat	5th grass ley	
1992	W. wheat	W. wheat	
1993	1st grass ley	W. wheat	
1994	2nd grass ley	1st grass ley	
1995	3rd grass ley	2nd grass ley	
1996	4th grass ley	3rd grass ley	
Gleadthorpe	**South**	**Balk**	**Near Kingston**
*1990**	*W. barley*	*W. barley*	*Su. beet*
1991	Potatoes	Su. beet	S. barley
1992	S. wheat	S. wheat	W. barley
1993	W. barley	W. barley	S. beans
1994	Su. beet	Potatoes	W. wheat
1995	S. wheat	S. wheat	W. barley
1996	W. barley	W. barley	Su. beet
High Mowthorpe	**Bugdale**	**Old Type (North)**	**Old Type (South)**
*1990**	*W. barley*	*W. barley*	*W. barley*
1991	W. oilseed rape	S. beans	S. beans
1992	W. wheat	W. wheat	W. wheat
1993	S. barley	W. barley	W. barley
1994	S. beans	W. oilseed rape	W. oilseed rape
1995	W. wheat	W. wheat	W. wheat
1996	W. barley	S. barley	S. barley

* Italics denotes baseline year; W, Winter; S, Spring; Su, Sugar.

Table 3.1.3. A summary of the type and number of crops harvested in SCARAB, 1991–1996.

Crop	Site			Total
	Drayton	Gleadthorpe	H. Mowthorpe	
Winter wheat	4	1	6	11
Winter barley	-	6	3	9
Spring wheat	-	4	-	4
Spring barley	-	1	3	4
Winter oilseed rape	-	-	3	3
Spring beans	-	1	3	4
Potatoes	-	2	-	2
Sugar beet	-	3	-	3
Grass	8	-	-	8
Total all crops	12	18	18	48

Table 3.1.4. Pesticide use in SCARAB cereal crops (excluding seed treatments). Data given are the average number of pesticide units applied per crop. One pesticide unit equals one full label-rate application of a single active ingredient.

Crop (no. grown)	Pesticide group	CFP	RIA	% reduction in RIA cf. CFP
Winter wheat (11)	Herbicide	3.2	1.7	47
	Fungicide	4.0	1.3	68
	Insecticide	1.1	0	100
	All pesticides	8.3	3.0	64
Winter barley (9)	Herbicide	2.1	1.0	52
	Fungicide	2.6	0.9	65
	Insecticide	1.0	0	100
	All pesticides	5.7	1.9	67
Spring wheat (4)	Herbicide	1.5	0.8	47
	Fungicide	2.0	1.0	50
	Insecticide	1.5	0	100
	All pesticides	5.0	1.8	64
Spring barley (4)	Herbicide	3.0	1.8	40
	Fungicide	2.3	1.4	39
	Insecticide	1.0	0	100
	All pesticides	6.3	3.2	49

Table 3.1.5. Pesticide use in SCARAB break crops (excluding seed treatments). Data given are the average number of pesticide units applied per crop. One pesticide unit equals one full label-rate application of a single active ingredient.

Crop (no. grown)	Pesticide group	CFP	RIA	% reduction in RIA cf. CFP
Winter oilseed rape (3)	Herbicide	1.0	0.8	20
	Fungicide	0.3	0	100
	Insecticide	1.0	0	100
	All pesticides	2.3	0.8	65
Spring beans (4)	Herbicide	2.0	1.0	50
	Fungicide	2.0	1.0	50
	Insecticide	1.0	0	100
	All pesticides	5.0	2.0	60
Potatoes (2)	Herbicide	2.4	2.1	13
	Fungicide	11.5	10.0	13
	Insecticide	1.0	0	100
	All pesticides	14.9	12.1	19
Sugar beet (3)	Herbicide	10.0	6.5	35
	Fungicide	0	0	0
	Insecticide	1.7	0	100
	All pesticides	11.7	6.5	44
Grass (8)	Herbicide	0.3	0.1	67
	Fungicide	0.6	0	100
	Insecticide	0.5	0	100
	All pesticides	1.4	0.1	93

Table 3.1.6. Seed treatment use in SCARAB cereal and break crops. Data given are the average number of pesticide units applied per crop. One pesticide unit equals one full label-rate application of a single active ingredient.

Crop (no. grown)	Pesticide group	CFP	RIA	% reduction in RIA cf. CFP
Winter wheat (11)	Fungicide	1.9	1.7	11
	Insecticide	0	0	0
Winter barley (9)	Fungicide	2.2	2.2	0
	Insecticide	0	0	0
Spring wheat (4)	Fungicide	2.0	2.0	0
	Insecticide	0.2	0	100
Spring barley (4)	Fungicide	2.5	2.5	0
	Insecticide	0	0	0
Winter oilseed rape (3)	Fungicide	2.0	1.3	35
	Insecticide	1.0	0.7	30
Spring beans (4)	Fungicide	0	0	0
	Insecticide	0	0	0
Potatoes (2)	Fungicide	1.0	0	100
	Insecticide	0	0	0
Sugar beet (3)	Fungicide	2.0	2.0	0
	Insecticide	0	0	0
Grass (8)	Fungicide	0	0	0
	Insecticide	0	0	0

Table 3.1.7. Insecticide use in CFP in SCARAB at Drayton, dates applied and target pests.

Field and crop year	Crop	Active ingredient	Date applied	Target pest	
				Common name	Latin name
'Field 1'					
1991	Winter wheat	deltamethrin	8 November	autumn aphids	*Rhopalosiphum padi, Sitobion avenae*
1992	Winter wheat	deltamethrin	27 November	autumn aphids	*R. padi, S. avenae*
1993	Grass	omethoate	28 May	frit fly	*Oscinella frit*
1994	Grass	nil	-	-	-
1995	Grass	nil	-	-	-
1996	Grass	nil	-	-	-
'Field 5'					
1991	Grass	chlorpyrifos	28 January	leatherjackets	*Tipula paludosa*
1992	Winter wheat	dimethoate	23 June	summer aphids	*S. avenae, Metopolophium dirhodum*
1993	Winter wheat	dimethoate	23 June	summer aphids	*S. avenae, M. dirhodum*
1994	Grass	chlorpyrifos	14 June	leatherjackets	*T. paludosa*
1995	Grass	chlorpyrifos	22 March	leatherjackets	*T. paludosa*
1996	Grass	nil	-	-	-

Table 3.1.8. Insecticide use in CFP in SCARAB at Gleadthorpe, dates applied and target pests.

Field and crop year	Crop	Active ingredient	Date applied	Target pest: Common name	Target pest: Latin name
'Balk'					
1991	Sugar beet	aldicarb	5 March	migratory nematodes	*Trichodorus* & *Longidorus* spp.
		pirimicarb	17 July	aphids	*Myzus persicae, Aphis fabae*
1992	Spring wheat	dimethoate	17 June	summer aphids	*Sitobion avenae, Metopolophium dirhodum*
1993	Winter barley	cypermethrin	5 November	autumn aphids	*Rhopalosiphum padi, S. avenae*
1994	Potato	pirimicarb	7 July	aphids	*M. persicae, Macrosiphon euphorbiae*
1995	Spring wheat	fonofos (ST)*	31 December	wheat bulb fly	*Delia coarctata*
		chlorpyrifos	19 June	orange wheat blossom midge	*Sitodiplosis mosellana*
1996	Winter barley	cypermethrin	21 October	autumn aphids	*R. padi, S. avenae*
'Near Kingston'					
1991	Spring barley	chlorpyrifos	25 February	wheat bulb fly	*D. coarctata*
1992	Winter barley	cypermethrin	14 November	autumn aphids	*R. padi, S. avenae*
1993	Spring beans	pirimicarb	21 June	black bean aphid	*A. fabae*
1994	Winter wheat	pirimicarb	8 July	summer aphids	*S. avenae, M. dirhodum*
1995	Winter barley	cypermethrin	2 November	autumn aphids	*R. padi, S. avenae*
1996	Sugar beet	aldicarb	2 April	migratory nematodes	*Trichodorus* & *Longidorus* spp.
		cypermethrin	15 July	silver y moth	*Autographa gamma*
'South'					
1991	Potato	pirimicarb	17 July	aphids	*M. persicae, M. euphorbiae*
1992	Spring wheat	omethoate	3 March	wheat bulb fly	*D. coarctata*
		dimethoate	25 June	summer aphids	*S. avenae, M. dirhodum*
1993	Winter barley	cypermethrin	5 November	autumn aphids	*R. padi, S. avenae*
1994	Sugar beet	aldicarb	10 April	migratory nematodes	*Trichodorus* & *Longidorus* spp.
1995	Spring wheat	dimethoate	30 March	wheat bulb fly	*D. coarctata*
		dimethoate	28 June	summer aphids	*S. avenae, M. dirhodum*
1996	Winter barley	cypermethrin	21 October	autumn aphids	*R. padi, S. avenae*

*ST - Seed treatment.

Table 3.1.9. Insecticide use in CFP in SCARAB at High Mowthorpe, dates applied and target pests.

Field and crop year	Crop	Active ingredient	Date applied	Target pest	
				Common name	Latin name
'Bugdale'					
1991	Winter oilseed rape	gamma-HCH (ST)	3 September	flea beetles	*Phyllotreta* spp., *Psylliodes chrysocephala*
		triazophos	24 June	cabbage seed weevil pod midge	*Ceutorhynchus assimilis* *Dasineura brassicae*
1992	Winter wheat	dimethoate	15 July	summer aphids	*Sitobion avenae, Metopolophium dirhodum*
1993	Spring barley	dimethoate	13 June	grain aphids	*S. avenae, M. dirhodum*
1994	Spring beans	cypermethrin	13 June	pea and bean weevil	*Sitona* spp.
1995	Winter wheat	chlorpyrifos	28 June	orange wheat blossom midge	*Sitodiplosis mosellana*
		dimethoate	15 July	summer aphids	*S. avenae, M. dirhodum*
1996	Winter barley	cypermethrin	28 October	autumn aphids	*Rhopalosiphum padi, S. avenae*
'Old Type N & S'					
1991	Spring beans	pirimicarb	24 July	black bean aphid	*Aphis fabae*
1992	Winter wheat	dimethoate	15 July	summer aphids	*S. avenae, M. dirhodum*
1993	Winter barley	cypermethrin	24 November	autumn aphids	*R. padi, S. avenae*
1994	Winter oilseed rape	gamma-HCH (ST)*	25 August	flea beetles	*Phyllotreta* spp., *P. chrysocephala*
		triazophos	25 June	cabbage seed weevil pod midge	*C. assimilis* *D. brassicae*
1995	Winter wheat	dimethoate	17 July	summer aphids	*S. avenae, M. dirhodum*
1996	Spring barley	dimethoate	8 August	summer aphids	*S. avenae, M. dirhodum*

ST - Seed treatment.
* Seed treatment also used on RIA crop to prevent crop loss at emergence.

Table 3.1.10. Most commonly used insecticides on arable crops and grass leys. Data quoted from the Pesticide Usage Surveys, 1990, 1992, 1994 and 1996 (*1993 and 1997 for grass leys only), are in treated thousand hectares.

Active ingredient	Insecticide type	Treated hectares (000s)			
		1990	1992	1994	1996
Insecticide					
Cypermethrin (arable)	pyrethroid	1617.1	1582.3	906.0	2374.4
Cypermethrin (grass)	pyrethroid	no survey	1.0*	no survey	0.4*
Deltamethrin	pyrethroid	580.9	257.0	142.4	177.1
Pirimicarb	carbamate	535.7	333.2	441.2	273.2
Dimethoate	organophosphate (OP)	512.2	389.9	607.1	291.6
Fenvalerate	pyrethroid	195.2	218.5	not listed	not listed
Demeton-S-methyl	organophosphate	179.9	95.7	65.2	44.5
Oxy-demeton methyl	organophosphate	139.7	42.8	not listed	not listed
Alpha-cypermethrin	pyrethroid	115.9	195.8	170.1	183.3
Triazophos	organophosphate	84.9	not listed	91.3	not listed
Gamma-HCH	organochlorine	41.1	24.9	38.4	27.8
Lambda-cyhalothrin	pyrethroid	not listed	113.5	103.0	485.1
Deltamethrin/heptenophos	pyrethroid/OP	not listed	82.4	102.2	82.2
Chlorpyrifos (arable)	organophosphate	not listed	35.8	271.9	52.2
Chlorpyrifos (grass)	organophosphate	no survey	7.8*	no survey	28.8*
Esfenvalerate	pyrethroid	not listed	not listed	40.7	247.6
Nematicide/insecticide					
Aldicarb	carbamate	57.8	37.7	39.6	not listed
Molluscicide					
Methiocarb	carbamate	156.0	148.3	316.8	137.9
Metaldehyde	other	48.1	143.6	438.6	297.0

References for Pesticide Usage Survey Reports :
1990 - Davis, Garthwaite & Thomas (1991);
1992 - Davis, Thomas, Garthwaite & Bowen (1993);
1993 - Thomas & Garthwaite (1994);
1994 - Garthwaite, Thomas & Hart (1995);
1996 - Thomas, Garthwaite & Banham (1997);
1997 - Garthwaite, Thomas, Banham & De'Ath (1999).

Table 3.1.11. Annual pesticide use in the Full Insurance and Supervised treatment areas during the Boxworth Project (1984-88). Figures are the average numbers of applications of pesticide products.

Pesticide group	Full Insurance	Supervised
Herbicide	5.2	3.4
Fungicide	4.0	2.6
Insecticide	5.2	0.8
All pesticides	14.4	6.8

(After Greig-Smith *et al.*, 1992).

THE EFFECTS OF PESTICIDE REGIMES ON NON–TARGET ARTHROPODS

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Introduction

Farmland is a substantial geographical feature throughout Europe and provides habitats for many species of wildlife. One fifth of the land area of Great Britain is sown to arable crops (Thomas *et al.*, 1997) and cereal farming (which occupies about one sixth of the land area) covers sixteen times as great an area as all UK nature reserves combined (Potts, 1991). Arable farmland may appear barren if crop monocultures extend over large areas but cereal crops have a diverse invertebrate fauna of dynamically interacting herbivores, fungus-feeders, predators and parasitoids (Potts & Vickerman, 1974; Jones, 1976a). At least 180 species of spider live in arable ecosystems (26% of all the UK species) and the figure for insects has been estimated to exceed 1,800 species (Potts, 1991). Most inhabitants of farmland are not themselves pests. However, they may encounter harmful residues of chemicals applied to combat crop pests, diseases and weeds, or they may experience indirect effects of pesticide use on their habitat or food supply. These 'non-target' species include predators and parasitoids that are beneficial as natural antagonists of pests such as cereal aphids (Wratten & Powell, 1991). They also include pollinators, species of aesthetic or conservation value (e.g. butterflies), those involved in nutrient cycling and maintaining soil fertility (earthworms, springtails) and species which may serve as indicators of ecosystem health. The beneficial value of the non-target arthropod fauna of farmland is now widely accepted, with the protection and enhancement of predatory species important ingredients in programmes of Integrated Crop Management (ICM). There is concern, however, that current farming practices, including pesticide use, may be to blame for long-term declines in the abundance of a variety of farmland wildlife species (Sotherton, 1998; Ewald & Aebischer, 1999).

The Boxworth Project

During the 1970s, monitoring by the Game Conservancy Trust in cereals in southern England revealed long-term declines in the abundance of some arthropods, particularly rove beetles and spiders (Aebischer, 1991). These changes occurred at a time of considerable growth in pesticide usage on arable crops. The number of fields treated with foliar fungicides had increased steadily during that decade and the first widespread use of summer aphicides in Britain occurred in 1975 (Potts, 1991). The number of available chemicals, the proportion of fields treated with pesticides, the frequency of applications within a season and the incidence of spraying several pesticide products together as mixtures all increased during the 1970s, raising concerns that pesticide use could have contributed to the observed declines in arthropod populations. Orthodox field trials, which usually lasted no longer than one season and involved single applications of individual pesticides within one or few fields, could not detect large-scale or long-term effects and so a new experimental approach was needed. Following a period of consultation and planning to develop the most appropriate experimental design (Greig-Smith, 1992) the Boxworth Project was initiated in 1981, at the then Boxworth Experimental Husbandry Farm in eastern England. The aim of the Boxworth Project was to investigate the effects on wildlife of the high pesticide inputs then associated with commercial wheat production, using an experimental scale large enough to detect long-term effects.

Reducing Agrochemical use on the Arable Farm: The TALISMAN and SCARAB Projects.

Young J E B, Griffin M J, Alford D V, Ogilvy S E. [*eds*] 2001. London: DEFRA.

The Boxworth Project comprised a 67 ha block of four 'Full Insurance' fields and a 68 ha block of six lower-input fields, three of which received 'Supervised' pesticide inputs and the remaining three 'Integrated' inputs. Fields were cropped with winter wheat. The pros and cons of the Boxworth experimental design were considered by Greig-Smith (1992). The Full Insurance regime involved prophylactic use of pesticides designed to eliminate any pest, disease or weed problems, whereas the Supervised and Integrated regimes, which had similar pesticide inputs, were managed such that chemicals were applied only in response to a threat of crop yield loss or unacceptable damage. During the 'baseline' (pre-treatment) phase of the Project (1981–1983) all fields received Supervised pesticide inputs; then, in autumn 1983, the Full Insurance treatment was initiated and operated until autumn 1988 (Greig-Smith *et al.*, 1992). The responses of a wide range of wildlife (including plants, birds, small mammals and arthropods) to the pesticide regimes were monitored throughout the Project by specialist scientists using a variety of methods. At the end of the Project, it was apparent that some sub-lethal and short-term effects of insecticide and molluscicide use had occurred among birds and mammals, but it was only arthropods that had exhibited long-term responses to the pesticide regimes. Some species of ground beetles and surface-dwelling springtails were immediately reduced in abundance by the implementation of the Full Insurance regime in 1983, and failed to recover while Full Insurance pesticide use continued (Burn, 1992; Vickerman, 1992). More subtle long-term changes occurred among soil-dwelling springtails, with some species showing a gradual decline and others a gradual increase in density under the Full Insurance regime (Frampton *et al.*, 1992). At the end of the Project, reversion of some Full Insurance fields to Supervised inputs (Greig-Smith & Griffin, 1992) did not immediately reverse effects of the Full Insurance regime on the most vulnerable arthropod species.

SCARAB arthropod monitoring

Results from the Boxworth Project implied that intensive, prophylactic use of pesticides in commercial wheat production could be damaging to arthropod populations. However, it was not known whether similar results would have been obtained under different crops or on farms sited elsewhere. The SCARAB Project, which included several crops on different farms, was initiated in 1990 to clarify the situation (Cooper, 1990; see also Chapter 1.1). SCARAB focused on arthropods, the group of wildlife most vulnerable to Boxworth's Full Insurance regime. To permit studies of invertebrate species without the need for the large experimental areas employed at Boxworth, a split-field design was adopted for SCARAB, employing paired comparisons of conventional and reduced-input pesticide regimes within each of seven fields (Chapter 3.1). As at Boxworth (Greig-Smith, 1992), the trade-off between statistical replication and realism of the study meant that orthodox statistical designs were inappropriate for studying the long-term impact of overall pesticide regimes where effects of many variables are not readily separable. Nevertheless, the long time-scale of the study and its coverage of three UK farms provided a substantial amount of data from which effects of the pesticide regimes could reasonably be inferred with confidence. This chapter presents results from arthropod monitoring in the SCARAB Project during 1990 (the 'baseline' or pre-treatment year) and 1991–1996 (the phase of pesticide regime contrasts). An extension to the original SCARAB Project was initiated in 1996 to further explore long-term changes in arthropod distributions that had developed during the treatment phase of the Project in two of the study fields. Some results from this follow-up study are also presented here as they lend support to inferences drawn from the original SCARAB Project.

Methods and materials

Farms and fields

The design of the Project involved seven arable fields sited at three ADAS Research Centres (**Table 3.2.1**). The largest field, 'Old Type', was divided into two 15 ha units which are treated here as separate fields ('Old Type North' and 'Old Type South') but which had identical cropping, pesticide regimes and soil types. These contiguous fields were included in the Project to provide information on variation in effects of the CFP and RIA regimes between similarly-managed fields with different field margins. Cropping in each field varied from year to year, in accordance with the typical rotation for the locality (Chapter 3.1).

Pesticide regimes

Two regimes of pesticide use were compared in the SCARAB Project: 'Current Farm Practice' (CFP) and a 'Reduced Input Approach' (RIA) (Chapter 3.1). The pesticide regimes were flexible to accommodate the pesticide needs of different crops and year-to-year changes in farming practice. CFP mimicked conventional farming practice for the crop according to survey data (e.g. Thomas *et al.*, 1997), with the proviso that at least one insecticide was applied to each arable crop (except grass) to ensure that arthropods were exposed to a representative range of pesticides (Chapter 3.1). In comparison with CFP, lower pesticide inputs in the RIA regime reflected the omission of some applications, or the use of reduced application rates (Chapter 3.1). The major difference between the pesticide regimes was that no insecticides or nematicides were applied under the RIA regime and so all insecticide use documented below refers to the CFP regime. Over the Project as a whole, the RIA regime had 44% fewer label-recommended-rate herbicide applications and 52% fewer label-recommended-rate fungicide applications than CFP. Molluscicides were not included in either pesticide regime because the three SCARAB Project farms had not historically experienced problems of slug damage to crops. The CFP regime would have permitted molluscicide use in the event that slug damage unexpectedly threatened crop yields but such a scenario did not occur during the SCARAB Project.

Layout of the Project

To compare the effects of the pesticide regimes on the invertebrate fauna, each field was divided in half at the start of the 1990–1991 crop season, then, Current Farm Practice was applied to one half of the field whilst the other received the Reduced Input Approach. These contrasting regimes were operated until harvest 1996. As cropping and fertilisation were carried out on a whole-field basis, pesticide inputs were the only agronomic variables that differed between the RIA and CFP halves of each field. During summer and autumn in 1990, pre-treatment monitoring of arthropods was done to establish 'baseline' densities before the pesticide contrasts were applied.

Arthropod monitoring

'D-vac' suction sampling and pitfall trapping were the methods used to collect invertebrates. All species captured and identified during this work belong to the phylum Arthropoda, principally insects and spiders. Earthworms were monitored separately within the SCARAB Project, using different sampling procedures (Chapter 3.4). Arthropod monitoring was done at matched locations in the CFP and RIA areas of each field, following standard protocols for D-vac and pitfall sampling. The protocol for the former adopted a suction sampler nozzle that gave an area per sample of 0.46 m^2; that for the latter involved beakers (9 cm in diameter) open for periods of seven days (Chapter 3.1).

The follow-up study

Arthropod captures made during the treatment phase (1991–1996) revealed long-term differences in abundance between the pesticide regimes in two of the fields ('Bugdale' and 'Field 5') which persisted to the end of the monitoring period in autumn 1996. A follow-up study (1997–1999) involving these two fields was initiated to further explore these results. This study involved spatially reversing the CFP and RIA regimes in 1997, to permit monitoring of arthropod recovery (following a change from CFP to RIA pesticide inputs). Some initial results from this work in 'Field 5' are given to aid interpretation of effects of the CFP and RIA pesticide regimes.

Data interpretation

The SCARAB Project was designed to explore the overall effects of complete pesticide regimes rather than the effects of individual chemicals; however, the effects of some broad-spectrum insecticides were sometimes readily apparent where substantial changes in arthropod abundance concurred with insecticide applications. Replication of the pesticide regimes was incompatible with the long duration and large spatial scale of monitoring needed to detect large-scale effects, so standard statistical tests could not be invoked to detect pesticide effects. Instead, evidence that the pesticide regimes had influenced arthropod density or activity was based upon changes in arthropod abundance or distribution which:

- coincided with pesticide applications;
- differed between the pre-treatment year (1990) and treatment phase (1991–1996).

Confidence was increased if such changes also:

- were relatively large or persistent compared with 'background' fluctuations;
- were consistent, following pesticide applications in different fields or years;
- resulted in long-term differences in species composition between the two regimes.

The above criteria were applied to densities of individual species, species richness, species diversity and a measure of the similarity of the faunas under the two pesticide regimes. Arthropod species were grouped functionally to determine whether effects of the pesticide regimes on trophic structure could be detected. The multivariate ordination method Redundancy Analysis was also used to investigate changes in the species compositions of the two pesticide regimes over time in 'Field 5', where the largest differences in arthropod catches between the pesticide regimes were seen.

Multivariate analysis

Multivariate ordination techniques allow information from a complex data set, in this case containing more than 100 taxonomic groups (**Tables 3.2.2 & 3.2.3**), to be concisely summarised in a two-dimensional diagram. The axes of the diagram are drawn so as to represent the major sources of variation in the data. Various statistical methods are available to plot sample points or species points in an ordination diagram, such that the position of each data point relative to the ordination axes shows how strongly the point (representing a species or sample) is influenced by different environmental variables. Redundancy Analysis (RDA) is a particularly useful ordination technique in ecotoxicology because the environmental variables can be specified so that the ordination diagram displays only the part of the total variation which is explained by variables of interest, e.g. pesticide treatment and time (Van den Brink & Ter Braak, 1997; 1999). Redundancy analysis was used to investigate the responses of arthropods to the Current Farm Practice and Reduced Input Approach pesticide regimes in all SCARAB Project fields. For brevity, the focus here is on suction captures of arthropods in 'Field 5', where differences in arthropod abundance between the regimes were most pronounced (e.g. **Figs 3.2.1–3.2.5**). The analysis was performed using the computer program CANOCO 4 (Ter Braak & Šmilauer, 1998), using the same procedure as that described by Van den Brink & Ter Braak (1999). In this case, all levels of the factors 'pesticide regime' and 'sampling date' were introduced as dummy variables into the RDA to permit the analysis to focus on the variance in the data set attributed to time, pesticide regime, and their interaction.

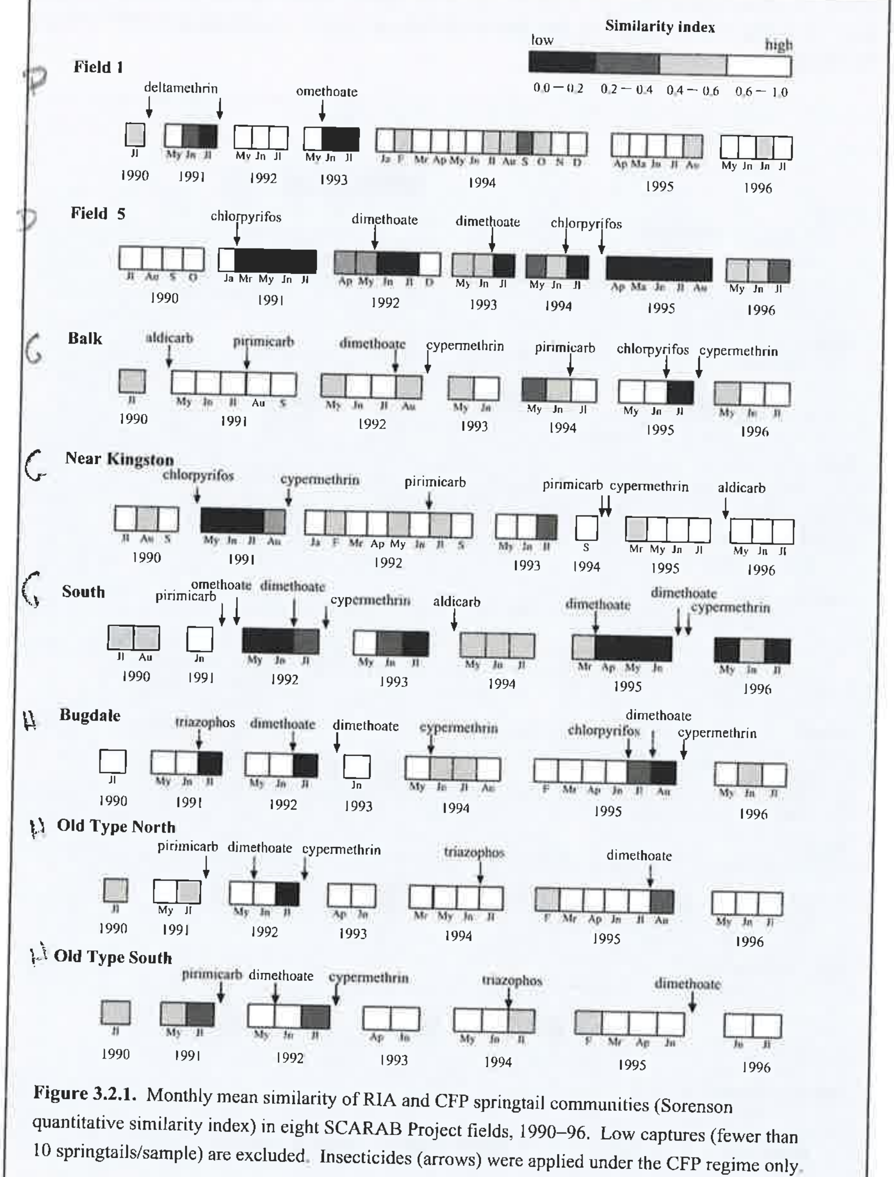

Figure 3.2.1. Monthly mean similarity of RIA and CFP springtail communities (Sorenson quantitative similarity index) in eight SCARAB Project fields, 1990–96. Low captures (fewer than 10 springtails/sample) are excluded. Insecticides (arrows) were applied under the CFP regime only.

Results

Overall composition of the arthropod fauna in SCARAB

The compositions of the fauna differed between pitfall trapping and D-vac suction sampling (**Tables 3.2.2 & 3.2.3**). It was not practical to sample the entire fauna trapped by these methods, the principal arthropod omissions being the exclusion of mites (Acari) from all samples and springtails (Collembola) from pitfall samples. Given these constraints, pitfall trapping captured predominantly carnivorous taxa (**Table 3.2.2**), whereas D-vac samples were dominated by detritivores (springtails) and herbivores (bugs: Hemiptera; and thrips: Thysanoptera) (**Table 3.2.3**). Pitfall catches included nocturnally active species, and some diurnally active beetles (Coleoptera) too large to be captured by the D-vac (e.g. large *Pterostichus* spp. ground beetles), whereas D-vac samples contained mainly diurnally active species. Both sampling techniques captured surface-active (epigeic) or litter-dwelling (hemiedaphic) arthropods; however, only rarely were soil-inhabiting (edaphic) species, e.g. of springtails, trapped. 'Kill' pitfall trapping (i.e. traps in which captured invertebrates are killed), as was used here, tends to record more specimens than 'live' trapping (Weeks & McIntyre, 1997), as predation within traps and escape are minimised.

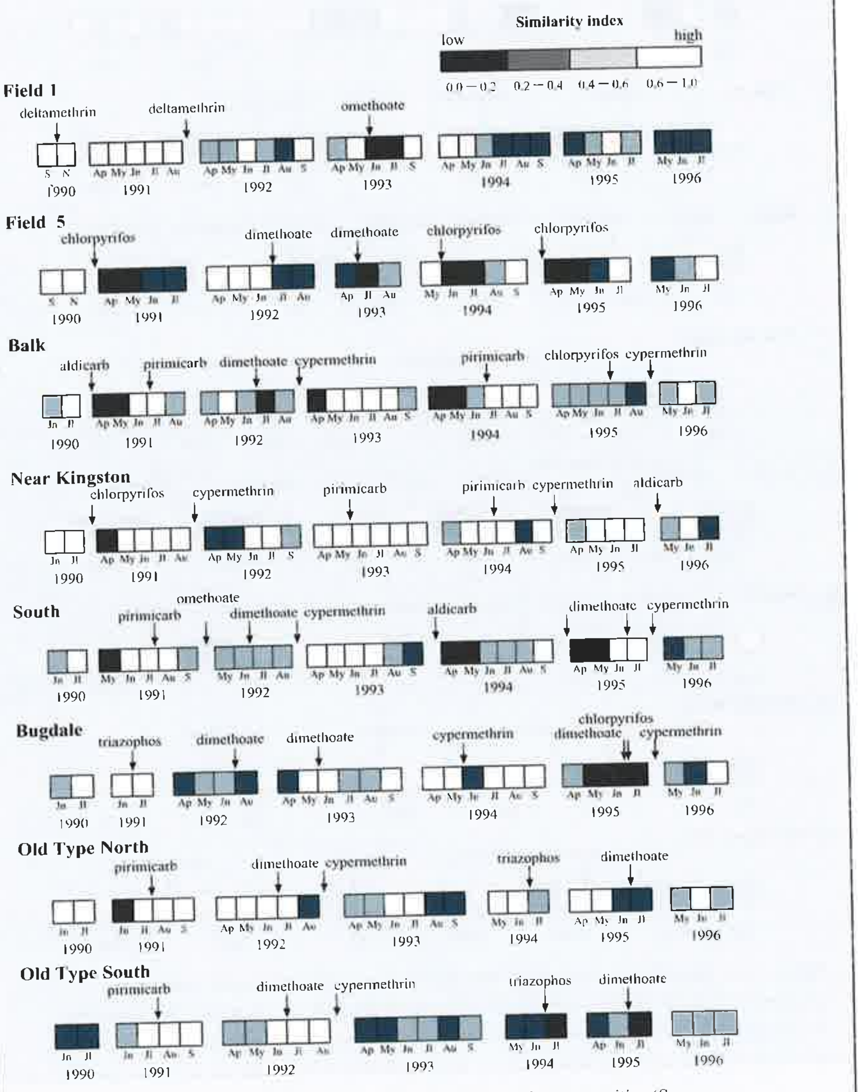

Figure 3.2.2. Monthly mean similarity of RIA and CFP ground beetle communities (Sorenson quantitative similarity index) in eight SCARAB Project fields, 1990–96. Low captures (fewer than 5 beetles/trap/7-day trapping period) are excluded. Insecticides (arrows) were applied under the CFP regime only.

The most numerous and widespread of the arthropods encountered during the SCARAB Project can be considered typical inhabitants of arable farmland in northern Europe. The ground beetle *Pterostichus melanarius* and the money spider *Erigone atra* were the predatory species most frequently encountered (i.e. in all fields and years) during the Project. Over the Project as a whole, *P. melanarius* and *Trechus quadristriatus* together comprised 57% of the total ground beetle catch. The dominance of these species, both of which are apparently favoured by conventional farming systems (Kromp, 1999), is consistent with other studies of

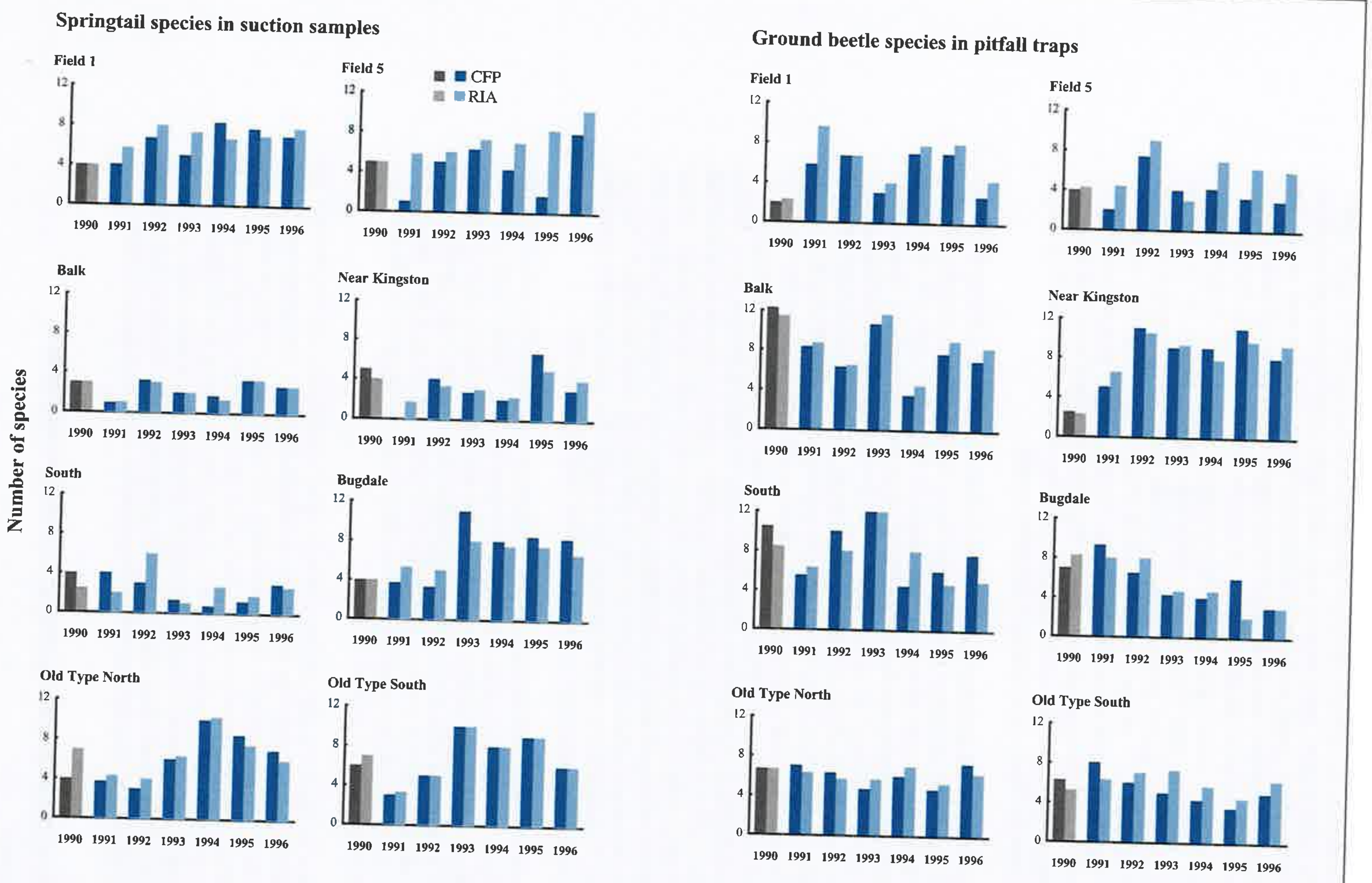

Figure 3.2.3. Number of springtail and ground beetle species captured in summer 1990–1996 in the eight SCARAB Project fields. Data are means from all sampling occasions in May, June and July in each year (except 'Field 1' and 'Field 5' 1990 data, which are from September). Grey bars denote pre-treatment year (1990).

ground beetles on farmland in northern Europe (Jones, 1976b; Thiele, 1977; Jones, 1979; Luff, 1987; Wallin, 1989; Hance, 1990; Luff, 1990; Lovei & Sárospataki, 1990; Thomas & Marshall, 1999), including the Boxworth Project (Vickerman, 1992). The dominant money spiders encountered in the SCARAB Project are representative of the most frequently occurring spiders of arable land in northern Europe. For example, five widespread species (*Bathyphantes gracilis*, *E. atra*, *E. dentipalpis*, *Meioneta rurestris* and *Oedothorax apicatus*), which Everts *et al.* (1989) recommended as a 'guild' of bioindicators for the detection of pesticide effects, together formed 62% of the overall SCARAB Project money spider catch. The species composition of rove beetles in the Project, which was dominated by Aleocharinae and *Tachyporus* spp., is also broadly consistent with that reported in the Boxworth Project (Vickerman, 1992) and other farmland studies (e.g. Jones, 1976b; Good & Giller, 1991; Krooss & Schaefer, 1998).

Although the overall species composition and abundance of arthropods in the SCARAB Project are typical of European farmland, the abundance and distribution of individual species varied considerably between fields and years. Differences in faunal composition between the SCARAB farms were the most obvious. Gleadthorpe had a smaller number of springtail species than Drayton or High Mowthorpe and a different composition of ground beetles. For example, *Calathus melanocephalus* and *Bembidion tetracolum* were found almost exclusively at Gleadthorpe whereas *Bembidion obtusum* was found only at Drayton and High Mowthorpe. It is possible that the sandy soil at Gleadthorpe played a part in these differences, as *C. melanocephalus* is characteristic of dry and sandy habitats (Lindroth, 1975; Eyre & Luff, 1990). Other notable spatial patterns in species' distributions within the SCARAB Project concern the ground beetles *Pterostichus cupreus* and *P. madidus* which were present only at Drayton and High Mowthorpe respectively. In England, *P. cupreus* has a predominantly southern distribution, which explains its presence only at Drayton, whereas *P. madidus* is more widespread (Luff, 1998); the reason for the restricted distribution of the latter species in the SCARAB Project is not clear.

Factors which could explain some of the temporal and spatial patterns in arthropod abundance include crop type and vegetation density (e.g. Thiele, 1977; Jensen *et al.*, 1989; Booij & Noorlander, 1992; Luff, 1987; Varchola & Dunn, 1999), field size (Wallin, 1985), intensity and timing of cultivation (Krooss & Schafer, 1998; Kromp, 1999), the proximity of source habitats for field colonisation (e.g. den Boer, 1977; Alvarez *et al.*, 2000), and weather such as patterns of spring rainfall (Alvarez *et al.*, 1999; Frampton *et al.*, 2000a; 2000b).

The spatial and temporal patterns of arthropod distribution as observed in the SCARAB Project must also be taken into consideration when comparing community-level effects of pesticides in different studies. For instance, *B. obtusum* was one of the ground beetles most seriously affected by pesticide use during the Boxworth Project (Vickerman, 1992) but was not always present during the SCARAB Project. In 'Field 5', the frequent usage of organophosphorus insecticides would be expected to have had a long-term impact on abundance of *B. obtusum*, but transient occurrence of the species precluded the possibility of detecting such effects.

Effects of the pesticide regimes on community composition

Similarity

The Sorenson quantitative index (Magurran, 1988) was used to investigate the similarity of RIA and CFP communities of springtails (**Fig. 3.2.1**) and ground beetles (**Fig. 3.2.2**), using data on species abundance. Low captures were excluded from the analysis, to reduce bias in the index. Applications of the broad-spectrum organophosphorus insecticide chlorpyrifos were consistently followed by a decrease in the similarity of RIA and CFP communities, both for springtails (**Fig. 3.2.1**) and for ground beetles (**Fig. 3.2.2**). Most other broad-spectrum insecticides (aldicarb, dimethoate, omethoate and triazophos) were also associated with declines in the similarity of RIA and CFP communities after application, but not following all applications. In contrast, applications of the synthetic pyrethroids cypermethrin and deltamethrin, and the selective aphicide pirimicarb, were not obviously associated with changes in the similarity of RIA and CFP communities (**Figs 3.2.1 & 3.2.2**). Some of the fluctuations in similarity that did not coincide with insecticide applications could reflect influences of other types of pesticide (see Discussion).

The longest periods of low similarity between RIA and CFP occurred after chlorpyrifos sprays (**Figs 3.2.1 & 3.2.2**), but only among springtails did very low similarity of RIA and CFP communities persist beyond one season (**Fig. 3.2.1**). In 'Field 5', following the use of chlorpyrifos in 1991, the similarity index for springtails remained below the pre-treatment (1990) values for most of the duration of the Project (**Fig. 3.2.1**).

Diversity

All measures of diversity have their limitations, so use of several complementary indices has been recommended (Magurran, 1988). The diversity of SCARAB springtail and ground beetle assemblages under the RIA and CFP pesticide regimes was, accordingly, investigated by calculating three widely accepted indices of diversity: species richness, the Shannon-Wiener index, and the Berger-Parker index. These indices give different views of arthropod diversity: species richness indicates the number of species (or other nominated taxonomic groups) present; Shannon-Wiener is a combined measure of species richness and abundance which is sensitive to species number (and most affected by rare species); Berger-Parker is a combined measure of species richness and abundance which is most sensitive to species dominance (and influenced most by the abundance of the commonest species). The latter two indices can condense information on the abundance of many taxa into a single value and are thus useful in summarising arthropod community data.

The average number of species of ground beetles and springtails trapped varied from year to year, and species richness of springtails was generally lowest on the sandy Gleadthorpe soil (in 'Balk', 'Near Kingston' and 'South' fields). Where a difference between the pesticide regimes persisted over several years, species richness was usually greater under the RIA regime than CFP, with the largest differences between the regimes being in 'Field 5' (**Fig. 3.2.3**). For springtails, differences between the regimes were most pronounced in years when there had been either winter or spring applications of chlorpyrifos ('Field 5' in 1991 and 1995, and 'Near Kingston' in 1991), omethoate ('South' in 1992) or aldicarb ('South' in 1994).

Over the SCARAB Project as a whole, the Shannon-Wiener and Berger-Parker indices gave similar results in 67% of RIA–CFP comparisons (135 of 201 sampling occasions examined). However, only after one insecticide application did a substantial RIA–CFP difference in ground beetle diversity persist for several months, following the 1991 use of chlorpyrifos in 'Field 5' (**Fig. 3.2.4**). On this occasion, only a small effect on springtail diversity could be discerned, even though chlorpyrifos has high toxicity both to ground beetles (Luff *et al.*, 1990; Asteraki *et al.*, 1992) and springtails (Van Straalen & Van Rijn, 1998; Frampton, 1999). These results are consistent with the idea that some measures of diversity (such as Shannon-Wiener) may be insensitive to the effects of pesticides (Siepel & Van de Bund, 1988), as other evidence (see below) indicated that springtails were in fact strongly affected by the use of chlorpyrifos in 'Field 5'. For ground beetles in 'Field 5', the lack of effects of other chlorpyrifos sprays (in 1994 and 1995) on diversity could reflect species turnover, as some vulnerable species (such as *Bembidion obtusum*) were present in the field in 1991 but rare or absent in subsequent years.

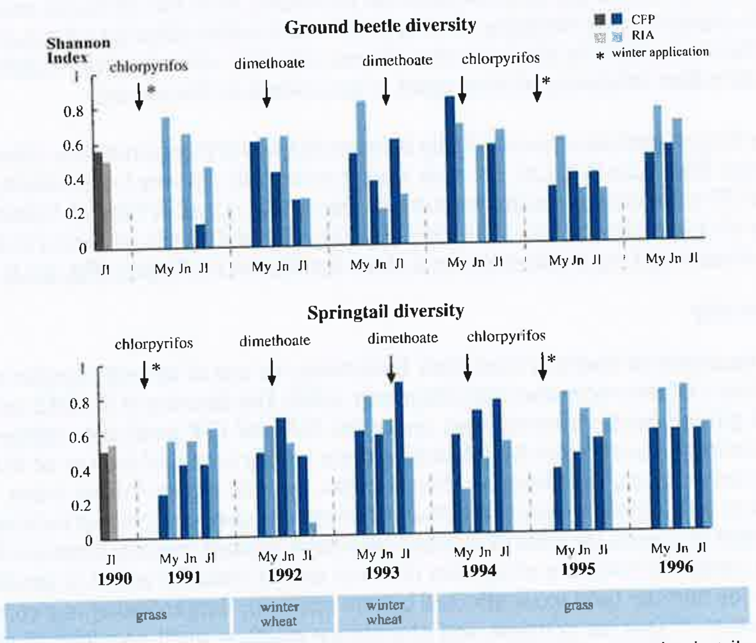

Figure 3.2.4. Shannon diversity index for 'Field 5' for ground beetles in pitfall traps and springtails in suction samples. Low captures (fewer than 10 springtails/sample or 5 beetles/trap/7-day trapping period) are excluded. Grey bars denote pre-treatment year (1990).

Distribution between the pesticide regimes

The average summer distribution between the two pesticide regimes (**Fig. 3.2.5**) was more even for ground beetles than for springtails. There were year-to-year fluctuations, which were particularly large for springtails in 'South' field where, in some years, numbers caught were considerably higher under the CFP regime. There were also differences in distribution between 'Old Type North' and 'Old Type South', two fields which had received identical pesticide inputs. However, with the exception of springtails in 'Field 5', no long-term trends in distribution were evident. In this field, catches of springtails declined under the CFP regime relative to catches under RIA when the treatment phase of the Project was initiated, and subsequently did not recover (**Fig. 3.2.5**).

Functional groups

Arthropods were assigned to functional groups (**Table 3.2.4**), to permit examination of effects of the pesticide regimes on trophic structure of the arthropod community. It is important to recognise that the functional groups used here relate to the surface-dwelling cohort of the fauna as sampled using pitfall trapping and D-vac sampling, hence omitting some important burrowing species. This limitation is not serious, because the aim was to make comparisons between the two pesticide regimes.

Allocation of some species to functional groups was not straightforward, because the degree of taxonomic resolution employed did not always discriminate between different feeding guilds. For instance, many rove beetles regarded as beneficial predators (e.g. Coombes & Sotherton, 1986) also eat fungi (Dennis *et al.*, 1991). Thus, for present purposes, all rove beetles, cecid midges (Diptera: Cecidomyiidae) and *Helophorus* spp. (mud beetles) (Coleoptera: Hydrophilidae) were classified as omnivores, because the carnivorous, fungus-feeding and herbivorous guilds among them could not be readily separated. Facultative insectivory occurs among the ground beetles *Amara* spp. (Jørgensen & Toft, 1997) and thrips (Milne & Walter, 1997), but these arthropods are mostly herbivores. Conversely, springtails include among them herbivorous and carnivorous species, but the majority are detritivorous.

Captures of total carnivores did not show any long-term declines under the CFP regime (**Fig. 3.2.6**). This is in contrast to the situation observed during the Boxworth Project, where the 'Full Insurance' regime had an overall negative impact on predators (Vickerman, 1992).

Total herbivore catches in SCARAB deviated strongly between the RIA and CFP regimes in some years, but only in 'Balk' field was a consistent decline in the CFP herbivore captures seen at the end of the treatment phase, both for suction samples and pitfall catches (**Fig. 3.2.7**). A possible explanation is that RIA herbicide use in 'Balk' failed to adequately control weeds, which increased in abundance in the RIA area of the field during the latter part of the treatment phase (Ogilvy *et al.*, 1996). Higher RIA densities of weeds would have favoured some groups of herbivores by providing food plants and refuges.

Detritivores (**Fig. 3.2.8**) generally did not exhibit any long-term patterns in distribution between the RIA and CFP pesticide regimes. This situation was true for all fields when springtails were not included in the detritivore class (**Fig. 3.2.8**). However, when springtails were included as detritivores, a long-term difference between the pesticide regimes emerged in 'Field 5' after the onset of the treatment phase, with lower CFP than RIA captures persisting over the remaining six years (**Fig. 3.2.8**). These results illustrate the importance of carefully assigning arthropods to functional groups. Vickerman (1992) omitted springtails from the detritivore class, which probably explains why he did not detect effects of the Boxworth pesticide regimes on detritivores.

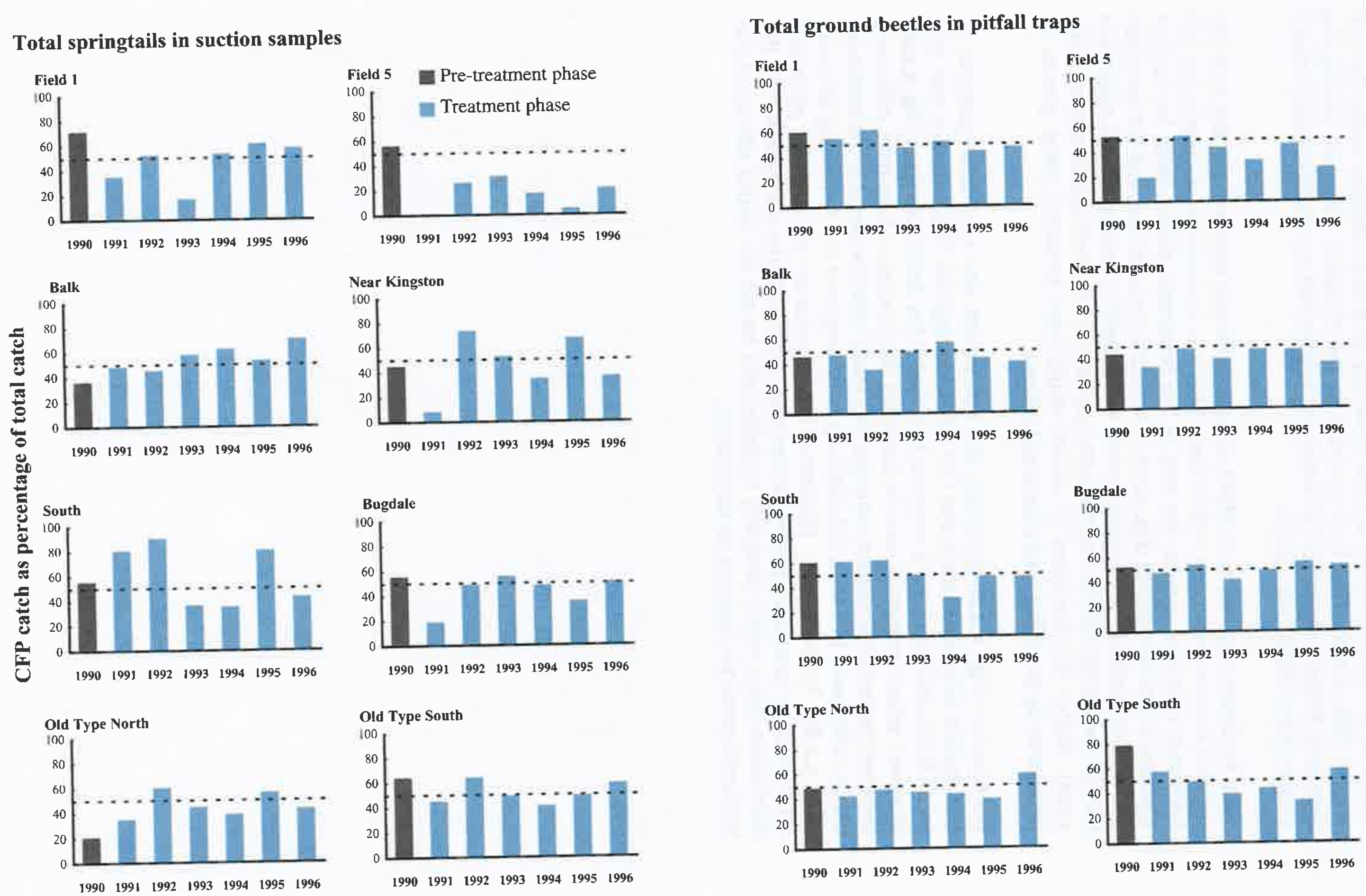

Figure 3.2.5. Distribution of springtails and ground beetles between RIA and CFP pesticide regimes. Based on total summer (May–July inclusive) catches (except 'Field 1' and ' Field 5' 1990 pitfall trap data, which are from September). Bars below 50% line indicate CFP catches lower than RIA catches. Grey bars denote pre-treatment year (1990).

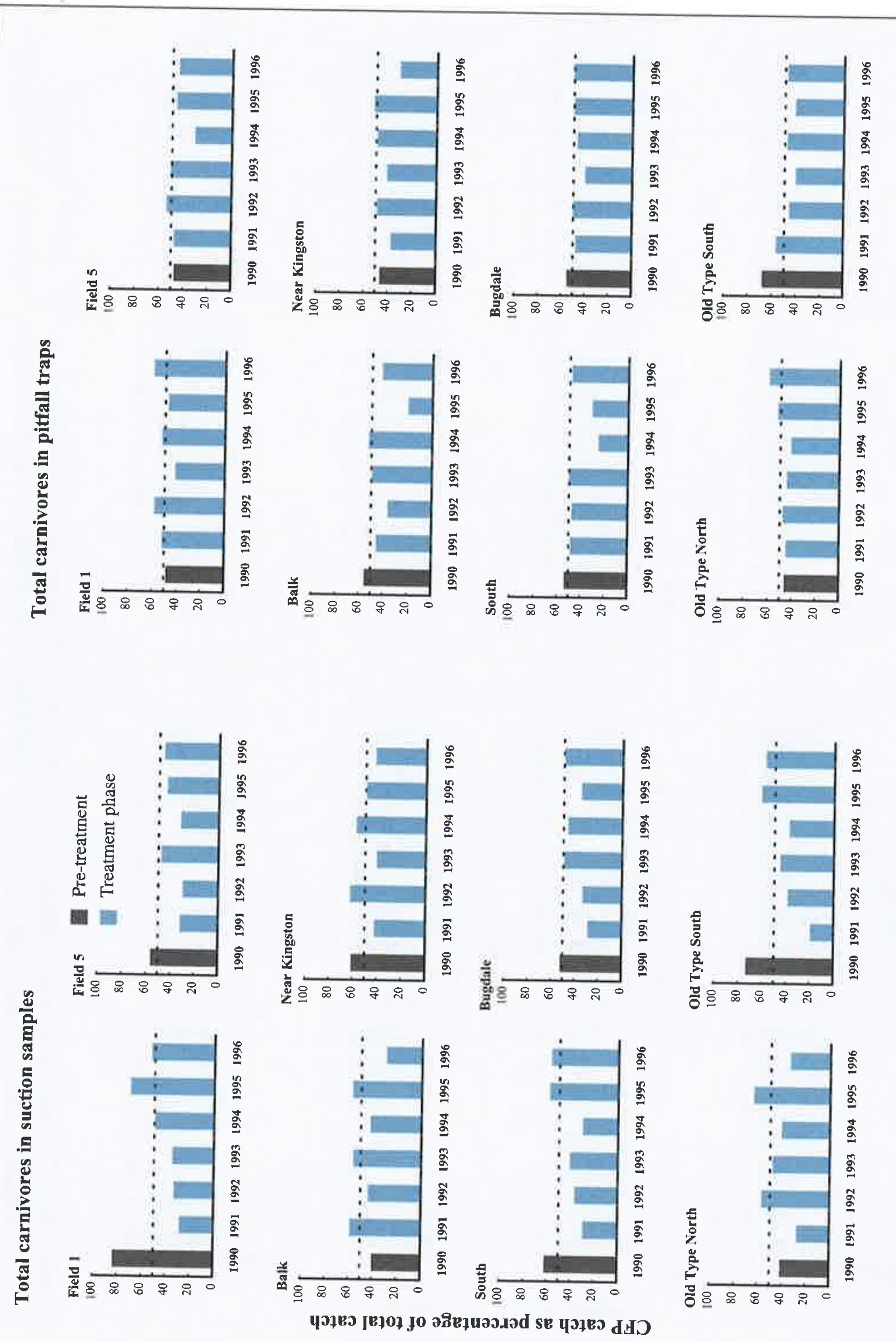

Figure 3.2.6. Distribution of total carnivores between RIA and CFP pesticide regimes. Based on total summer (May–July inclusive) catches (except 'Field 1' and ' Field 5' 1990 pitfall trap data, which are from September). Bars below 50% line show where CFP catches are lower than RIA catches. Grey bars denote pre-treatment year (1990).

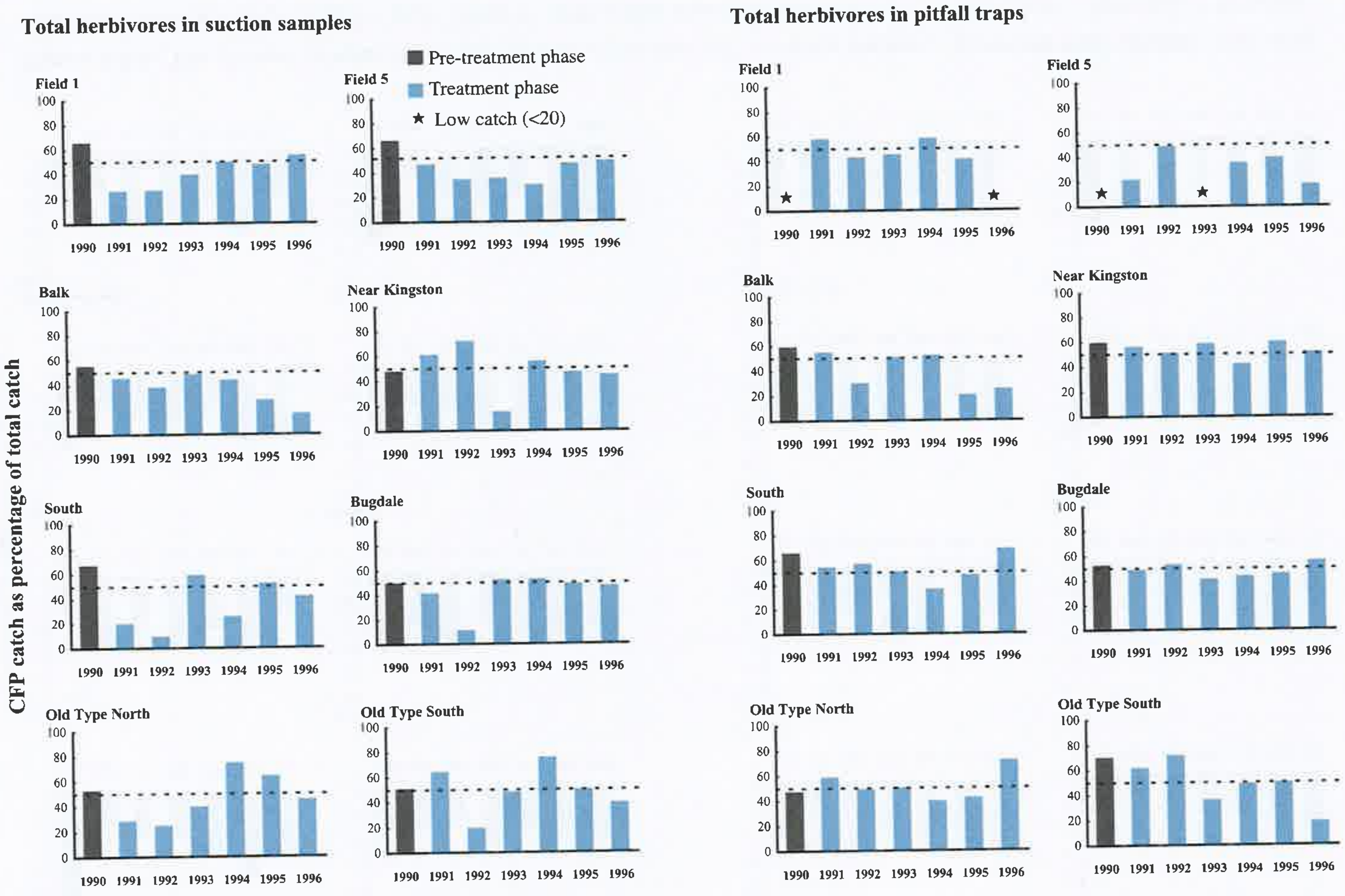

Figure 3.2.7. Distribution of total herbivores between RIA and CFP pesticide regimes. Based on total summer (May–July inclusive) catches (except 'Field 1' and ' Field 5' 1990 pitfall trap data, which are from September). Bars below 50% line show where CFP catches are lower than RIA catches. Grey bars denote pre-treatment year (1990).

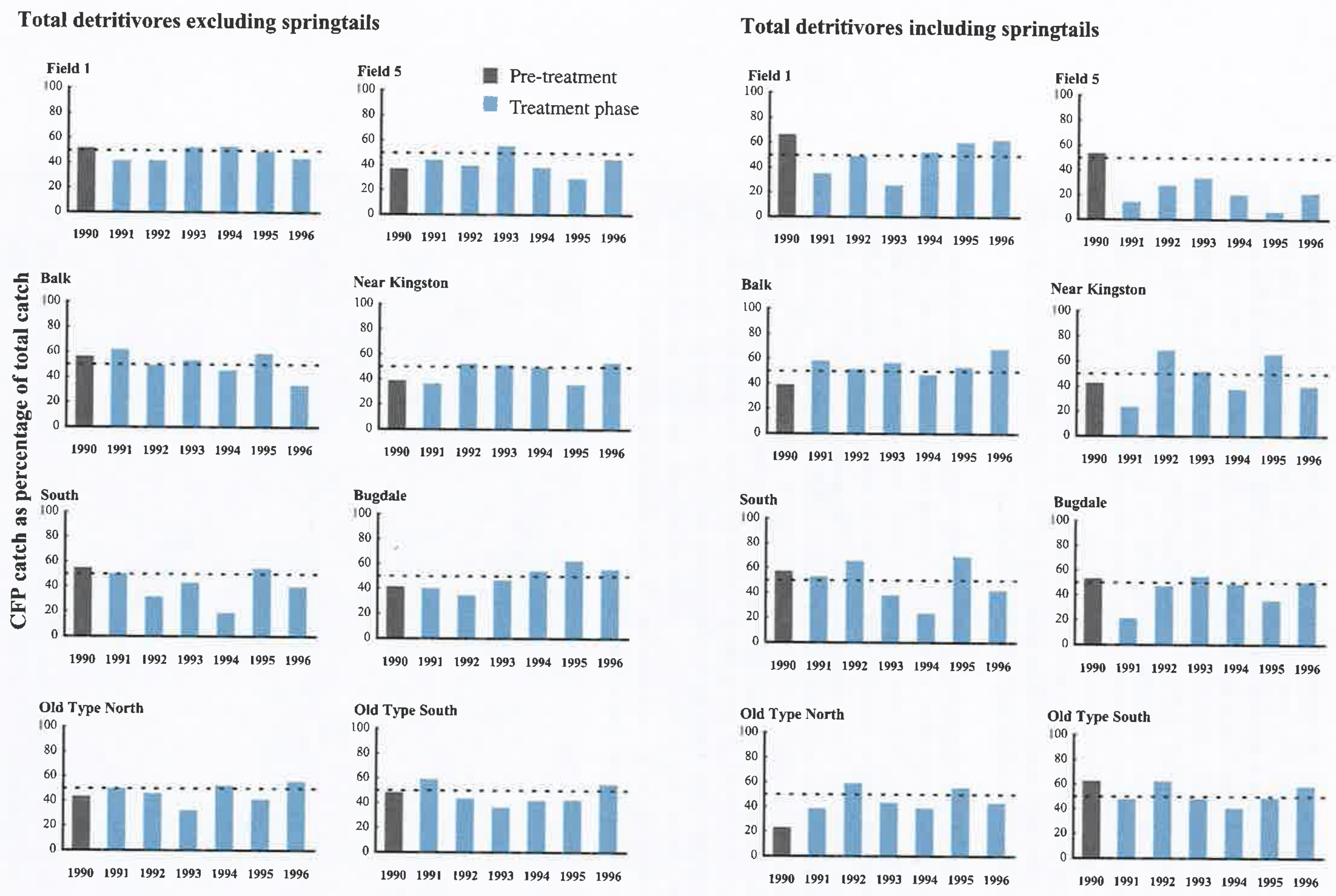

Figure 3.2.8. Distribution of total detritivores between RIA and CFP pesticide regimes. Based on total summer (May–July inclusive) suction trap catches. Bars below 50% line show where CFP catches are lower than RIA catches.

Redundancy analysis

Sample points and species points may be plotted together in a single ordination diagram but for clarity the samples and species data from 'Field 5' are plotted separately (**Figs 3.2.9 & 3.2.10**). Sample points (**Fig. 3.2.9**) represent the species composition in a given pesticide regime and year, based on the combined abundance of all species present. The closer points are together in the ordination diagram, the more similar their species composition. Species' points (**Fig. 3.2.10**) indicate the contribution of individual species or groups to the overall variation exhibited by the data, with points further from the origin of the ordination diagram indicating a greater contribution. The sample and species points are based on summer captures, with each point representing the pooled catch from three sampling dates (one each in May, June and July). An exception is the 1997 data, which are based on a single sampling date in January.

The separation of sample points in the ordination shows that the first (horizontal) axis mainly reflects the effect of time whilst the second axis reflects effects of treatment (**Fig. 3.2.9**). Of the total variance, 66% was accounted for by time and 17% by treatment regime. RIA and CFP treatments were initially similar in species composition (1990) but diverged over time (**Fig. 3.2.9**). The majority of species points were positive in value in relation to axis 2 (**Fig. 3.2.10**) which is also true of the distribution of sample points for the RIA regime, but not the CFP regime (**Fig. 3.2.9**). This indicates that overall abundance of many taxonomic groups was higher under RIA than CFP. Of all the arthropods included in the analysis (**Table 3.2.3**), springtails showed the strongest relationship with the second (treatment effect) axis, whilst species points for many other arthropods lie close to the origin (**Fig. 3.2.10**), indicating little contribution to the observed differences in species composition between the pesticide regimes.

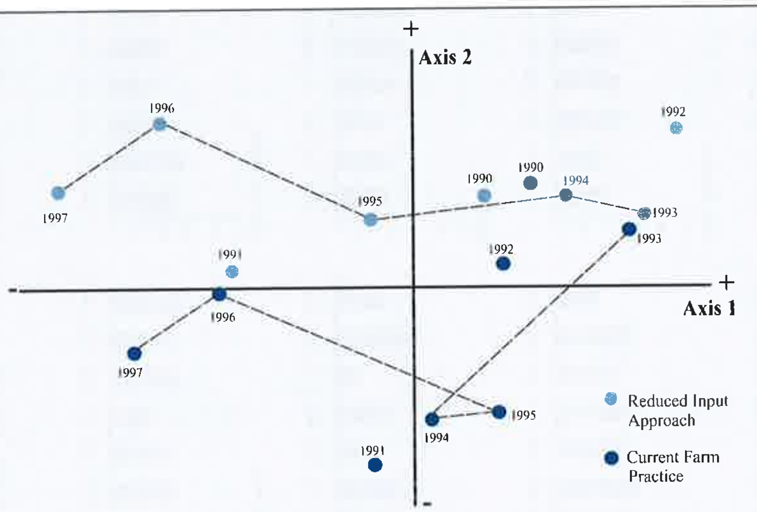

Figure 3.2.9. Arthropod suction captures in Field 5 displayed as sample points in an ordination diagram (redundancy analysis) to show relative differences in species composition between pesticide regimes and years. Distance from the origin indicates deviation (+ or -) in arthropod abundance from the overall mean abundance for the field. Sample points closer together in the diagram are more similar in species composition. Horizontal and vertical axes reflect effects of time (Axis 1) and pesticide regime (Axis 2). Dashed lines show separation of Current Farm Practice and Reduced Input Approach samples after 1993.

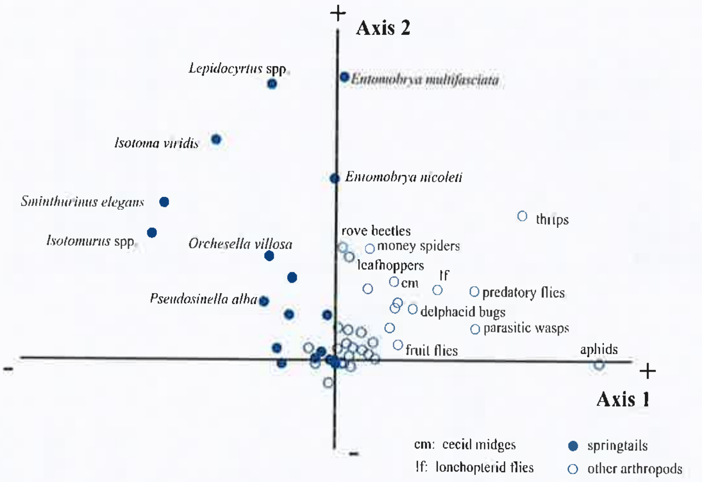

Figure 3.2.10. Arthropod suction captures in Field 5 displayed as species points in an ordination diagram (redundancy analysis), with the same axes as Figure 3.2.9. Points further from the origin indicate stronger species responses to effect of time (horizontal direction) or pesticide regime (vertical direction). Some species points close to the origin omitted for clarity.

The overall impact of Current Farm Practice

The foregoing results show that long-term effects of the CFP pesticide regime were mainly restricted to the wheat and grass rotation of 'Field 5'. Short-term effects of insecticide use did, however, occur more widely. One way of gauging the overall impact of the CFP regime is to compare the effects of the CFP regime in each treatment-phase year, relative to the corresponding pre-treatment data. For each field, the contribution that the CFP catch made to the total (CFP + RIA) catch in each of the six treatment-phase years (1991–1996) was compared with the CFP contribution in the pre-treatment year (1990). Over the Project as a whole, this gave up to 48 pre- to post-treatment contrasts (eight fields and six years). Overall, in the treatment phase of the Project, the CFP share of the catch decreased relative to the pre-treatment share on more occasions than it increased (**Table 3.2.5**). These results indicate that the overall impact of the CFP regime on arthropod abundance was a negative one.

Recovery responses: the follow-up study

Of all the arthropods monitored (**Tables 3.2.2 & 3.2.3**), only springtails exhibited long-term responses to the pesticide regimes. In 'Field 5', some species showed a clear response which coincided with the onset of the contrasting regimes, with *Entomobrya nicoleti* and *Lepidocyrtus* spp. (**Fig. 3.2.11**) being among the species which almost disappeared from CFP catches during the treatment phase of the Project (1991–1996). The only other field in which long-term patterns in springtail catches were seen was 'Bugdale'. Here, *Lepidocyrtus* spp. and *Pseudosinella octopunctata* (**Fig. 3.2.12**) occupied mutually exclusive distributions, the former being trapped only in the RIA half of the field and the latter only in the CFP half. Unlike the situation in 'Field 5', neither of these species in 'Bugdale' was trapped in the pre-treatment year (1990), so the possibility that factors other than the pesticide regimes were responsible for their patterns of distribution could not be ruled out. The species *P. octopunctata* recorded in the CFP regime of 'Bugdale' was not trapped anywhere else within the SCARAB Project, so opportunities for investigating its response to the pesticide regimes were limited.

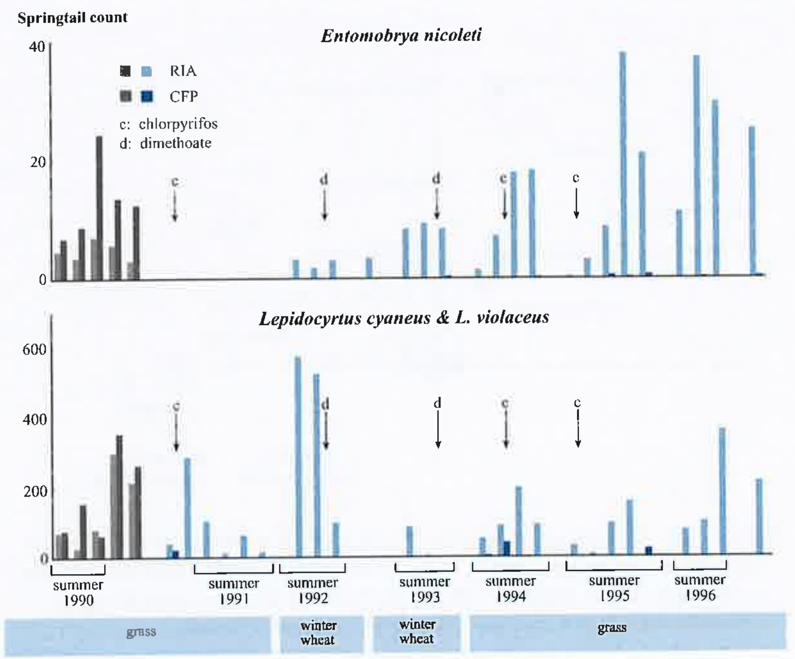

Figure 3.2.11. Mean catches per suction sample of the springtails *Entomobrya nicoleti*, *Lepidocyrtus cyaneus* and *L. violaceus* in 'Field 5', 1990–97. Grey bars denote numbers in pre-treatment year (1990).

Spatial reversal of the RIA and CFP pesticide regimes was the method used to investigate recovery in 'Field 5' and the spatial distributions of the species in 'Bugdale'. This follow-up study was conducted only in these two fields, and entailed changing the CFP regime to RIA and *vice versa*, in April 1997. Both regimes of pesticide use were administered in accordance with the protocol used for the SCARAB Project itself (Chapter 3.1). Although not part of the original SCARAB Project, some initial results from the follow-up study in 'Field 5' are presented here, to illustrate the value of the experimental approach. In 'Bugdale', the restricted spatial distributions of *Lepidocyrtus* spp. and *P. octopunctata* in the RIA and CFP halves of the field (**Fig. 3.2.12**) did not change when the pesticide regimes were reversed in 1997, and further monitoring provided no evidence that the manipulation of pesticide inputs had affected these species up to summer 1998 (Frampton, 2000b). The distribution patterns of Collembola in 'Bugdale' thus appear to be independent of the RIA and CFP pesticide regimes. In 'Field 5' however, reversal of the pesticide regimes had an immediate effect on the spatial distribution of Collembola and other arthropods.

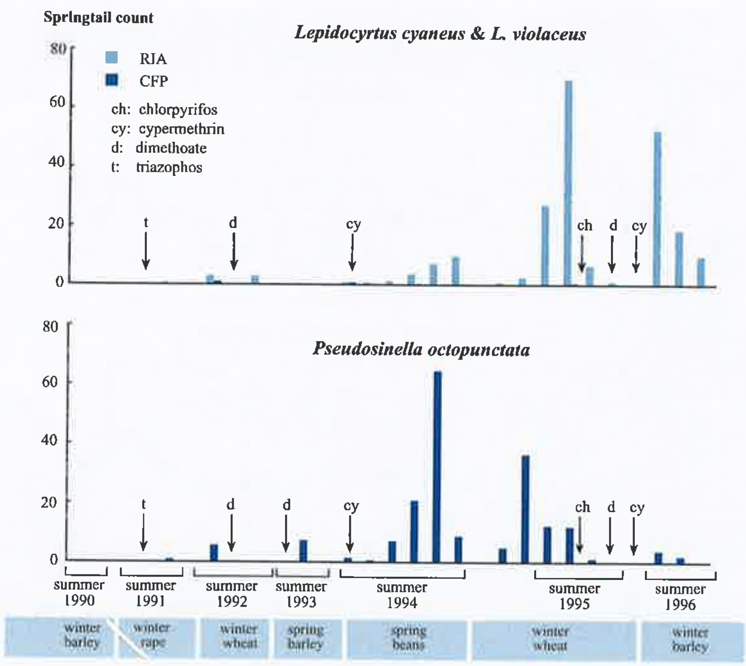

Figure 3.2.12. Mean catches per suction sample of the springtails *Lepidocyrtus cyaneus*, *L. violaceus* and *Pseudosinella octopunctata* in 'Bugdale' field, 1990–96.

Reversing the pesticide regimes in 'Field 5' provided unequivocal evidence that pesticides had long-term effects on springtails. For example, a reversal of the abundance patterns of *Isotoma viridis* and *Lepidocyrtus* spp. in the east and west areas of the field (**Fig. 3.2.13**) occurred when the RIA regime was switched to CFP and the CFP regime to RIA. There was an indication that springtails as a group and total arthropods (**Fig. 3.2.14**) may have been capable of rapid recovery once the CFP regime was removed (i.e. replaced by RIA inputs), but certain individual species of springtails exhibited little or no evidence for recovery at least within two years after removal of the CFP regime (Frampton, 2000; 2001).

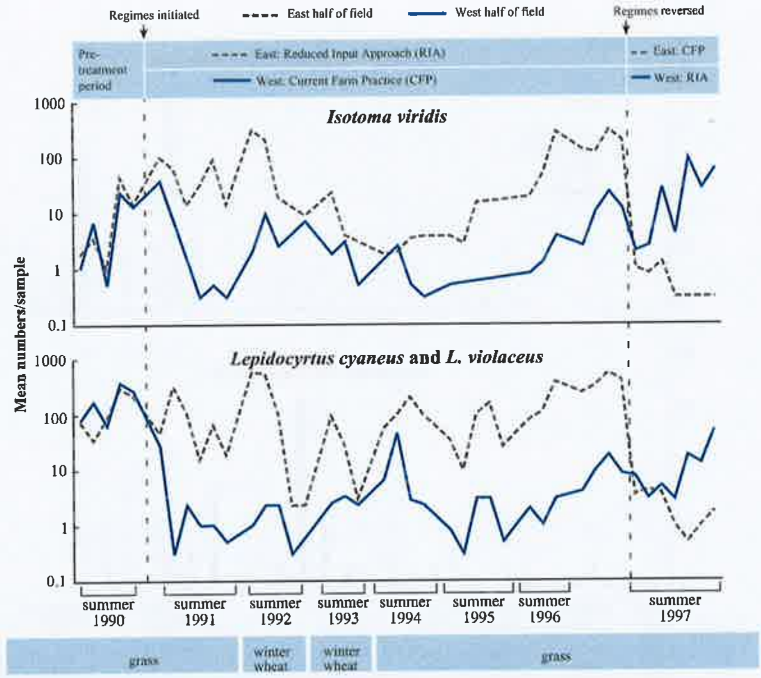

Figure 3.2.13. Mean catches per suction sample of the springtails *Isotoma viridis*, *Lepidocyrtus cyaneus* and *L. violaceus* under RIA and CFP pesticide regimes in 'Field 5', 1990–97.

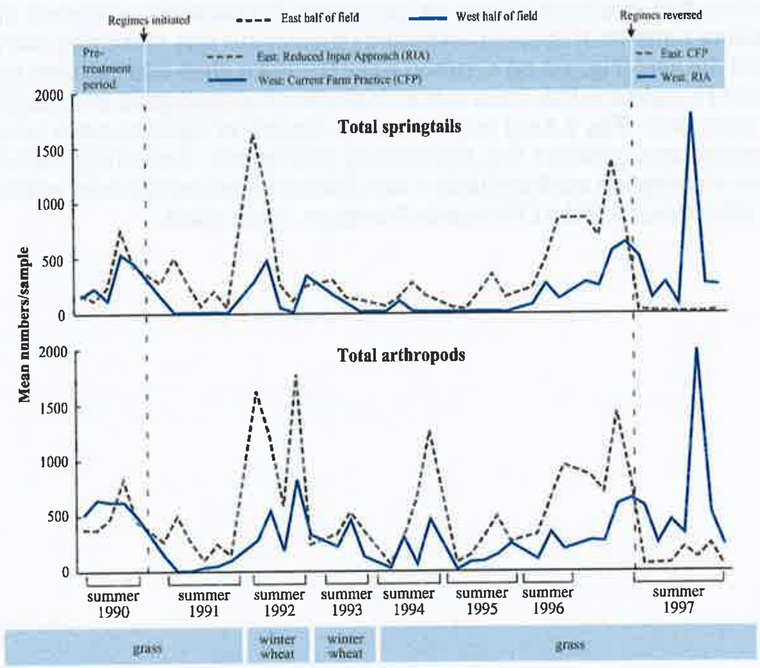

Figure 3.2.14. Mean catches per suction sample of total springtails and total arthropods under RIA and CFP pesticide regimes in 'Field 5', 1990–97.

Predictability of species in space and time

The large scale of the SCARAB Project provided a sizeable set of data that can be used to explore species' distributions in space and time. One of the findings of the Project was that relatively few species were common to all fields, or occurred in all years. This can be illustrated by ranking species according to the number of field-by-year occasions on which they were trapped. If rankings are based simply on the presence or absence of species in summer (May–July inclusive) in each year, a range of ranks from 1 (present in all fields in all summers) to 70 (present in only one field in only one summer) is obtained. On this scale, only the following captured by pitfall trapping were ubiquitous in summer distribution (rank 1): the ground beetle *Pterostichus melanarius*, rove beetles of the subfamily Aleocharinae, and the money spiders *Erigone atra* and *Lepthyphantes tenuis*. The ground beetle *Bembidion obtusum*, a species vulnerable to effects of broad-spectrum insecticides (Vickerman, 1992), was sporadic in occurrence (rank 39), whereas another ground beetle, *Pterostichus* (= *Poecilus*) *cupreus* (which is used as an indicator species in regulatory testing procedures with pesticides) (Barrett *et al.*, 1994) also had a limited distribution (rank 57). The beetle *Helophorus aequalis* was trapped only in 'Field 5' in 1991 (rank 70) but RIA catches were much larger than CFP, suggesting that the species may have been affected adversely by the use of chlorpyrifos. The 'low' occurrence ranking of this species shows that its presence in the field was actually a rare event and that, although effects of chlorpyrifos might have been severe, it would not usually be exposed to the chemical.

Discussion

Potential influence on arthropods of pre-SCARAB farm management

Crop rotations in the SCARAB Project fields prior to the Project (1987–1989) were similar to those employed during the Project itself (1990–1996, **Table 3.1.1**). However, pesticide inputs before the Project began were not the same for all fields, meaning that the impact of the CFP regime relative to previous farming practice differed between fields (**Appendix Tables 3.1.1 – 3.1.8**). At Drayton, no pesticides had been used in either 'Field 1' or 'Field 5' for at least five years prior to the SCARAB Project (Chapter 3.1), so the CFP pesticide regime represented a substantial increase in pesticide inputs. The RIA regime on the other hand represented no change in insecticide use but an increase in fungicide and herbicide use. In contrast, pesticide inputs in 'Bugdale' and 'Old Type' fields at High Mowthorpe, and 'Balk' and 'South' fields at Gleadthorpe were similar prior to the SCARAB Project (1987–1989) to the CFP inputs used during the Project itself (Chapter 3.1). In these fields, the CFP regime thus gave little change on previous pesticide inputs whereas RIA effectively represented a decrease in pesticide use from former conventional management; the change was most pronounced for insecticides (**Appendix Tables 3.1.3–3.1.8**), which were avoided altogether during the Project. In 'Near Kingston' field at Gleadthorpe, the CFP and RIA regimes both represented a general decrease in average annual inputs of fungicides, herbicides and insecticides relative to previous farming practice, with the decrease greater under RIA than CFP (**Appendix Table 3.1.5**). The type of insecticides used in 'Near Kingston' also changed, with a greater frequency of use of cypermethrin and pirimicarb under the SCARAB CFP regime (1990-1996) than previously (1987-1990); these insecticides are, respectively, less persistent and more selective than the organophosphates and aldicarb which dominated prior to the Project.

It is clear that only at Drayton ('Field 1' and 'Field 5') did the CFP pesticide regime result in an increase in pesticide inputs relative to previous practice. At Gleadthorpe and High Mowthorpe (i.e. in all other Project fields) the most obvious change from previous practice was a reduction in pesticide usage under the RIA regime. The situation at Drayton mirrors the increase in pesticide inputs which occurred at the start of the Boxworth Project (Greig-Smith *et al.*, 1992), except that overall intensity of CFP pesticide use in SCARAB was lower than in the Full Insurance regime at Boxworth (Chapter 3.1). As the fields at Gleadthorpe and High Mowthorpe received lower pesticide inputs under the RIA regime than those used prior to the Project, the RIA regime could be viewed as providing an opportunity for recovery of any arthropods whose populations had been adversely affected by previous conventional pesticide use. In fact, arthropod monitoring provided no indication of long-term increases in arthropod abundance under the RIA regime, with the exception of the springtails *Lepidocyrtus* spp. in 'Bugdale' (**Fig. 3.2.12**) and *Entomobrya multifasciata* in 'Near Kingston' (Frampton, 1997a), but it is not possible to say conclusively whether these changes were related directly to changes in pesticide use.

Comparisons with the Boxworth Project and other studies

The SCARAB Project was initiated to extend the information obtained from the Boxworth Project which focused on winter wheat (Cooper, 1990; Greig-Smith *et al.*, 1992). SCARAB set out specifically to investigate whether long-term effects of pesticides observed during the Boxworth Project (Burn, 1992; Frampton *et al.*, 1992; Vickerman, 1992) could occur in other cropping systems and at other geographical locations. One of the findings from SCARAB was that some of the species vulnerable to pesticide use at Boxworth, such as the ground beetle *Bembidion obtusum* or the springtail *Sminthurus viridis*, did not occur in all years or in all fields. The implication of these findings is that the same results might not have been obtained from the Boxworth Project had it been conducted in different years or at another site. However, a consistent result both from Boxworth and SCARAB is that a rotation which involves repeated use of organophosphorus insecticides in consecutive seasons is likely to be detrimental to arthropods, especially springtails, in the long term.

Short-term effects of synthetic pyrethroid insecticides such as cypermethrin and deltamethrin were also clearly evident but were generally short-lived. A possible explanation for the lack of long-term effects of pyrethroid insecticides is that the arthropods most sensitive to them (e.g. money spiders, aphids and flies) are capable of rapid recolonisation of fields. Conversely, arthropods which seem to have poorer recovery ability such as springtails (Frampton, 1997b) appear not to be sensitive to these insecticides (Frampton, 1999). The lack of long-term effects of pyrethroid use in SCARAB contrasts with recent findings from an analysis of the Game Conservancy Trust's long-term monitoring (1970–1995) of cereal fields in Sussex, which revealed that effects on arthropods of synthetic pyrethroid insecticides persisted over more than one season (Ewald & Aebischer, 1999). Effects of pyrethroid insecticides are spatially and temporally variable, as the persistence of residues is highly dependent upon the weather conditions after application. It is not surprising therefore that long-term effects of these insecticides were not readily detected within the relatively short duration of the SCARAB Project. The possibility that increases in the abundance of springtails could be a sensitive indicator of adverse effects of pyrethroid insecticides on their natural enemies (Frampton, 1999) warrants more detailed investigation, as springtail catches in one field ('Near Kingston') were considerably higher under the CFP regime than the RIA regime when cypermethrin had been used as a CFP treatment in the previous autumn.

Relevance of SCARAB data to risk assessments with pesticides

Knowledge of the spatial and temporal distribution of species is important for risk assessment. Species that occur rarely are less likely to be exposed to a pesticide than those that are widespread and abundant; however, if exposed, the former may have a poorer ability to recover. Pesticide applications in SCARAB often gave different effects in different fields and years, partly because vulnerable species such as *Bembidion obtusum* or *Pterostichus cupreus* were not present in all fields and in all years. Long-term data on species' distributions are therefore needed to put the results of single-field, single-season field trials into context (Eijsackers, 1997). The large data set obtained during the SCARAB Project includes information on spatial, temporal and taxonomic variability in arthropod occurrences between sites and years; this may be used in a probabilistic manner to improve estimates of exposure likelihood and persistence of effects in the field.

Prediction of recovery rates

Recovery among predatory arthropods has been investigated in a series of field experiments with broad-spectrum insecticides (Jepson & Thacker, 1990; Thomas *et al.*, 1990; Duffield & Aebischer, 1994; Duffield *et al.*, 1996), and factors affecting recovery at a landscape scale have been investigated using modelling approaches (e.g. Sherratt & Jepson, 1993; Halley *et al.*, 1996). The large empirical data set obtained from the SCARAB Project should be valuable for the refinement and validation of such models. Despite this work on predator recovery, most of the studies set up specifically to investigate pesticide side-effects on arthropods have focused on initial responses rather than on recovery (Van Straalen & Van Rijn, 1998), even though recovery is as critical to assess as is the initial response (Kelly & Harwell, 1990).

Using ecotoxicological data on pesticide toxicity and residue persistence, Van Straalen & Van Rijn (1998) predicted that arthropod recovery following the use of chlorpyrifos in 1991 in SCARAB 'Field 5' would take 0.82 years. In fact, the SCARAB data for springtails (Çilgi & Frampton, 1994) and also the Boxworth arthropod data (Çilgi *et al.*, 1993) 'provide evidence for ecological recovery lagging considerably behind expectation' (Van Straalen & Van Rijn, 1998). A plausible explanation for the discrepancy between the observed (ecological) recovery rates and predicted (ecotoxicological) rates is that arthropods in Boxworth and SCARAB were influenced by more than one pesticide, whereas Van Straalen & Van Rijn based their predictions upon single applications. Another possible explanation is that poor dispersal ability of springtails precluded the immediate recolonisation of the CFP regime after the chlorpyrifos residue had decayed. The importance of ecological processes such as dispersal has been underestimated in risk assessment (Jepson, 1997). Even among ground beetles, which have been studied extensively by ecologists, there is a need to acquire further information on biology and population dynamics (Luff, 1996). The ecology of springtails in temperate agriculture is less well known than that of beetles, despite springtails' vulnerability to pesticide use.

Side-effects of the different pesticide types

The pesticide effects observed in the SCARAB Project varied between chemical types, arthropod species, fields and years. Variation between chemical types was broadly as would be expected from previous work. A wide spectrum of non-target species is known to be affected by the organophosphates chlorpyrifos (e.g. Luff *et al.*, 1990; Asteraki *et al.*, 1992; Van Straalen & Van Rijn, 1998; Frampton, 1999) and dimethoate (Vickerman & Sunderland, 1977; Løkke, 1994); however, compared with those of dimethoate, residues of chlorpyrifos are up to 10 times more persistent, the half-life of chlorpyrifos being 16–210 days (Van Straalen & Van Rijn, 1998). Synthetic pyrethroids have broad-spectrum effects, but the range of affected species may be smaller than for dimethoate (Cole *et al.*, 1986), as residues have short persistence and are readily diluted by rainfall (e.g. Everts *et al.*, 1991). Results from the SCARAB Project agree with other recent studies which suggest that synthetic pyrethroid insecticides are not in general harmful to springtails (Wiles & Frampton, 1996; Frampton, 1999). Synthetic pyrethroids are, however, particularly toxic to spiders. For example, the non-target money spider *E. atra* is more susceptible to deltamethrin than the grain aphid (*Sitobion avenae*) target pest (Wiles & Jepson, 1992).

Previous field studies have yielded mixed effects of pirimicarb on non-target arthropods. In some studies in wheat, pirimicarb had no adverse effect on ground beetles and rove beetles (DeClercq & Pietraszko, 1984; Powell *et al.*, 1985) or on springtails (Wiles & Frampton, 1996; Frampton, 1999). In others, however (compared with controls), it reduced catches of rove beetles by 27% and catches of ground beetles by 26% (Vickerman *et al.*, 1987a) and, apparently, also caused slight reductions in the numbers of rove beetle and hoverfly larvae (Poehling, 1987). Declines in the numbers of parasitoid wasps and ladybird larvae after pirimicarb treatment were thought by Vickerman *et al.* (1987b) to be a result of starvation rather than of direct toxicity, whereas Powell *et al.* (1985) attributed effects of pirimicarb on parasitoid wasps to both direct toxicity and host removal.

In addition to the effects of insecticides, it is possible that fungicides could have influenced arthropod catches in SCARAB. Carbendazim, which was used on a number of occasions in the Project, is toxic to at least one springtail species (Frampton, 1988) and is highly persistent; indeed, effects of benomyl, which degrades immediately to carbendazim after application, may persist for 2–3 years (Krogh, 1991; Van Straalen & Van Rijn, 1998). Other fungicides used in the SCARAB Project, such as propiconazole and triadimenol have been found to be harmful to several springtail species (Frampton & Wratten, 2000). Fungicides may also indirectly affect carnivorous arthropod species, either by reducing the availability of fungi for facultative fungus-feeding predator species or by reducing the abundance of fungus-feeding prey (Sunderland, 1992).

It seems unlikely that direct side-effects of herbicides on arthropods would have occurred in SCARAB, as few (none of which was used during the Project) have exhibited direct effects in other studies (Edwards & Stafford, 1979). However, indirect effects of herbicide use could explain the higher RIA than CFP catches of herbivores in 'Balk' field during 1995 and 1996, where RIA weed densities tended to increase during the Project as a result of low herbicide inputs (Ogilvy *et al.*, 1996).

Aspects of the SCARAB Project design

The large scale of the SCARAB Project precluded the use of routine statistical tests for investigating effects of the pesticide regimes, because the experimental areas could not be properly replicated. Lack of replication in farming systems' studies is not uncommon, and the coincidence of changes in faunal abundance with pesticide applications is often used as a yardstick to judge whether pesticide side-effects have (e.g. Stinner *et al.*, 1986; Vreeken-Buijs *et al.*, 1994) or have not (e.g. House *et al.*, 1987) taken place.

The sporadic occurrence of many arthropod species poses problems for the assessment of pesticide effects. In SCARAB, several species were trapped during the phase of treatment contrasts, but were absent in the pre-treatment year. Some species were so restricted in their spatial distribution (e.g. *Pseudosinella octopunctata* – found only in part of 'Bugdale' field) that replication of the experimental areas, even if it had been feasible, would have made no improvement. Results from the original SCARAB Project and the follow-up study in which the spatial orientation of the pesticide regimes was reversed show that the SCARAB split-field design could be a valuable experimental approach where space is limited; the need for replication may be eliminated altogether if adequate pre-treatment monitoring and later spatial reversal of treatments are incorporated.

Wider relevance of the results

Of the arthropods monitored (which excluded mites), only springtails were adversely affected in the long term by Current Farm Practice pesticide use. The affected species constituted a small proportion of all species monitored (<3%) so it could be argued that arthropods in general would be unlikely to be affected adversely in the long term by regimes of pesticide use similar to Current Farm Practice. In terms of abundance, however, vulnerable species of springtail were important components of the overall arthropod fauna. *Lepidocyrtus* spp., for instance (**Fig. 3.2.11**), made up on average 26% of the total suction-sampled arthropod catch under the reduced input regime of 'Field 5' (up to 83% of the total arthropod catch on some sampling occasions). Unfortunately, it is difficult to predict the wider ecological significance of these observations without knowing the ecological importance of the species concerned. As springtails are important in the arthropod food web, and not all their predators were monitored during the

SCARAB Project, a cautious interpretation would be to assume that effects of the Current Farm Practice regime in 'Field 5' could be potentially serious if allowed to occur more widely in farmland. It is important therefore to consider the realism of the pesticide regime which led to the long-term effects in 'Field 5'.

In the SCARAB Project, long-term adverse effects of Current Farm Practice occurred under a grass and wheat rotation but not under rotations of cereals and break crops. However, such effects of pesticide use were manifest only in one of two fields under the grass and wheat rotation, largely because insecticide inputs differed between fields; long-term adverse effects of the CFP regime in 'Field 5' resulted from the repeated use of organophosphorus insecticides in consecutive seasons, especially of chlorpyrifos in grass. The grass and wheat rotation of SCARAB roughly approximates the crop survey category 'grassland less than 5 years old' (e.g. Thomas & Garthwaite, 1994). In Great Britain, such short-term grassland occupies an area *c.* 28% of that sown to arable crops, but the figure varies regionally, from only *c.* 4% in eastern England to *c.* 57% in the south west (cf. Thomas & Garthwaite, 1994; Thomas *et al.*, 1997). Besides being less widespread than arable rotations, most short-term grassland is not treated with insecticides (Thomas & Garthwaite, 1994), so the Current Farm Practice use of insecticides in 'Field 5' would appear representative only of a minority of agricultural situations. A reasonable conclusion would be that although ecological consequences of Current Farm Practice in 'Field 5' are difficult to determine, such long-term effects would be unlikely to occur in UK arable agriculture except in a minority of cropping scenarios where pest outbreaks and usage of organophosphorus insecticides occur in consecutive seasons.

Conclusions

Results from SCARAB confirm one of the findings at Boxworth, that repeated use of organophosphorus insecticides in successive seasons can lead to long-term declines in abundance of certain arthropods. However, geographic variation in the occurrence of vulnerable species suggests that some effects of pesticides seen in the Boxworth Project might not have occurred had the experiment been conducted at other sites or in different years.

Springtails were the only group of arthropods to exhibit long-term adverse responses to the SCARAB pesticide regimes, though many other arthropod groups were temporarily affected by insecticide applications and subsequently recovered. Detection of long-term effects at functional group or community level depended wholly upon the inclusion of springtail data. The information currently available shows that, among springtails, long-term effects persisted at least two years after the conventional pesticide inputs ended.

Long-term effects of Current Farm Practice pesticide use on springtails in the SCARAB Project were confined to a grass and wheat rotation which employed frequent use of organophosphorus insecticides. Such a pest management situation, though legally permissible, is relatively uncommon in UK agriculture.

Restricted spatial and temporal distributions of some arthropods means that pre-treatment monitoring in one year may not be sufficient to provide a baseline against which to contrast post-treatment data. Monitoring arthropods before and after spatial reversal of experimental regimes is an alternative approach that may be substituted for orthodox replication where site availability is limited.

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Table 3.2.1. SCARAB Project fields and cropping.

Farm:	**Drayton**		**Gleadthorpe**			**High Mowthorpe**	
Location:	52.2°N 1.8°W		53.2°N 1.1°W			54.1°N 0.6°W	
Soil:	Heavy clay		Loamy sand/sandy loam			Silty clay loam	
Field name:	Field 1	Field 5	Balk	Near Kingston	South	Bugdale	Old Type
Area (ha):	11	8	12	8	12	15	30
Cropping:							
1989–90	Grass	Grass	W. barley	Sugar beet	W. barley	W. barley	W. barley
1990–91	W. wheat	Grass	Sugar beet	S. barley	Potatoes	W. rape	S. beans
1991–92	W. wheat	W. wheat	S. wheat	W. barley	S. wheat	W. wheat	W. wheat
1992–93	Grass	W. wheat	W. barley	S. beans	W. barley	S. barley	W. barley
1993–94	Grass	Grass	Potatoes	W. wheat	Sugar beet	S. beans	W. rape
1994–95	Grass	Grass	S. wheat	W. barley	S. wheat	W. wheat	W. wheat
1995–96	Grass	Grass	W. barley	Sugar beet	W. barley	W. barley	S. barley

W = Winter; S = Spring.

Table 3.2.2. Rounded mean catch of arthropods per pitfall trap per 7-day trapping period in samples taken from the RIA area of SCARAB fields during summer (May to July). Within each site, data are averaged across all fields and years (1990–1996).

Arthropod group	**Life stage**	**No. taxa monitored**	**Mean catch per trap per 7 days (% of total catch per trap)**					
			Drayton		**Gleadthorpe**		**High Mowthorpe**	
Carabidae (ground beetles)	adults	33	21	(27.2)	19	(23.7)	12	(36.4)
Staphylinidae (rove beetles)	adults	24	13	(16.9)	13	(16.2)	4	(12.1)
	larvae	3	2	(2.6)	6	(7.5)	1	(3.0)
Lathridiidae (fungus beetles)	adults	4	1	(1.3)	3	(3.8)	1	(3.0)
Leiodidae (scavenger beetles)	adults	1	4	(5.2)	1	(1.3)	1	(3.0)
Cryptophagidae (fungus beetles)	adults	1	1	(1.3)	2	(2.5)	1	(3.0)
Other beetles	adults	16	3	(3.9)	2	(2.5)	1	(3.0)
	larvae	9	1	(1.3)	7	(8.7)	1	(3.0)
Total beetles		**91**	**46**	**(59.7)**	**53**	**(66.2)**	**22**	**(66.5)**
Linyphiidae (money spiders)	all*	12	18	(23.4)	26	(32.5)	11	(33.3)
Lycosidae (wolf spiders)	all*	1	12	(15.6)	1	(1.3)	<1	(0.1)
Other spiders	all*	1	1	(1.3)	0	(0)	<1	(0.1)
Total spiders		**14**	**31**	**(40.3)**	**27**	**(33.8)**	**11**	**(33.5)**
Total monitored arthropods		**105**	**77**	**(100)**	**80**	**(100)**	**33**	**(100)**

*Excluding eggs.

Table 3.2.3. Rounded mean catch of arthropods per square metre in suction samples taken from the RIA area of SCARAB fields during summer (May to July). Within each site, data are averaged across all fields and years (1990–1996).

Arthropod group	Life stage	No. taxa monitored	Mean catch per square metre (% of total catch per square metre)					
			Drayton		Gleadthorpe		High Mowthorpe	
Carabidae (ground beetles)	adults	16	1	(0.1)	<1	(<0.1)	1	(0.1)
Staphylinidae (rove beetles)	adults	14	8	(0.6)	6	(0.9)	7	(0.4)
	larvae	1	8	(0.6)	6	(0.9)	11	(0.7)
Lathridiidae (fungus beetles)	adults	4	5	(0.3)	15	(2.2)	13	(0.8)
	larvae	1	5	(0.3)	4	(0.6)	15	(0.9)
Curculionidae (weevils)	adults	3	<1	(<0.1)	<1	(<0.1)	9	(0.5)
Cryptophagidae (fungus beetles)	adults	2	1	(0.1)	2	(0.3)	6	(0.4)
Nitidulidae (pollen beetles)	adults	1	2	(0.2)	<1	(<0.1)	2	(0.1)
Other beetles	adults	14	1	(0.1)	1	(0.1)	1	(0.1)
	larvae	3	2	(0.2)	1	(0.1)	1	(0.1)
Total beetles		**59**	**33**	**(2.5)**	**35**	**(5.1)**	**66**	**(4.1)**
Hemiptera (bugs, inc.aphids)	all*	11	199	(15.3)	241	(34.8)	213	(13.1)
Diptera (flies)	adults	22	147	(11.3)	53	(7.7)	106	(6.5)
Thysanoptera (thrips)	all*	1	93	(7.1)	197	(28.5)	113	(6.9)
Hymenoptera (parasitic wasps)	adults	5	36	(2.8)	16	(2.3)	43	(2.6)
Araneae (spiders)	all*	3	20	(1.5)	7	(1.0)	18	(1.1)
Collembola (springtails)	all*	33	774	(59.5)	143	(20.6)	1069	(65.7)
Total monitored arthropods		**134**	**1302**	**(100)**	**692**	**(100)**	**1628**	**(100)**

*Excluding eggs.

Table 3.2.4. Functional grouping of arthropods captured by (a) D-vac suction sampling and (b) pitfall trapping.

(a)	**Coleoptera (beetles)**	**Diptera (flies)**	**Other arthropods**
Predators	Carabidae (excl. *Amara* spp.) Cantharidae some Coccinellidae	Dolichopodidae Empididae	Nabidae Araneae
Herbivores	*Amara* spp. (Carabidae) Chrysomelidae some Cryptophagidae Curculionidae Elateridae Nitidulidae	Agromyzidae some Chloropidae Opomyzidae Tipulidae	Aphididae Cicadellidae Delphacidae Miridae Thysanoptera
Detritivores	some Cryptophagidae Lathridiidae Phalacridae	Bibionidae Chironomidae Drosophilidae Lonchopteridae Mycetophilidae Phoridae Sciaridae Sepsidae Sphaeroceridae	Collembola
Omnivores	Staphylinidae	Cecidomyiidae	

(b)	**Coleoptera (beetles)**	**Other arthropods**
Predators	Carabidae (excluding *Amara* spp.), Cantharidae, some Coccinellidae	Araneae, Opiliones Syrphidae (larvae)
Herbivores	*Amara* spp. (Carabidae), Chrysomelidae, some Cryptophagidae, Curculionidae, Nitidulidae, Elateridae	Tipulidae (larvae)
Detritivores	some Cryptophagidae Lathridiidae Leiodidae Silphidae	
Omnivores	*Helophorus* spp. (Hydrophilidae) Staphylinidae	

Table 3.2.5. Proportion of treatment-phase years in which the CFP contribution to the total catch deviated by more than 20% from the pre-treatment CFP contribution. Based on summer data (May–July inclusive).

Arthropod group	Sample type	Change in CFP share of catch relative to pre-treatment phase		
		% of years with decrease	% of years with increase	Number of observations*
Total beetles	D-vac	10	0	48
Total bugs (Hemiptera)	D-vac	48	13	48
Total thrips	D-vac	33	4	48
Total flies	D-vac	8	0	48
Total parasitic wasps	D-vac	17	2	48
Total spiders	D-vac	27	2	48
Total Isotomidae (springtails)	D-vac	42	6	36
Total Entomobryidae (springtails)	D-vac	38	36	39
Total springtails	D-vac	25	17	48
Total arthropods	D-vac	29	2	48
Bembidion spp. ground beetles	Pitfalls	25	0	8
Total ground beetles	Pitfalls	21	0	48
Total rove beetles	Pitfalls	17	0	48
Total beetles	Pitfalls	15	0	48
Erigone dentipalpis spiders	Pitfalls	35	0	31
Total spiders	Pitfalls	8	0	48
Total carnivores	D-vac	38	2	48
Herbivorous flies	D-vac	11	4	47
Total herbivores	D-vac	40	6	48
Detritivorous beetles	D-vac	15	2	46
Detritivorous flies	D-vac	15	10	48
Total detritivores [- springtails]	D-vac	6	0	48
Total detritivores [+ springtails]	D-vac	25	6	48
Total carnivores	Pitfalls	13	0	48
Total herbivores	Pitfalls	19	3	36
Total detritivores	Pitfalls	27	5	44
Total omnivores	Pitfalls	15	0	48

*There were up to a total of 48 observations (8 fields × 6 years).

THE EFFECTS OF PESTICIDE REGIMES ON SOIL MICROFLORA

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Introduction

The significance of soil microflora in agroecosystems

Soil microorganisms (bacteria, fungi, algae, viruses and protozoa) form an important living portion of the organic matter content of soil. Although by definition they are individually small, their presence at very high numbers in all agricultural soils accounts for the vast bulk of (non-root) soil biomass; in addition, microbial activities (e.g. transformations of organic soil components) play a central role in maintaining soil fertility. Fungi generally form the largest sub-component of soil biomass on a weight basis (typically about 70%), whereas bacteria tend to be the most numerous soil microorganisms (*c.* 10^9 bacteria/g). Despite accounting for only 1-3% of organic carbon, microbial populations (the soil microbial biomass) are the major agents of chemical and biochemical transformations in soil (e.g. nutrient cycling, biodecomposition, detoxification of man-made compounds such as pesticides). Microbial processes are largely responsible for soil humus generation and the decomposition of animal and plant matter, which release nutrients (e.g. phosphate and ammonium) necessary for higher plants. By immobilising inorganic elements such as nitrogen, phosphorus and potassium, soil microorganisms also act as a nutrient store for crop plants, since the microbial forms of these elements are more readily available than those forms present in non-living organic soil fractions. Any factor that affects the composition and activities of individual soil microbial communities may, therefore, have the potential to influence the entire soil chemical environment. Thus, since it is recognised that agricultural pesticides influence soil microbial communities (Domsch & Greaves, 1987) and therefore soil health, the impact that pesticide treatments may have on soil microflora is an important environmental issue.

Effects of pesticides on soil microflora

Alterations in agricultural management practices influence the long-term quantity and composition of soil organic matter content and, hence, soil quality. However, these changes are difficult to detect in gross chemical determinations in the short and medium term (i.e. less than ten years). Since microbial populations, as the reactive fraction of soil organic matter, are much more sensitive to changes in land management practice than soil organic matter as a whole, measurement of soil microflora and their activities can give early warnings of deleterious changes in soil chemistry long before they can be detected by other means (Powlson & Jenkinson, 1976). Specifically in relation to pesticide usage, it is essential to understand the consequences of long-term application of these compounds on soil microflora if sustainable productive agriculture is to be achieved. Continuous and long-term soil exposure to damaging pesticides might be expected to reduce or eliminate populations of non-target soil microorganisms, leading to alterations in biochemistry and, hence, nutrient dynamics of a soil. The physical properties of a soil can also be modified by pesticide usage; for instance, pesticide-mediated massive reductions of soil fungi can decrease structural stability and water-holding capacity of the soil (Van Doorn, 1987).

In relation to possible consequences to non-target soil microbial biomass, an applied pesticide may have a direct effect (resulting in toxicity and death or impairment/enhancement of growth, reproductive or survival strategies) or may

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exert an indirect effect. The latter is less easily defined and may be manifested by subtle changes in community interactions, or may arise from changes within the crop plant, e.g. herbicide-induced alterations in root exudation. A change at community level may predispose, or discourage, the survival of economically important crop pathogens. Irrespective of whether the pesticide acts on non-target microbiota in a direct or indirect fashion, soil microbial biomass may respond positively (= stimulation) or negatively (= inhibition). Stimulation of variable components of the biomass can occur if the pesticide: (a) is metabolised as a growth substrate for microorganisms; (b) increases root exudation into the soil by stressed crop or target weeds; (c) releases available nutrients from killed target and non-target organisms (e.g. soil invertebrate pests and non-target soil protozoa, respectively); or (d) selectively removes predation (e.g. fungus-feeding mites). Inhibition of components, or all, of the soil microbial biomass can occur if the pesticide exerts a general biocidal effect (e.g. broad-spectrum fungicides on non-target soil fungi), or selectively removes an important nutrient source for the soil community.

The influence of climate on soil microflora

The prominent influence of climate must be considered when assessing pesticide side-effects on non-target microflora. Soil microbial populations and activities are subject to very high degrees of natural variability, owing to the influence of, for example, season, moisture contents and soil temperature (Cook & Greaves, 1987). Seasonal variations in microbial communities in the same soil can be very great. Depressions in microbial parameters of up to 90% occur quite frequently (Somerville, 1987). Also, as well as seasonal variability, spatial variability in microbial populations within the soil profile occurs, and numerous investigators have correlated microbial parameters with other spatially dependent soil physical or chemical properties (see Wollum, 1994). Therefore, variability in microbiological measurements must therefore be expected to occur in the absence of any biological disturbance arising from pesticide application.

Methods for studying soil microbial communities

Techniques that are available to the soil microbiologist can be divided into four types of approach: (a) measurement of all or parts of the microbial biomass; (b) detection of specific biochemical 'fingerprints' or molecular markers; (c) assessment of microbial metabolic activity; and (d) isolation and characterisation of culturable microorganisms. In addition, it is highly desirable to monitor soil chemistry (carbon (C) and nitrogen (N), etc.) in tandem with microbiological examination, since organic soil components are essential to the microflora, not only as nutrient sources but also as physical soil conditioners that affect soil aggregation and water-holding capacity and availability.

Soil microbial biomass

Estimation of the size of the soil microbial biomass can provide a more sensitive measure of change than total organic matter contents because it has a much faster rate of turnover, and can usefully reveal changes within 1-5 years rather than decades (Jenkinson & Ladd, 1981). Early work showed that broad-spectrum soil fumigants caused great and persistent reductions in microbial biomass (Jenkinson & Powlson, 1970). The more selective pesticides that are currently used will have less drastic effects on microbial biomass as a whole, yet gross changes in the size of the soil microbial pool following pesticide treatment are widely reported in field studies (Anderson *et al.*, 1981; Jones *et al.*, 1992; Harden *et al.*, 1993). Thus, measurement of the total soil microbial biomass is considered to be a valuable tool for monitoring pesticide side-effects on non-target soil microbiota. Techniques for selectively quantifying component parts of microbial biomass are traditionally based on microscopic direct measurement of appropriately stained fungal mycelia

(Soderstrom, 1977) and soil bacteria (Fry, 1990). Mass conversion factors are then applied to calculate microbial biomass C (determined as µg C/g soil) from individual measurements of microbial size (μm^3/g soil).

Metabolic activities

Microbial activities (e.g. C and N mineralisation and transformation, dehydrogenase activity) are often measured as part of soil monitoring programmes. Soil microbial respiration may be quantified by measuring carbon dioxide production in the absence or in the presence of an added substrate (= basal respiration or substrate-induced respiration, respectively). This technique is sensitive to soil management practices and has frequently been used for assessment of side-effects of pesticides (Malkomes, 1987), though its sensitivity has been questioned (e.g. by Vonk & Barug, 1987).

Microbial population dynamics in soil

Conventionally, individual microbial populations in soil have been identified by counting individual microbial colonies growing on agar plates. Soil microorganisms that are amenable to plate isolation probably form much less than 2% of the total population (Torsvik *et al.*, 1994), and viable counts often correlate poorly with microbial biomass and activity (Frankenburger & Dick, 1983). Also, bacterial populations from the same soil exhibit variations in size and composition when cultured on a variety of different growth media (Sorheim *et al.*, 1989). Thus, enrichment and isolation procedures cannot provide information on the relative ecological importance and subtle trophic interactions of *in situ* soil micro-organisms. However, if cultural procedures have been criticised as quantitative determinants for microbial communities (Cook & Greaves, 1987), they still have some value from a qualitative point of view; the diversity of culturable species is likely to be related to that of the total microflora (Soulas, 1996). Counting soil microorganisms on agar plates is often incorporated into microbiological protocols for comparative purposes, and may sometimes provide useful additional information when stress (such as application of a pesticide) is placed on the soil microbial community (e.g. Voets *et al.*, 1974; Suyama *et al.*, 1993).

Sampling sites and methods

Sampling sites

'Old Type' field (High Mowthorpe) and 'South' and 'Balk' fields (Gleadthorpe) were chosen for study within SCARAB because these sites provided contrasting soil types with similar crop rotation systems. 'Old Type' field was divided into two distinct study areas: 'Old Type North' and 'Old Type South' (Chapter 3.1). The effect of pesticide regime on soil microbial communities was studied using a range of validated methods for soil microbiology. During the baseline year (1990), soils were sampled on six occasions (at *c.* 2-month intervals) and, following the inception of the differential pesticide regimes in 1991, at times dictated by pesticide applications (normally pre-treatment and seven days post-treatment). The two contrasted pesticide regimes were Current Farm Practice (CFP) and Reduced Input Approach (RIA) as detailed in Chapter 3.1. Soil sampling involved taking six samples from each treatment plot (each of *c.* 1 kg from a depth of between 2 and 10 cm) at intervals of 10 m on an oblong grid pattern. Soils were sealed in polyethylene bags and returned, cooled, to the laboratory where they were sieved (mesh < 6.7 mm) and stored refrigerated (at 4°C) before processing.

Microbiological methodologies

Soil microbial biomass estimation

Total microbial biomass and fungal biomass were assessed using chemical assay and visual observation methods respectively; these methods provide comparative and complementary approaches for estimating microbial pool sizes. The fumigation-extraction technique (Vance *et al.*, 1987) was used to measure total microbial biomass. Fungal biomass was assessed by measuring stained fungal mycelia, and a dual staining technique of Williamson & Johnson (1990) was used to differentiate between metabolically active and moribund fungal hyphae.

Isolation and enumeration of soil microbial populations

Microbial populations were routinely monitored by counting bacterial and fungal colonies grown on nutrient media (agar plate enumeration) during the first four years of the project in 'Old Type' field. Thereafter, these populations were monitored occasionally (treatment dependent) in both the High Mowthorpe and Gleadthorpe sites. A range of selective media was used to enumerate populations of bacteria, including Actinomycetes, and fungi (methodologies cited in Duah-Yentumi & Johnson, 1986).

Growth rates of soil bacteria extracted from 'Old Type' field, High Mowthorpe, were analysed periodically from 1994 onwards, using a radiolabelled thymidine assay (Baath, 1990).

Soil metabolic activities

Soil respiration in the presence or absence of glucose amendment was estimated by titrimetric measurement of CO_2 release, following a slightly modified method described by Williamson & Johnson (1990). Methods of measurement of soil dehydrogenase and hydrolysis of fluorescein diacetate were investigated periodically as possible side-effect indicators of soil microbial activities. Dehydrogenase activity has been used as a measure for overall microbial activity (Casida, 1977), and was proposed as a test for assessing pesticide side-effects on soil microflora (Malkomes, 1987). Schnurer & Rosswall (1977) used the hydrolysis of fluorescein diacetate to estimate microbial activities in soil, and this test was evaluated for use in the test array in 1993.

Physico-chemical analyses

In tandem with the microbiological measurements, soil and air temperatures were recorded at the time of sample collection, and soil physical and chemical analyses were carried out (total organic C, total organic N, soil pH and water content).

Results

Limitations in the interpretation of pesticide side-effects on soil microflora

The design of the experiment dictated that differences found between CFP and RIA microbial populations were the inferred result of differential pesticide treatment. However, some results from specific experiments supported field observations, e.g. the behaviour of soil microflora following dimethoate insecticide treatment in laboratory-based experiments. Detection of pesticide side-effects was also complicated by the variability of soil microbial communities to pesticide applications, ranging from 'positive', 'no effect' and 'negative effects' on microbial variables, even when the same pesticide formulation was used. Similar findings have been reported elsewhere (e.g. Somerville, 1987; Schuster & Schroder, 1990).

Some side-effects on microflora may have been masked as, on one occasion, owing to adverse weather conditions, mancozeb was applied on different dates to CFP and RIA (17 and 19 July 1991, respectively) in 'South' field at Gleadthorpe.

Additionally, the CFP and RIA pesticide regimes in potato and sugar beet at Gleadthorpe in 1991 were too similar to differentiate any pesticide side-effects. A further complication was that previously applied pesticides may have persisted in the soil, which would then potentially mask the effects of newly-applied compounds. Lastly, any slight variation in the soil environment (e.g. differences in soil moisture content) between the selected plots was likely to influence the outcome of pesticide side-effects. Identification of persistence of pesticides was accounted for by sampling before and after pesticide applications, whenever circumstances allowed. However, the remaining problems (e.g. variations in soil environment) could not be addressed, and sometimes complicated interpretations of pesticide regime effects. Nevertheless, differences in microbial parameters between individual treatments were observed in both soil types, and measurements of trends in microbial biomass size of the two regimes became increasingly divergent in 'Old Type' field (High Mowthorpe).

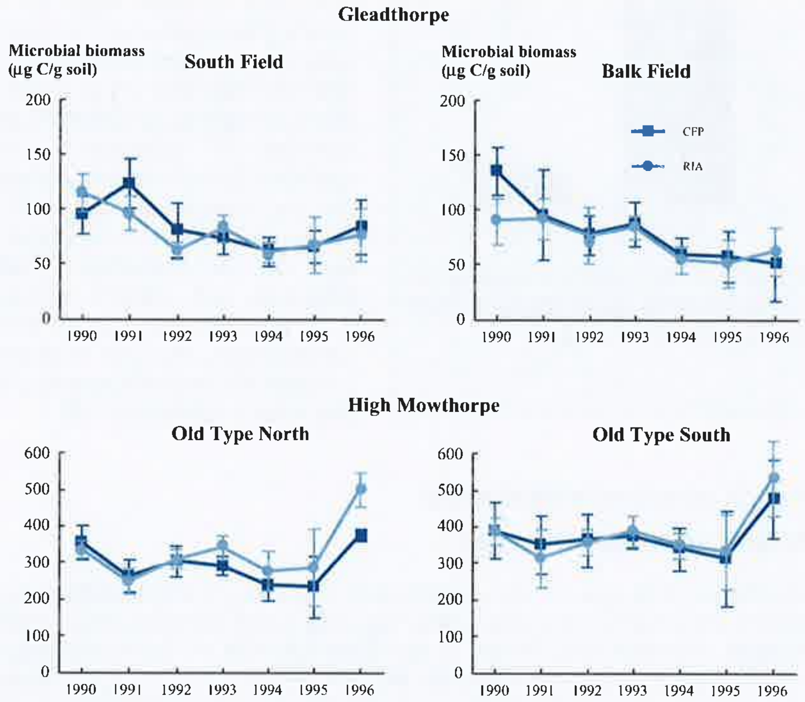

Figure 3.3.1. Changes in annual average microbial biomass at the Gleadthorpe and High Mowthorpe sites (error bars denote standard deviation).

Effect of weather patterns on soil microbial variables

Weather conditions are important factors. They govern the outcome of microbial responses to chemical exposure, and extreme variations in microbial variables have been reported in field trials elsewhere (Schuster & Schroder, 1990). Similarly, weather conditions (such as rainfall and temperature) were considered to be dominant factors in quantity, and possibly quality, of microbial indicators in the SCARAB sites. There was indirect evidence that weather patterns played a role in the disclosure of longer-term regime effects on microbial biomass in 'Old Type' field in 1996. The years 1991, 1995 and 1996 were exceptionally dry, compared with the 30-year mean average rainfall (738 mm for High Mowthorpe: data from the High Mowthorpe meteorological station), and soil microbial population sizes were often lower than average in these years (**Fig. 3.3.1**). The massive effect of soil desiccation on biomass parameters was demonstrated during monitoring carried out in August 1995: the total monthly precipitation was exceptionally low (4.9 mm) and the biomass was temporarily reduced by up to 87% in all plots (47–177 µg microbial C/g soil), compared with an expected average of 350 µg microbial C/g soil for the crop and time of year (**Fig. 3.3.2**). This phenomenon has also been reported elsewhere (Van Gestel *et al.*, 1992). Concurrently with the dramatic fall, 'labile' extractable C (considered to be a nutrient source for microbial biomass) in soils sampled in August 1995 doubled in concentration from a mid-summer average of 54 µg to 100 µg in 1995, and it remained elevated in all soil samples from 'Old Type' field taken in 1996. The rises in extractable C were probably the result of a slower rate of utilisation of soil labile C by drought-stressed, dying, soil microflora that was, in turn, increasingly contributing to the 'labile' C pool. Weather conditions prevailing during the following severe winter then further increased nutrient availability for the soil microbial community — freeze-thaw episodes are known to influence chemical and biological properties of soil (Edwards & Cresser, 1992), and to release large quantities of 'labile' compounds (Christensen & Tiedje, 1990). The final sampling year, 1996, was characterised by an increase in microbial biomass in 'Old Type' field (**Fig. 3.3.1**). Therefore, this flush might be considered to be an outcome of increased nutrient availability for soil microbiota following the dry summer of 1995 and the subsequent severe winter. Since the size of the microbial biomass influences soil nutrient dynamics, it is possible that, under certain circumstances, the type of pesticide management may modify soil cycling processes in agricultural soil.

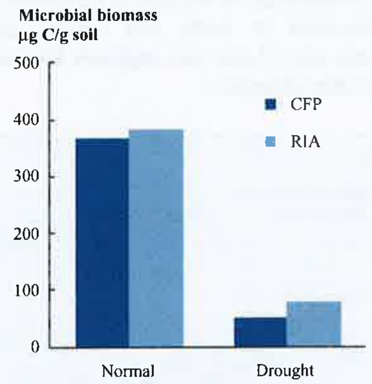

Figure 3.3.2. The effect of drought during the summer of 1995 on microbial biomass in 'Old Type North', High Mowthorpe.

Trends in annual microbial biomass

'Old Type' field, High Mowthorpe

The effect of crop type on the average size of the soil microbial biomass was demonstrated clearly in the years 1990–1995 (**Fig. 3.3.1**). Cereal cropping tends to stimulate microbial and faunal populations because of increased nutrient availability via rhizodeposition from the fine root networks (Jensen, 1993), whereas the root systems of certain break-crops (e.g. oilseed rape) are unlikely to support similar deposition rates. Thus, soil microbial biomass was generally less under break-crops (1991 and 1994) than in years where cereals were grown: 299 µg/g under beans and rape, compared with 368 µg/g under barley and wheat. Similar differences have been found elsewhere with rotations of oats and alfalfa (Fyles *et al.*, 1988) and sugar beet and cereals (Kaiser & Heinemeyer, 1993). For the first six years of the project, although individual pesticide treatments did produce transient changes (see below), there were no significant differences in average annual microbial biomass between the two regimes in 'Old Type' field. However, after five years of differential applications, annual microbial biomass measured in 1996 was greater under RIA treatment than under CFP, and was significantly so in 'Old Type North' ($P = 0.002$, **Fig. 3.3.1**). It may be inferred from **Fig. 3.3.1** that the effects of the CFP regime were cumulative in 'Old Type North', at least over the duration of the study. Since the size of the microbial biomass influences soil nutrient dynamics, it is possible that, under certain circumstances, the type of pesticide management employed may modify soil-cycling processes in agricultural soil. Some underlying reasons for the apparent increases in microbial biomass are discussed below.

'South' and 'Balk' fields, Gleadthorpe

On average, the microbial biomass loading in Gleadthorpe soils was one third that of High Mowthorpe soils. In contrast to the latter, no trends were detected in microbial biomass that were ascribable to crop rotation and management practices (**Fig. 3.3.1**). Break crops (potatoes or beet) were subjected to higher-rate and more frequent herbicide and fungicide applications (even at RIA-input rates) than break crops in 'Old Type' field (High Mowthorpe). Although multiple applications appeared to depress soil microbiota (biomass remained low throughout the 1994 growing season in 'Balk' field, where fungicides were applied repeatedly), break crops at Gleadthorpe were not associated with significantly smaller average microbial biomass. The lack of response of the Gleadthorpe microflora to crop rotation was unexpected, for several reasons. In terms of a.i. units (Chapter 3.1), the rates of pesticide applications onto break crops were approximately double those used on cereals, and also higher than those employed on the break crops in 'Old Type' field. The underground root structures of the cereals and break crops in 'South' field and 'Balk' field were substantially different, as in 'Old Type' field. Given that the rotations between the two farm sites were not radically different, and assuming that the rates of rhizodeposition were broadly similar, it is curious that there was little relation between crop type and microbial biomass size in the Gleadthorpe soil. It may be conjectured that this may have been the outcome of increased leachability of root exudates in the light, sandy Gleadthorpe soil (thereby removing them as microbial growth substrates); it is considered unlikely that soil microflora in the two soil types differed markedly in the rates of uptake of their substrates.

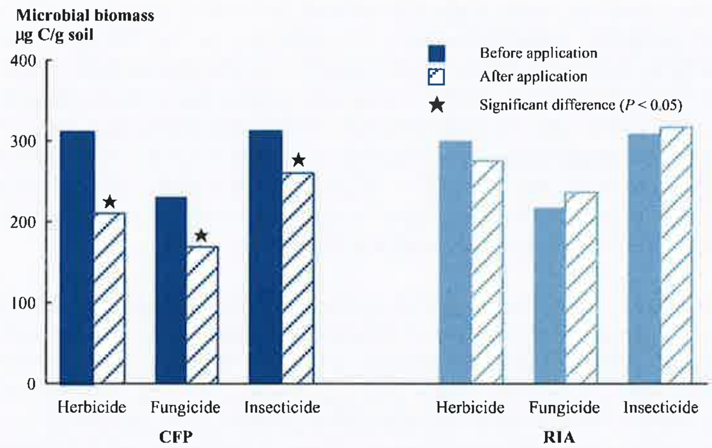

Figure 3.3.3. The effect of differential pesticide treatments on microbial biomass in 'Old Type' field, High Mowthorpe. Herbicide: diflufenican + isoproturon applied February 1995; fungicide: flusilazole + carbendazim + fenpropimorph applied April 1993; insecticide: cypermethrin applied November 1992.

Effects of pesticide treatments on microbial biomass

In the absence of recent (within 12 weeks) pesticide applications, and where there were no differences in soil water contents, microbial biomass in the two treatment regimes tended to be similar (i.e. not significantly different, $P > 0.05$). However, following pesticide treatment, although gross differences between CFP and RIA plot pairs generally represented only *c.* 30-40 µg microbial biomass C/g soil, these alterations were frequently significantly different. Analyses of plots sampled prior to, as well as following, pesticide applications strengthened the argument that transient changes in soil microbial biomass values could be attributable to the effect of pesticide treatment (**Fig. 3.3.3**). Generally, in both soil types, the pattern of magnitude of pesticide effects on soil microbiology was fungicides > insecticides & herbicides (**Table 3.3.1**), a trend that has been observed elsewhere (Gupta & Yeates, 1997).

'Old Type' field, High Mowthorpe

Differences in total and fungal biomass were usually greater following recent (within 12 weeks) differential pesticide inputs, than in the absence of such treatments. During the baseline year in 'Old Type' field, biomass variations between replicate plot pairs were small and generally not significantly different. The exceptions to this (e.g. 'Old Type South', in June and December 1990) arose from small, but significant, variations in soil water content in the plot pair. In subsequent years, when the differential pesticide regimes were imposed, temporary fluctuations of up to 60% occurred between plot pairs, and a pattern of treatment effect gradually emerged. Although the magnitude varied (probably as a result of the slightly different organic matter contents), microbial biomass in both plots responded similarly to individual pesticide applications. In the first differential treatment year (1991), herbicide and fungicide treatments appeared to stimulate microbial biomass in CFP plots. Thereafter, increasingly, biomass became consistently and significantly lower in CFP plots compared with RIA plots. However, this did not translate into an average annual reduced microbial biomass content under CFP treatment until the final (sixth) year of the rotation (**Fig. 3.3.1**).

'South' and 'Balk' fields, Gleadthorpe

Generally, compared with High Mowthorpe, microbial biomass responses to identical pesticide treatments were less obvious in the Gleadthorpe fields, particularly in 'Balk' field (**Table 3.3.1**). A significant difference between paired plots in the absence of recent (12 weeks or less) differential inputs could often be related to variations in soil water content between CFP and RIA portions of the same field. The two Gleadthorpe fields were situated on a slight hill, which often produced a water gradient from top ('South', CFP) to bottom ('Balk', CFP). Additionally, although difficult to verify, differences in soil water content probably sometimes concealed effects generated by pesticide treatment.

Explanations for the lack of response in the Gleadthorpe fields may be related to the lower organic matter content of this soil, its greater leaching properties and greater (and more frequent) differences in soil environment (e.g. water content) between paired CFP and RIA plots. Soils of varying organic matter and microbial biomass content have correspondingly different rates of degradation of pesticides and, thus, different durations of exposure (Voos & Groffman, 1997). Therefore, the same pesticide may not produce the same effect on soil microflora in different soils, as occurred with pirimicarb application onto 'Old Type' field at High Mowthorpe (inhibition) and 'South' and 'Balk' fields (no effect) at Gleadthorpe in 1991.

Microbial population changes in SCARAB plots

During the course of the baseline year, soil microbial populations in 'Old Type' field were found to fluctuate, depending on the season, but there were no significant differences between plots. In contrast, plate counts in soil sampled before and after differential pesticide applications frequently produced significant alterations in culturable microorganisms, with effects most evident following fungicide applications. Changes in numbers of culturable microorganisms were frequently supported by other experimental data (i.e. microbial biomass). In May 1993, both High Mowthorpe (**Table 3.3.2**) and Gleadthorpe sites recorded significant reductions ($P < 0.05$–0.001) in culturable non-target fungal populations following differential fungicide inputs (with soil fungi forming the largest component of the microbial population); at the same time, significant transient decreases were found in microbial biomass values in CFP plots. Coincidentally, populations of culturable bacteria were seen to increase transiently in CFP plots. This shift in fungal/bacterial populations was observed frequently during SCARAB, and elsewhere (Anderson *et al.*, 1981; Jones *et al.*, 1992), and was explained as growth of faster-growing bacterial populations on dead fungicide-susceptible biomass.

Application of the insecticide dimethoate onto CFP sections only was followed by highly significant reductions in fungal and bacterial plate enumerations in soil from CFP sections of 'Old Type' field, High Mowthorpe, in 1996. Here, data from plate counts were supported by similar patterns in total and fungal biomass C measurements and some significant reductions in bacterial growth rates (measured by thymidine uptake) (**Table 3.3.3**). CFP plots produced lower microbial population counts than RIA, and these scores were also lower than those typically recorded for the site (i.e. CFP counts for August 1996 compared with CFP counts averaged over the period 1990–1995). Whether this was an anomaly, or symptomatic of change consequent on the six-year management regime, could not be addressed with the data available.

Although transient population shifts were detected following differential fungicide applications, comparisons of microbial populations in the final soil samples taken in 1996 indicated that there were no obvious differences in species of culturable fungi and bacteria within the two management regimes.

Soil microorganisms amenable to isolation by agar plate techniques represent only a small proportion of the entire soil microbial community (Torsvik *et al.*, 1994). However, comparisons of abundant microbial groups and genera (total bacterial and fungal counts, actinomycetes, *Trichoderma* and *Penicillium* populations) in CFP and RIA plot pairs often produced data that were amenable to statistical analysis and interpretation. It can be argued that the pesticide-sensitive microbial populations are over-represented when using plating methods and, therefore, that agar plate enumerations form a more sensitive parameter when monitoring side-effects.

Soil microbial activity measurements

Soil mineralisation rates

No large alterations in soil mineralisation rates (basal and substrate-amended) were detected in the course of the project in either of the two pesticide regimes. The fact that the relatively mild CFP regime (e.g. compared with the Full Insurance regime of the Boxworth Project) produced no disruption in soil CO_2 release may not be surprising, since it has been shown that only a few pesticides elicited changes in soil respiration rates, and then mostly at concentrations ten times greater than field rates (Vonk & Barug, 1987).

Soil enzyme activities

Dehydrogenase was measured in 'Old Type' field towards the end of the SCARAB project (August 1996), where there were found to be site-dependent, but not regime-dependent, differences in activity. Fluorescein diacetate hydrolysis was used to detect the hydrolytic capacities of SCARAB soils. However, initial experiments (using field soils that had been manipulated to contain varying proportions of bacterial and fungal populations) failed to produce meaningful microbial activity differences. It was concluded that this test was not sensitive enough to detect changes brought about by CFP rates of pesticide application.

Effect of herbicides on soil microflora

The effects of herbicides on non-target soil microbial communities are often highly variable (Malkomes, 1987; Schuster & Schroder, 1990; this study). It is probable that this variability is related to the indirect nature of the effect arising from changes in the quantity or quality of plant inputs (organic matter from dying vegetation, herbicide-induced root exudation) to the soil, rather than to direct toxicity of the herbicide.

Most post-emergence herbicides are designed to have residual soil activity. Therefore, their apparent lack of major influence on microbiological parameters in SCARAB was reassuring (**Table 3.3.4**). Exceptions to this were bentazone, glyphosate, metsulfuron-methyl and formulations of isoproturon. Total and fungal biomass measurements were transiently, but repeatedly, reduced following treatment with CFP-rate herbicide mixtures containing isoproturon, although the effects were more marked in 'Old Type' field, High Mowthorpe, compared with the Gleadthorpe fields ('Old Type North' in 1992, $P < 0.01$; 'Old Type North' and 'South' in 1993 and 1995, $P < 0.05$). In 1995, analysis of 'Old Type' soil following an application of diflufenican + isoproturon indicated that, whereas the biomass parameters were significantly reduced, the bacterial biomass and activity (measured by radiolabelled thymidine assay) increased (significantly so in 'Old Type South'). Such population shifts in soil following pesticide treatment have been identified elsewhere, using a range of discriminative techniques (Heilman *et al.*, 1995). Dose-related transient reductions in microbial biomass were also recorded at Gleadthorpe following metsulfuron-methyl treatment in 1992, but not in 1995 when extremely arid soil conditions impeded analyses. Similar findings with isoproturon mixtures and sulphonylurea herbicides have been reported in other field experiments (Schuster & Schroder, 1990; Harden *et al.*, 1993; Junnila *et al.*, 1994) and, as in SCARAB, these effects were found to be transitory.

Significant temporary increases in microbial biomass were found in 'Old Type' field following treatment with bentazone and glyphosate. This apparent stimulation was probably due to herbicide-induced increased root exudation rather than to any direct effects of the pesticides, since their bioavailability (necessary for imposition of direct effects) would have been curtailed by rapid deactivation following soil contact (Kidd & James, 1991). Examples of short-term stimulation of soil microbial populations by herbicides, sometimes preceded by initial inhibition, have been reported widely (Chakravarty & Chatarpaul, 1990; Junnila *et al.*, 1994).

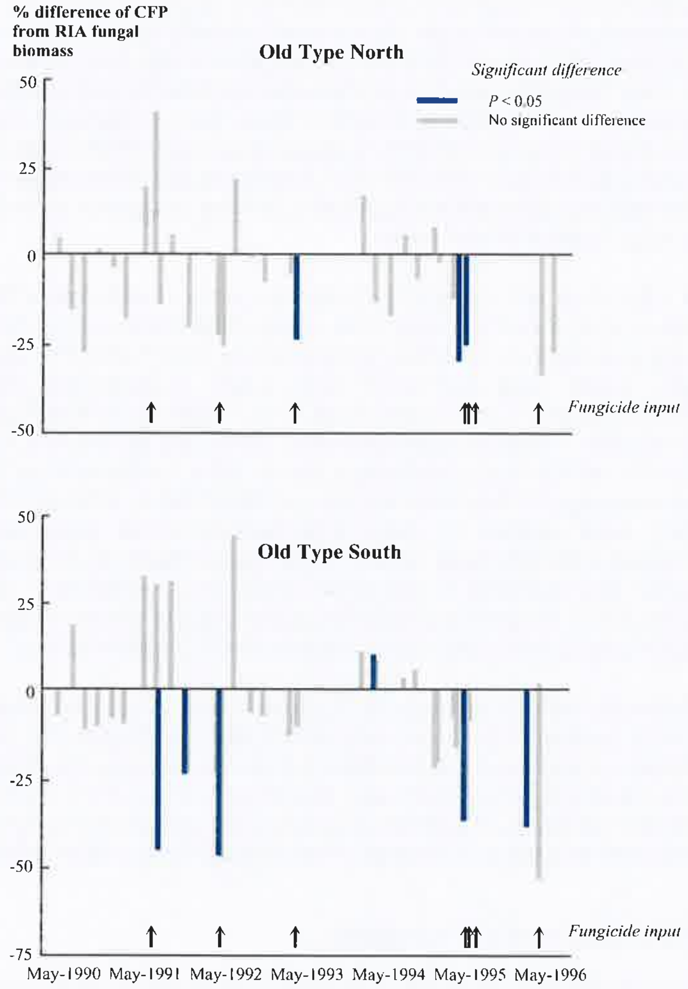

Figure 3.3.4. The effect of differential fungicide applications on fungal biomass in 'Old Type North' and 'Old Type South', High Mowthorpe (% difference of CFP from RIA fungal biomass).

Effect of fungicides on soil microflora

Treatment with differential rates of fungicides usually led to significantly lower biomass parameters in CFP plots compared with RIA. Fungicides tended to have the most long-lasting effects on the soil microflora, both at High Mowthorpe and Gleadthorpe. Multiple fungicide applications in most years led to detectable, reproducible and often significant temporary decreases in biological parameters (total biomass C and N, total and metabolically active fungal biomass, culturable fungi), with fewer reductions observed at half-rate applications (**Table 3.3.5**). Not surprisingly, the fungal component of the microbial biomass was generally most severely affected by fungicides. A clear association could be seen between differential fungicide application and net differences in soil fungal C on comparing replicate plots in 'Old Type' field: following such applications, fungal biomass was consistently higher in RIA plots compared with CFP (**Fig. 3.3.4**). Furthermore, there were only minor differences between treatment pairs in the years where no differential fungicide treatments were applied (1990 and 1994) and greatest significant divergence occurred when fungicides with known soil-persistent properties were used, e.g. chlorothalonil, metalaxyl, propiconazole and triadimenol (see **Table 3.3.5**).

The harmful effects of fungicides on non-target soil microflora found in this study are not surprising since the target sites of most systemic fungicides are common to large portions of the fungal community: disruption of ergosterol synthesis is an example. Thus, fungicide applications often result in reductions of non-target soil fungal populations (Schuster & Schroder, 1990; Hart & Brookes, 1996) and disruption of soil metabolic activities (Suyama *et al.*, 1993). Reductions in fungal biomass by fungicides then diminish other sections of soil communities (such as nematodes and protozoa) that are dependent on fungi as a source of food (Petz & Foissner, 1989; Gupta & Yeates, 1997).

Negative effects on soil microbial parameters were demonstrated following treatments of prochloraz ('Old Type' field, 1992), chlorothalonil ('Old Type' field, 1992, 1995) and mixtures containing propiconazole ('Old Type' field, 1992, 1995 and 1996; 'South' field and 'Balk' field, 1993). Formulations containing carbendazim, flusilazole and triadimenol were inhibitory in 'Old Type' field, whereas microbial indicators appeared to be unaffected by identical fungicide treatments on the fields at Gleadthorpe. Some residual effects from fungicide treatment were suggested by these results: namely, inhibitory effects on microbial parameters were evident 55 days after application of propiconazole + fenpropimorph onto 'Old Type' field in 1996. Fewer effects were found at the Gleadthorpe site, because of (a) there being fewer differential fungicide applications, (b) the choice of particular fungicides with low environmental impact (e.g. epoxiconazole) and (c) less discrimination of effect in this soil type.

Although negative effects of fungicide treatment were usually indicated in this study, a single incident of stimulation occurred in 'Old Type' field in 1991, following the application of metalaxyl + chlorothalonil. Since the site was not sampled just prior to the treatment, it is possible that this effect was not due to the fungicide but to the residual effects of a herbicide (bentazone) applied two months earlier. Later treatments containing chlorothalonil were found to be mildly inhibitory.

Effect of insecticides on soil microflora

The three groups of insecticide used in SCARAB sites monitored in this study were carbamates (aldicarb, pirimicarb), organophosphates (chlorpyrifos, dimethoate, fonofos, omethoate, triazophos) and synthetic pyrethroids (cypermethrin). The insecticides used in SCARAB were all relatively non-persistent (**Table 3.3.6**) and, where detectable, non-target effects on soil microflora were transient.

The insecticide dimethoate was applied on three occasions to CFP 'Old Type' (1992, 1995 and 1996), once to CFP 'Balk' (1992) and three times to CFP 'South' (once in 1992 and twice in 1995). Additionally, CFP 'South' was treated in 1992 with omethoate, a systemic insecticide with very similar chemical and biological properties to dimethoate. In July 1992, soil sampling prior to and following a dimethoate treatment showed highly significant ($P < 0.001$) and dramatic rises in biomass size in both plots in 'Old Type' field. In contrast, subsequent dimethoate applications reduced ($P < 0.01$) biomass measurements, both in 1995 and 1996. Soil fungal biomass, as the largest population component, was the variable factor, although the radiolabelled thymidine assay suggested that bacterial growth and activity might also have been transiently inhibited. A possible explanation for this effect of stimulation in one year, followed by inhibition in succeeding years, may lie in microbial responses to population changes in soil fauna brought about by insecticide treatment. The first differential application of dimethoate in 1992 selectively removed invertebrate predation on soil fungi, which then resulted in an increase in soil fungal biomass in CFP plots.

Following usage of organophosphorus (OP) insecticides, long-term removal of certain Collembola and short-term reductions of fungivorous Diptera and Coleoptera were detected during the course of the SCARAB project (Chapter 3.2), particularly at the Drayton site; this could be a factor in allowing microbial build-up. Increased fungal activity and microbial biomass stimulation have been observed elsewhere, following biocidal treatment against nematodes and arthropods (Ingham *et al.*, 1994). Thus, it is suggested that the first application of dimethoate (see above) reduced feeding pressures on soil fungi only in the CFP plots in 'Old Type' field. Later applications of dimethoate possibly allowed disclosure of direct toxic effects of the pesticide, which (in laboratory experiments) was demonstrated to be inhibitory to bacteria isolated from 'Old Type' field soil in laboratory experiments. The negative effects of dimethoate may also have been further exacerbated by earlier multiple applications of fungicides: pre-exposure to other pesticides, for example prochloraz, has been found to increase OP toxicity (Pesticide News, 19 March, 1993).

Toxicity of dimethoate for non-target soil microbiota is well documented (Lal, 1982; Ekelund *et al.*, 1994). However, the effects of this pesticide are considered to be short-lived under normal agricultural conditions. Although dimethoate is mobile in soil and plant environments, and may be persistent under some soil conditions, it does not remain active in aerobic soils for longer than four weeks (Tomlin, 1994). The lack of effects in 'South' field in 1995 may be connected with the dry soil conditions that existed at this time; although pesticides may persist for longer under arid conditions (Caverly, 1980), the low microbial biomass in this soil may be less metabolically responsive and subsequent effects of the pesticide may be reduced.

The effects of carbamate pesticides used in the SCARAB trials were highly variable (**Table 3.3.6**) and probably influenced by coincident treatment with other pesticides (e.g. aldicarb treatment was rapidly followed by herbicide application onto 'South' field in 1994). Aldicarb treatments produced no clear changes in microbial measurements in this study. In other experiments, applications of aldicarb to microbial communities in soil have led to reductions in parameters (i.e. population size and composition, metabolic activities, etc.) (Turco & Konopka, 1990), minor stimulation (Bromilow *et al.*, 1996), slight perturbations in community composition (Duah-Yentumi & Johnson, 1986) or no changes at all (Ingham *et al.*, 1994). Aldicarb is listed as having low soil persistence (Kidd & James, 1991); however, its occasional presence in groundwater (Zaki *et al.*, 1982) suggests that, under certain circumstances, it may persist long enough to have environmental consequences. Similarly, the other carbamate insecticide (pirimicarb) monitored in SCARAB sites was followed by variable effects. Marked significant depressions in total and fungal biomass were observed after pirimicarb treatment in 'Old Type' field in 1991 but this compound did not elicit any detectable changes in microbiological analyses at the Gleadthorpe sites in 1991 or 1994. Negative effects from pirimicarb have been reported in field studies (Schuster & Schroder, 1990), but it is likely that the response to the compound is strongly affected by soil type or physical environment, since it is listed as being of low to moderately high (> 6 months) persistence in soils (Kidd & James, 1991).

The pyrethroid cypermethrin was used twice on Gleadthorpe sites (1992 and 1995) and once on 'Old Type' field, High Mowthorpe (1992), with only minor disturbances evident in microbial parameters. Treatment appeared to slightly depress temporarily microbial biomass measurements in most sites ($P < 0.05$). The transient nature of the effect was likely to be related to its relatively low persistence and ease of degradation in soil (Tomlin, 1994) and low soil bioavailability (Roberts & Standem, 1994).

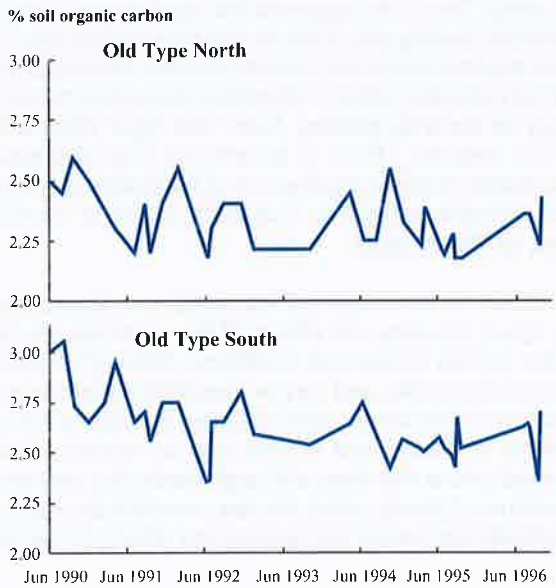

Figure 3.3.5. Changes in total soil organic carbon (average of CFP and RIA) in 'Old Type North' and 'Old Type South' at High Mowthorpe.

Changes in soil organic matter during SCARAB

High Mowthorpe

Soil organic C concentrations remained constant at *c.* 2.3% in 'Old Type North' but declined from *c.* 3% to 2.6% in 'Old Type South' from 1990 to 1996 (**Fig. 3.3.5**). Generally, there were no differences in concentrations of organic C in the two treatment regimes. However, following five differential input years, organic C measurements in 1996 were frequently and consistently very slightly lower in CFP plots (not noted in previous years), and CFP and RIA were significantly different in the two final sampling occasions in August (**Table 3.3.7**).

Although other undetermined factors may be responsible for this decline, it is possible that the slightly lower soil carbon levels were the outcome of the CFP treatment regime on microbial processes. Throughout the period of differential application onto 'Old Type'field, microbial indicators (e.g. biomass size, **Fig. 3.3.3**; culturable microorganisms, **Tables 3.3.2 & 3.3.3**) fluctuated far more widely under CFP treatment than under RIA treatment. It is known that intermittent physical and nutritional changes imposed on soil microorganisms may result in increased decomposition of the native soil organic matter fraction. During the so-called 'priming effect' of soil microflora on soil organic matter, rates of decay of soil organic matter were increased by 12-30% following repeated cycles of drying and rewetting of the soil (Sorensen, 1974). It is possible, therefore, that the effects arising from CFP treatment (release of decomposable material from pesticide-susceptible, dead organisms, followed by a flush of growth of surviving microflora), coupled with environmental conditions (large fluctuations in microbial cell populations, owing to soil desiccation in the summer and freezing in the winter of 1995) led to increased rate of decay of the soil organic matter fraction under CFP in 'Old Type' field at High Mowthorpe.

Gleadthorpe

Soil organic C concentrations were much lower in the Gleadthorpe soils compared with High Mowthorpe, and averaged 0.9% in both fields, with little difference between treatments. However, analysis of all soil C data for 'Balk' field in the final differential input year showed a small disparity between CFP and RIA (CFP, mean =

0.8%; RIA, mean = 1.0%: $P = 0.004$). Although it is not possible to definitely ascribe short-term changes in soil chemistry to agricultural practice, it is interesting to note that a similar phenomenon was observed in 'Old Type North'. It is possible, therefore, that the relatively mild CFP regime may have had a minor effect on nutrient cycling, and thence soil C concentrations. Although not proven, this is likely to be transient, and implementation of uniform field management may remove this slight divergence.

Conclusions

This study has found that certain changes in microbial variables, which were short-lived, could be attributed to pesticide regime. Weather conditions and soil type also appeared to moderate the effects of pesticides on the soil microflora.

Generally, in both soil types studied, the pattern of magnitude of pesticide effects on soil microbiology was fungicides > insecticides & herbicides. Effects were most often found with the more persistent types of pesticide. Fungicides generally had a short-term negative effect on soil microbial activity and biomass whilst insecticide and herbicide effects were more variable, with both positive and negative short-term effects being observed.

Since it appears from this study that climatic conditions can influence pesticide side-effects on soil microbial populations and processes, any climate changes brought about by global warming may exacerbate the effects of pesticide usage at current application rates.

At High Mowthorpe, soil microbial biomass was often a sensitive indicator of pesticide treatment, whereas other measurements (mineralisation rates, soil enzyme activities) did not discriminate between the two (CFP, RIA) pesticide regimes. A gradual divergence in trends in certain soil microbial indicators occurred at High Mowthorpe under the two treatment regimes, with microbial parameters tending to be lower under CFP. It was found that soil managed under the CFP regime frequently possessed smaller microbial populations, both in terms of biomass and numerical counts. In the final year of testing, there was some indication that these populations were less responsive to nutrient inputs since microbial biomass was consistently greater in RIA-managed soil. Also, in the final month of sampling, organic C concentrations (which are known to be influenced by biological factors) were slightly lower in CFP.

Two consequences could be envisaged if this trend were to continue. Either, detectable reductions in soil organic matter turnover may arise as a result of fluctuations in microbial biomass content under CFP management, or greater fertiliser inputs may be required to balance the shortfall of microbially-processed nutrients in soil managed under CFP conditions.

In contrast, at Gleadthorpe, soil microbial biomass was much less influenced by pesticide regime, although individual pesticide inputs occasionally elicited soil microbial responses. Possible reasons for this are: (a) the lower total carbon content of this soil type generated lower soil microbial biomass and therefore smaller, less detectable, differences between CFP and RIA soils; (b) soil desiccation was frequently an overriding factor affecting biomass size; (c) drought-stricken microbial populations may be less susceptible to pesticide impact; (d) inherent differences in soil environment between treatment pairs were often found.

Soil type clearly influences the suitability of soil microbial biomass as a measurement for testing pesticide effects. However, the site-specific changes in microbial biomass at High Mowthorpe may be related to early indications of reductions in soil fertility resulting from conventional pesticide use as represented by the Current Farm Practice regime in SCARAB.

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Table 3.3.1. Summary of transient effects (>10%) of differential pesticide treatments on microbial biomass of SCARAB sites.

Treatment	High Mowthorpe			Gleadthorpe		
	Increase	Decrease	No effect	Increase	Decrease	No effect
Herbicides	4	7	0	0	3	13
Fungicides	0	16	0	0	4	9
Insecticides	2	5	5	3	0	13
Total	6	28	5	3	7	35

Table 3.3.2. The effect of a differential fungicide treatment applied in 1993 on culturable microorganisms in 'Old Type' field, High Mowthorpe.

Microbial group, species or genus	Treatment*		
	CFP	RIA	*P* value
Bacteria(x 10^7/g)	16.9	12.5	0.0004
Fungi (x 10^5/g)	2.3	3.2	0.0030
Trichoderma viride (x 10^4/g)	1.8	2.7	0.0800
Penicillium spp. (x 10^4/g)	2.2	5.3	0.0002

* Flusilazole + carbendazim, plus fenpropimorph, applied at full-rate (in CFP) and half-rate (in RIA) on 24 April 1993.

Table 3.3.3. The effect of a differential insecticide, applied in 1996, on microbial populations in 'Old Type North', High Mowthorpe.

Microbial parameter	Treatment*		
	CFP	RIA	*P* value
Bacteria (x 10^7/g)	2.2	6.1	0.001
Bacterial growth rate (mol^{-21} thymidine uptake/cell/h)	3.4	4.2	0.030
Total microbial biomass (µg C /g)	403.0	590.0	< 0.001
Fungal biomass (µg C /g)	211.0	320.0	< 0.100

* Dimethoate application to CFP only, on 8 August 1996.

Table 3.3.4. Effects of herbicides on soil microflora in SCARAB and the associated persistence in soil.

Active ingredient	Field(s)	Date of application	Microbial response	Soil persistence*
Metsulfuron-methyl	SF, BF BF	April 1992 May 1995	Inhibition No effect	Low
Isoproturon + pendimethalin	SF, BF	November 1993	V. slight inhibition	Isoproturon – slight Pendimethalin – moderate
Chloridazon SF	April 1994	No effect	Moderate	
Chlorpropham + fenuron + propham	SF	April 1994	No effect	Fenuron – moderate Others – low
Metamitron	SF	May 1994	No effect	Moderate
Ethofumesate + phenmedipham	SF	May 1994	No effect	Slight
Phenmedipham + lenacil	SF	May 1994	No effect	Slight
Clopyralid	SF	May & June 1994	No effect	Slight
Bromoxynil + ioxynil + mecoprop P	SF OT	May 1995 June 1996	Inhibition Inhibition	Mecoprop P – moderate Others – non-persistent
Terbutryn + paraquat	SF, BF	September 1995	No effect	Terbutryn – low Paraquat – non-persistent
Glufosinate-ammonium	BF	May 1994	No effect	Low
Bentazone	OT	May 1991	Stimulation	Low
Glyphosate	OT	September 1991	Stimulation	Low
Diflufenican + isoproturon	OT OT OT	December 1991 October 1992 February 1995	Inhibition, some bacterial stimulation	Slight

SF = 'South' field, Gleadthorpe; BF = 'Balk' field, Gleadthorpe; OT = 'Old Type' field, High Mowthorpe.
* 'Non-persistent': $DT_{50} < 14$ days; 'of low persistence': DT_{50} = 15–40 days; 'slightly persistent': DT_{50} = 40–70 days; 'moderately persistent': DT_{50} = 70–180 days (Kidd & James, 1991).

Table 3.3.5. Effects of fungicides on soil microbial measurements. (Abbreviations and persistence ratings as for Table 3.3.4.).

Active ingredient	Field(s)	Date of application	Microbial response	Soil persistence
Tolclofos-methyl	SF BF	March 1991 April 1994	No effect	Not persistent
Fenpropidin	SF, BF	May 1992	No immediate effect	Low
Triadimenol + tridemorph	SF	June 1992	No immediate effect	Triadimenol – moderate Tridemorph – low
Carbendazim + flusilazole	SF, BF	April 1993	No immediate effect	Carbendazim – slight Flusilazole – low
Propiconazole + tridemorph	SF, BF	May 1993	Reductions in biomass and culturable fungi	Propiconazole – slight Tridemorph – low
Tebuconazole	SF, BF	May 1995	Reductions in fungal biomass	Low
Epoxiconazole	SF, BF	May 1996	No effect	Low
Metalaxyl + chlorothalonil	OT	July 1991	Stimulation	Slight
Prochloraz	OT	May 1992	Inhibition	Moderate
Propiconazole + chlorothalonil	OT	June 1992	Inhibition	Both – slight
Flusilazole + carbendazim + fenpropimorph	OT	April 1993	Fungal inhibition and bacterial stimulation	Carbendazim – slight Others – low
Tebuconazole + triadimenol + chlorothalonil	OT	May (x2) 1995	Inhibition	Tebuconazole – low Triadimenol – moderate Chlorothalonil – slight
Propiconazole	OT	July 1995	Fungal inhibition but bacterial stimulation	Slight
Propiconazole + fenpropimorph	OT	June 1996	Inhibition	Propiconazole – slight Fenpropimorph – low

Table 3.3.6. Effects of insecticides on soil microbial measurements. (Abbreviations and persistence rating as for Table 3.3.4.).

Active ingredient	Field(s)	Date of application	Microbial response	Soil persistence
Pirimicarb	SF, BF	July 1991	No effect	Highly dependent on soil type: 7–234 days
	BF	July 1994	No effect	
	OT	July 1991	Inhibition	
Omethoate	SF	March 1992	Stimulation	Low
Dimethoate	SF, BF	June 1992	Stimulation	Low
	SF	March & June 1995	No effect	
	OT	July 1992	Stimulation	
	OT	July 1995	Inhibition	
	OT	August 1996	Inhibition	
Cypermethrin	SF, BF	November 1992	Slight inhibition	Low to slight
	SF, BF	October 1995	Slight inhibition	
	OT	November 1992	Slight inhibition	
Aldicarb	SF	April 1994	Possible inhibition	Low
	BF	March 1991	No effect	
Chlorpyrifos	BF	June 1995	No effect	Slight
Fonofos	BF	December 1994	No effect	Slight
Triazophos	OT	June 1994	No effect	Low

Table 3.3.7. Comparison of % soil organic C in 'Old Type' field, High Mowthorpe (1990–1996).

Mean % organic C measurements	'Old Type North'		'Old Type South'	
	CFP	RIA	CFP	RIA
1990–1996	2.3	2.4	2.6	2.6
August 1996*	2.2	2.4	2.3	2.6

* Differences in 'Old Type North', $P = 0.002$ and 'Old Type South', $P < 0.06$.

THE EFFECTS OF PESTICIDE REGIMES ON EARTHWORMS

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Introduction

Earthworms play a number of important functions in the soil ecosystem by assisting in the decomposition of organic matter and in maintaining soil structure and fertility (Edwards & Lofty, 1977). They are also an important component of terrestrial food chains. Therefore, earthworms that contain pesticide residues may present a significant environmental hazard if ingested by birds and other vertebrates (Cooke *et al.*, 1992).

The toxicity of individual agricultural pesticides to earthworms has been studied extensively in the laboratory (Stenersen, 1979; Heimbach, 1985; Edwards & Coulson, 1992; Ma & Bodt, 1993). Further, some pesticides have been shown to have an adverse effect on earthworm populations under field conditions (Thompson, 1970; Tomlin & Gore, 1974; Saunders & Forgie, 1977; Tomlin *et al.*, 1981; Barker, 1982; Edwards & Brown, 1982; Clements *et al.*, 1986; Goats & Edwards, 1988; Potter *et al.*, 1994). However, there is a shortage of long-term studies of repeated or prolonged exposure to pesticide applications on earthworm populations in arable fields. As well as direct toxic effects, pesticides may have indirect effects on earthworm populations by affecting factors such as predation, food supply, soil moisture and microbial activity. These indirect effects may be either detrimental or beneficial to earthworm populations. The aim of the work was to investigate any long-term effects of the SCARAB pesticide regimes on earthworm populations.

Methods

Sampling for monitoring earthworm populations

Long-term trends in the overall abundance and diversity of earthworms were monitored by biannual sampling in the spring and autumn, when earthworm activity was expected to be at a maximum. Earthworm activity is biphasic: periods of dormancy in mid-summer and mid-winter, followed by cocoon production and hatching of juveniles (Edwards & Lofty, 1977). Therefore, any major effect on earthworm populations should be detected by biannual sampling.

Monitoring of earthworm populations did not begin until the third treatment year of the SCARAB Project. Thus, no data were available on earthworm populations prior to the establishment of the different treatment regimes. The first samples were taken in spring 1993 and sampling continued until spring 1996. On each sampling occasion, samples were taken from all eight SCARAB fields. For each field, three sub-samples were taken on both Current Farm Practice (CFP) and Reduced Input Approach (RIA) areas, using a 50 cm x 50 cm quadrat dropped at random at intervals of 10–20 m.

Initially, two methods of earthworm extraction were evaluated: the well-known 'formalin drench' method and a 'hand-dug to plough layer' method. The formalin drench method (Raw, 1959) involved applying 9.0 litres of a 0.2% aqueous formalin solution evenly over the soil surface contained within the quadrat. Any high vegetation was initially cut back to ground level and the soil spiked with a hand

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fork to aid penetration of the formalin solution into the soil. Earthworms coming to the soil surface during the following twenty minutes after drenching were collected.

The 'hand-dug' method involved the removal of soil within the quadrat down to plough depth; the latter was easily identified from the presence of a layer of vegetation in the soil. The soil was then sorted by hand and any earthworms present removed.

Comparison of the methods indicated that a combination of both was required to obtain fully representative samples. Subsequent monitoring, to assess possible differences between treatment areas, therefore, was based on a combined method. This involved hand-digging to plough layer, followed by extraction of additional earthworms from below the plough layer using 1.14 litres of a 0.2% formalin solution. Sampled earthworms were placed immediately in water, and subsequently removed and weighed before being returned to the laboratory in a 5% formalin solution. Individuals in each sample were later identified to species and age class, using the taxonomical details listed by Sims & Gerard (1985).

Sampling after selected pesticide applications

The standard biannual sampling programme was not suitable for monitoring short-term effects of individual pesticide applications; therefore, a further programme was introduced of sampling shortly after selected pesticide applications. Sampling was carried out during the first three days after the day of application. It was not always possible to stick rigidly to this schedule and, on some occasions, sampling was stopped after two days whereas, on others, samples were taken four or five days after (instead of three days after) application. The occurrence of gross short-term mortality was monitored by searching four 1 m x 100 m transects of field surface in both the CFP and RIA areas. All earthworms found were counted and weighed, then stored at -20°C for subsequent residue analysis. A 0.5 kg sub-sample of soil was collected from the top 5 cm of soil, using a corer of 2.5 cm diameter. Samples were taken in transects at intervals of 2 m, to provide a pooled sample which was stored, for subsequent residue analysis, at -20°C. In addition, any earthworms within the cores were separated from the soil and taken for residue analysis. The core depth was selected to be consistent with that used for estimating exposure of earthworms to pesticides in risk assessment studies (EPPO/CoE, 1993). The results of residue analysis could be used to estimate exposure of earthworms to particular pesticides, and to assist in identifying the pesticides responsible for any changes observed in the biannual sampling.

Results

Earthworm populations on SCARAB sites

There were large differences in earthworm density and biomass between the three farms, with smaller differences between fields within the same farm (**Fig. 3.4.1**).

Drayton

Earthworm numbers were greatest at Drayton, where densities of over 1,000 per square metre were recorded in spring 1994. Although the population declined markedly after this, densities still remained high for arable fields. The population at Drayton was dominated by juveniles of the two species *Aporrectodea caliginosa* and *Allolobophora chlorotica* (**Fig. 3.4.2**) which, rather than forming permanent, vertical burrows, move horizontally through the top few centimetres of soil. Densities were more representative of those generally found in pasture rather than of arable soil. This is probably linked to the fact that both fields at Drayton were down to grass leys for all but two years of the SCARAB Project. Soil and husbandry factors at Drayton, such as reduced frequency of cultivations and manuring by grazing animals, were thus more beneficial to earthworms than is generally the case for arable fields. Indeed, the combination of grass and poorly-draining clay

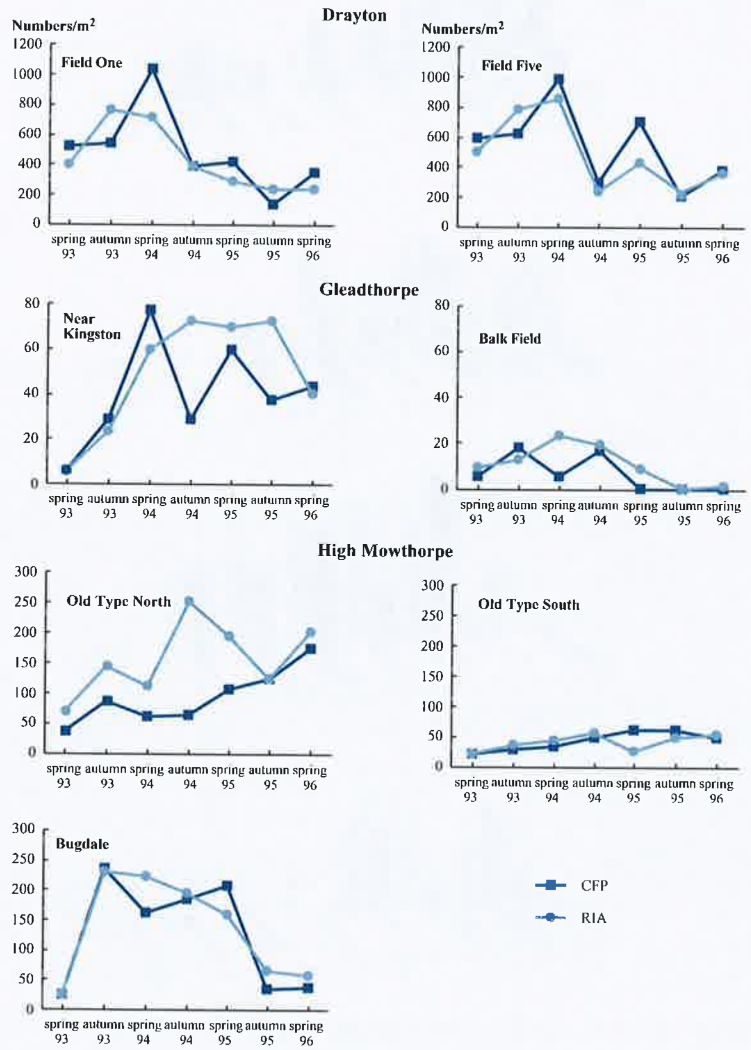

Figure 3.4.1. Trends in total earthworm numbers/m² in CFP and RIA areas of SCARAB sites. Results are not shown for 'South Field', Gleadthorpe, which contained negligible numbers of earthworms.

soil may be particularly beneficial to species such as *A. caliginosa* and *A. chlorotica*, since the resulting conditions mean that grass roots are liable to decompose, providing a readily available food source for these two species. This was supported during the sampling when it was observed that the majority of the populations of these two species were closely associated with grass roots. Cultivations are sometimes believed to have an adverse effect on earthworm populations. However, it is difficult to assess the effect of cultivations associated with the two winter wheat crops grown on each field during the SCARAB Project. On 'Field One', both wheat crops had been completed before monitoring of earthworms started and, on 'Field Five', the final wheat crop was grown during the first year of earthworm monitoring: 1992-93. What evidence there is suggests that cultivation of wheat had little effect, as populations were similar on both Drayton fields in spring 1993. In fact, there is no evidence for cultivations or husbandry practices having had any effect on earthworm populations; both fields showed similar fluctuations of earthworm population over time, despite being at different stages in the cropping cycle.

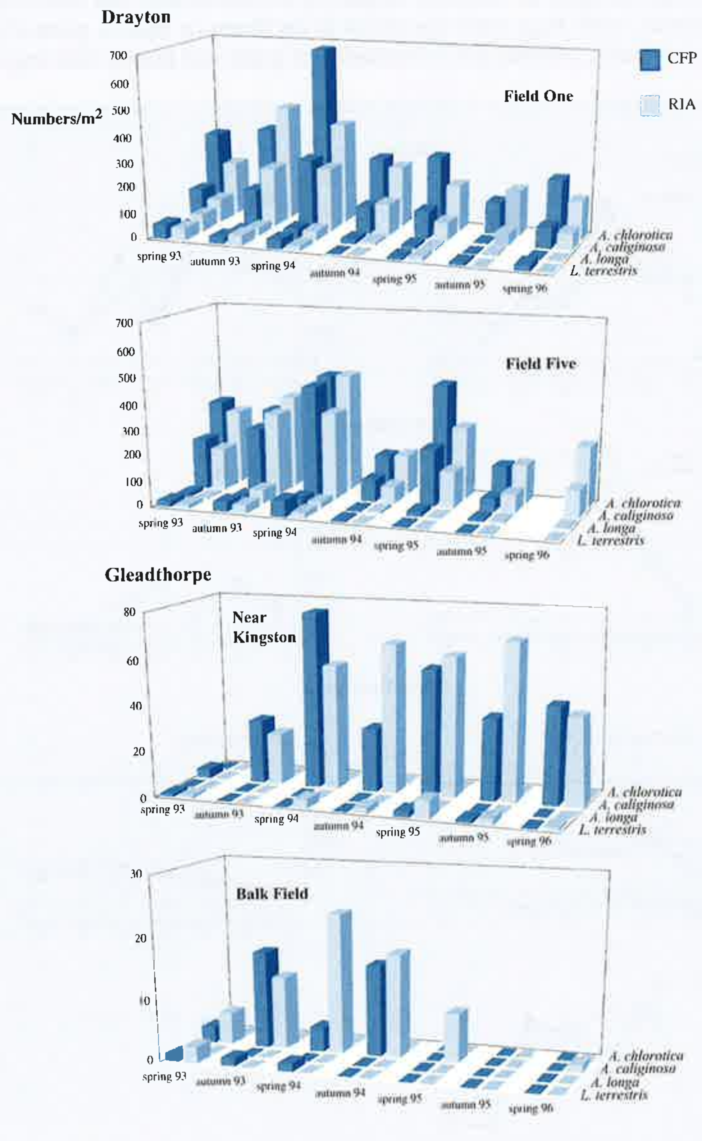

Figure 3.4.2. Species composition of earthworm populations in RIA and CFP areas of SCARAB sites at Drayton and Gleadthorpe. Data shown are numbers/m^2 for the four principal species found; numbers of other species were very low.

Gleadthorpe

The earthworm population at Gleadthorpe was dominated by one species, *A. caliginosa* **(Fig. 3.4.2)**. Earthworm numbers were very low on all three fields at Gleadthorpe in spring 1993. On 'South' field, no earthworms were detected and numbers remained extremely low throughout the period of monitoring. There was some increase in numbers on 'Balk' field by autumn 1993, with the population remaining at about this level during 1994, followed by a decline to negligible levels. Populations at 'Near Kingston' showed a sharp increase in numbers by autumn 1993, the increase continuing until spring 1994, after which numbers stabilised before declining slightly. The small size of the earthworm population at Gleadthorpe is probably due, principally, to the sandy nature of the soil. Sandy soil is unfavourable to earthworms because of its low moisture and organic matter content. The growing of root crops, which involves more frequent and deeper cultivations than other crops, may also have contributed to the low earthworm numbers although there is no obvious correlation between the timing of root crop cultivations and substantial reductions in the earthworm population. The decline in the population on 'Balk' field began when spring wheat was present, rather than when potatoes were present in 1994. However, this should not be taken as evidence that deeper cultivations do not generally affect earthworm populations since the dominance of one species at Gleadthorpe may be due, at least partly, to its ability to withstand such cultivations. It was apparent that 'Near Kingston' was capable of supporting larger numbers of earthworms than the other two fields at Gleadthorpe but it is not clear why numbers were so low in spring 1993.

High Mowthorpe

Populations at High Mowthorpe were intermediate in size between those at Drayton and Gleadthorpe, and were fairly typical for arable fields (Edwards & Lofty, 1977). As at the other sites, there were large variations over time. 'Bugdale' was particularly variable, with very low numbers at the first sampling point and at the last two. There is no obvious explanation for this variability; cereals were being grown on 'Bugdale' at the time at which low numbers were recorded, and such crops were grown at other times on this field and on other fields with no obvious adverse effects. The hot, dry summer alone is unlikely to be the cause of the decline between spring and autumn 1995, since there was no corresponding decline on other fields at High Mowthorpe. The loamy soil, with its relatively high organic matter content, should be particularly favourable for earthworms and it is perhaps surprising that earthworm numbers were not higher than they were. However, the prolonged low temperatures sometimes encountered at High Mowthorpe might inhibit reproduction and kill any immature earthworms unable to burrow deep enough to escape freezing. There was a more even distribution among species and age classes at High Mowthorpe than at the two other sites. As well as the topsoil-inhabiting species *A. caliginosa* and *A. chlorotica*, there were also significant numbers of the deep-burrowing species *Lumbricus terrestris* and *Aporrectodea longa* (**Fig. 3.4.3**).

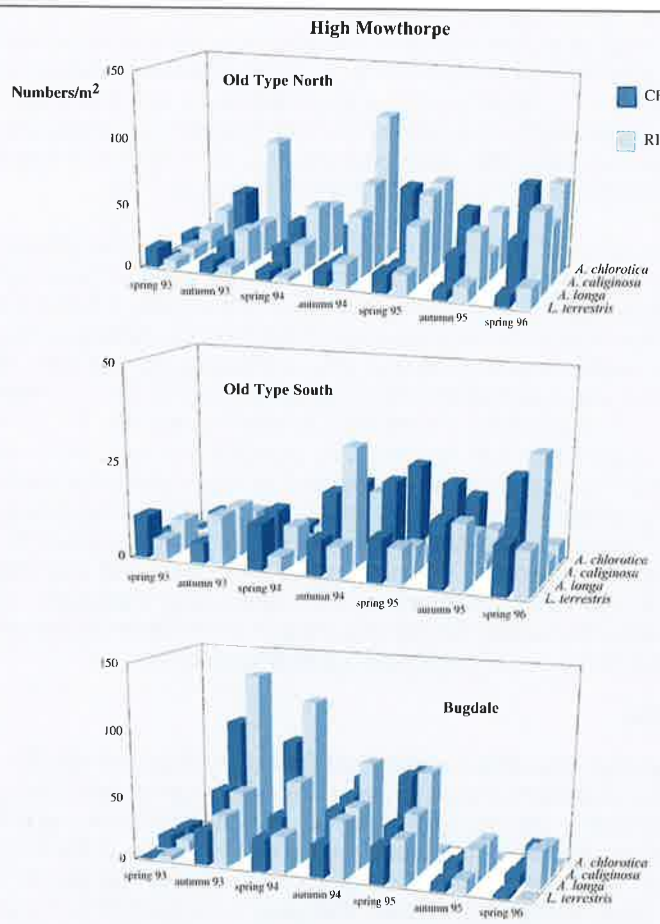

Figure 3.4.3. Species composition of earthworm populations in RIA and CFP areas of SCARAB sites at High Mowthorpe. Data shown are numbers/m^2 for the four principal species found; numbers of other species were very low.

Differences in earthworm populations between pesticide regimes

Trends in earthworm numbers and biomass were analysed both graphically and statistically. Statistical analysis of differences in trends on the two treatment areas of each field was by Analysis of Variance, with a square-root transformation, and corrected to allow for any correlation over time (Greenhouse & Geisser, 1959). For each field, this analysis was performed for total earthworm numbers and numbers of the four main species found: *L. terrestris*, *A. longa*, *A. caliginosa* and *A. chlorotica*. Statistically significant differences mean that the trends on the CFP and RIA areas follow different patterns. The detailed data available meant that it was possible, where numbers were sufficient to allow meaningful comparison, to assess trends in individual age classes (adult, sub-adult and juvenile) of each species although no statistical analyses were performed at this level.

Drayton

Trends in total earthworm numbers on both the fields at Drayton were broadly similar on the RIA and CFP areas (**Fig. 3.4.1**) but no statistically significant differences were found. This was also true for total biomass as well as for numbers and biomass of individual species. The only exception was a significant trend of differences in biomass of *A. longa* on 'Field Five'. However, in view of the low numbers of this species on 'Field Five' this trend may be of little ecological importance. Even at the level of age classes of each species, the trends appeared similar on both treatment areas. In no cases at Drayton were earthworms detected on the surface shortly after applications, suggesting that no significant short-term mortality took place. There were some transient differences in earthworm populations between treatment areas at Drayton. However, it was difficult to relate these to pesticide use. For instance, there was a relative decline in numbers on the RIA area of 'Field One' in spring 1994 compared with autumn 1993. This decline was mainly the result of relative reductions in *A. chlorotica* and juveniles of *A. longa* and cannot be due to the different treatments since no pesticides were applied over this period. In fact, there was not a great difference in the treatments at Drayton during the period in which earthworm monitoring was performed. The only insecticide applied to 'Field One' was omethoate in summer 1993, whereas 'Field Five' received dimethoate in 1993 and chlorpyrifos in 1994 and 1995.

In two cases, samples of soil from the top 5 cm were taken after chlorpyrifos applications to 'Field Five'. The results from chemical analysis of these samples give useful information on the amount of chemical that actually reached the soil and can be used to assess the likely exposure of earthworms. **Table 3.4.1** lists the maximum soil concentration measured after individual applications. These measured maxima are compared with the predicted environmental concentrations (PECs) used in risk assessment of pesticides to earthworms. The PEC in soil is calculated by assuming all of the pesticide reaches the soil and is evenly distributed in the top 5 cm, and can be regarded as representing the maximum expected soil concentration and, hence, maximum earthworm exposure. The results for the chlorpyrifos applications show that actual soil concentrations were around the maximum expected in June 1994 but were somewhat low in March 1995. The results indicate that earthworms were significantly exposed to at least some of the insecticides used. Despite this, there is no evidence of any adverse effect of any insecticides on any earthworm species at Drayton.

High Mowthorpe

Pesticide use at High Mowthorpe was greater than at Drayton, with the CFP areas of 'Old Type' and 'Bugdale' receiving two and five insecticides, respectively, over the period of earthworm monitoring. Despite this, no dead earthworms were found on the soil surface after any applications and there was no noticeable long-term trend toward differences in total numbers or biomass between RIA and CFP areas on any of the fields at High Mowthorpe. The latter is supported by the lack of statistically significant differences for total numbers or total biomass. Graphical examination showed that, as with Drayton, this lack of long-term differences was also true for numbers and biomass of individual species and for particular age classes of species. Nevertheless, statistical analysis did show some significant long-term differences in trends (**Table 3.4.2**). Examination of the data (**Fig. 3.4.3**) shows that, for *A. chlorotica* in 'Old Type North', there is a general trend towards a relative increase in the proportion of earthworms on the CFP area relative to RIA, suggesting that the CFP regime was more 'beneficial' to *A. chlorotica* on this field than was RIA. However, in the context of the general lack of long-term effects on earthworms, and the large variations in numbers on the RIA area, the most likely explanation for this result is random variation. The significant trend for biomass of *A. caliginosa* in 'Old Type North' is not supported by a similar trend for numbers of this species and appears to be of little ecological importance.

There were some transient differences in total numbers on 'Old Type' field. In 'Old Type South' there was an apparent relative decline in RIA, relative to CFP, between autumn 1994 and spring 1995. This is difficult to explain, being the opposite of the expected outcome of acute toxic effects from applications of insecticides to CFP. Earthworm numbers were quite low on this field so that the absolute difference in numbers detected is relatively small and may have been due to sampling variation. There was a sharp decrease in numbers in CFP relative to RIA in 'Old Type North', between spring and autumn 1994. The insecticide triazophos was applied to this field during summer 1994 and was regarded as a possible cause of this effect. No dead earthworms were noticed on the soil surface after this application and no soil samples were available for analysis, although a sample of earthworms was taken from the top 5 cm of soil one day after application. Chemical analysis revealed a concentration of 0.018 mg/kg triazophos in these earthworms. On the assumption that an earthworm contains 30% by weight of soil in its gut, then the soil concentration after this application was 0.06 mg/kg. This is approximately 10% of the soil PEC, and suggests that earthworm exposure to this application was low. Triazophos seems unlikely to have caused this difference, especially when its reported low toxicity to earthworms is taken into account (Heimbach, 1985). Soil samples were available after applications of some other insecticides to fields at High Mowthorpe and the results are given in **Table 3.4.1**.

The total numbers on both treatment areas of 'Bugdale' tracked each other closely during the whole of the observation period. However, the trend for total earthworm numbers obscures some very large variations in the numbers of *A. chlorotica* on the CFP area of 'Bugdale' (**Fig. 3.4.3**) (although the long-term trend was not statistically significant). The sharp reductions in the population on CFP between autumn 1993 and spring 1994 cannot be attributed to pesticide use since none was applied to the field over this period. The second sharp reduction on the CFP area, between spring and autumn 1995, is also difficult to attribute to pesticide use. Two insecticides, dimethoate and chlorpyrifos, were applied to the CFP area in summer 1995. Both are known to possess low toxicity to earthworms (Ma & Bodt, 1993; Larink & Kula, 1994) and residue analysis of soil samples (**Table 3.4.1**) indicated that less than 5% of the chemical actually reached the soil. All the applications at High Mowthorpe listed in **Table 3.4.1** were made to cereal crops in summer, and the results indicate that the high degree of ground cover afforded in such conditions allowed very little pesticide to reach the soil surface.

Gleadthorpe

At Gleadthorpe, earthworm numbers were only large enough to allow meaningful comparison between treatment areas on 'Near Kingston'. This field received four insecticide applications over the period of earthworm monitoring. As with fields at other sites, graphical examination did not indicate any long-term trends towards differences between treatment areas in total earthworm numbers and biomass, or numbers and biomass of individual species, or age classes of these species. Statistical analysis was possible only for total earthworm numbers and biomass, and numbers and biomass of *A. caliginosa*. No statistically significant differences in trends were found. Again, there were temporary differences, with a relative reduction in numbers on CFP in autumn 1994 and another similar, but smaller, drop in autumn 1995. The reduction in 1994 came after an application of pirimicarb, but this seems unlikely to be the cause of the difference as an earlier application of pirimicarb to the same field in 1993 was followed by a substantial increase in numbers on CFP and RIA areas.

Two of the chemicals used on this field have been reported to be toxic to earthworms: benomyl (Haque & Ebing, 1983; Edwards & Coulson, 1992) and aldicarb (Stenersen, 1979; Haque & Ebing, 1983). The fungicide benomyl was applied to both treatment areas (albeit at different rates). It was not possible, therefore, to monitor effects of this chemical by studying differential effects on the treatment areas. Nevertheless, it is notable that the benomyl application in 1993 was followed by substantial increase in earthworm numbers, suggesting that the chemical had little adverse effect on populations. Aldicarb was applied to the CFP area shortly after the last routine sample in the biannual monitoring programme was taken in spring 1996. Dead earthworms were observed on the soil surface on the first few days following application, the only occasion during the period of earthworm monitoring that this was seen on this, or any other, site. No samples were available for chemical analysis; however, it seems highly likely that earthworms would have been exposed to this chemical as this was applied directly to the soil at a time when earthworm activity would be expected to be maximal.

Conclusions

In the SCARAB study, earthworm populations showed considerable variability over time, but the reasons for this variability are not well understood and were not simply related to pesticide use. This variability, and the lack of understanding of its causes, has implications for the design and interpretation of studies investigating pesticide effects on earthworm populations. Therefore, field experiments to investigate effects of pesticides on earthworms need to be well designed with adequate controls and sampling procedures to differentiate pesticide effects from natural variation. The ecological significance of any adverse pesticide effects is difficult to gauge. Even large reductions in population from pesticide use might be considered acceptable provided the population is capable of recovering once pesticide concentrations have dropped below toxic levels (Goats & Edwards, 1988). However, the combination of a large reduction due to pesticides, concurrent with a reduction from other causes, may reduce the population to such an extent that recovery is greatly inhibited. Therefore, the significance of pesticide effects should be assessed in the context of other possible adverse effects on populations, and not considered in isolation.

The data collected in this study allowed differential effects of the two regimes on earthworm populations to be studied in great detail, in many cases down to separate age classes of individual species. Even then, no long-term trends were detected and, in most cases, even transient differences were not fully attributable to pesticide effects.

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Table 3.4.1 Maximum measured pesticide concentrations in soil after applications, compared with the predicted environmental exposure (PEC).

Field	Pesticide	Crop	Date	Concentration (mg/kg)	PEC (mg/kg)*
Drayton: 'Field Five'	Chlorpyrifos	Grass	June 1994	1.4	1.03
Drayton: 'Field Five'	Chlorpyrifos	Grass	March 1995	0.28	1.03
Gleadthorpe: 'Balk'	Chlorpyrifos	Spring wheat	June 1995	0.23	0.68
Gleadthorpe: 'South'	Dimethoate	Spring wheat	March 1995	0.39	1.16
Gleadthorpe: 'South'	Dimethoate	Spring wheat	June 1995	0.28	0.58
High Mowthope: 'Bugdale'	Chlorpyrifos	Winter wheat	June 1995	$<$ 0.026	0.68
High Mowthope: 'Bugdale'	Dimethoate	Winter wheat	July 1995	$<$ 0.045	0.58
High Mowthope: 'Old Type North'	Dimethoate	Winter wheat	July 1995	$<$ 0.023	0.58
High Mowthope: 'Old Type South'	Dimethoate	Winter wheat	July 1995	$<$ 0.040	0.58

* PEC calculated by assuming that all of the pesticide reached the soil and was evenly distributed in the top 5 cm.

Table 3.4.2 Statistically significant long-term differences in trends between treatment areas in numbers and biomass of earthworms/m^2. (All trends for other earthworm species, and for total earthworm numbers and biomass on other sites were not significant.)

Field	Species	Feature	*P* value
Drayton: 'Field Five'	*Aporrectodea longa*	Biomass	0.020
High Mowthorpe: 'Old Type North'	*Allolobophora chlorotica*	Numbers	0.019
High Mowthorpe: 'Old Type North'	*Allolobophora chlorotica*	Biomass	0.016
High Mowthorpe: 'Old Type North'	*Aporrectodea caliginosa*	Biomass	0.042

THE EFFECTS OF REDUCED INPUT PESTICIDE USE ON THE CONTROL OF WEEDS, PESTS AND DISEASES IN SCARAB

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Introduction

Opportunities for reducing pesticide use in cereal-based rotations have been demonstrated previously in small-plot field trials (Proven *et al.*, 1991), and in the Boxworth Project (Greig-Smith *et al.*, 1992). This chapter examines the effects of reducing herbicide, insecticide and fungicide inputs on the control of weeds, pests and diseases, respectively, at the three SCARAB sites over six-year arable rotations. SCARAB was designed as a large field-scale study (Chapter 3.1) of the ecological impact of pesticides and, as such, its design was not optimal for the determination of specific yield effects of individual pesticide treatments. However, it was possible within SCARAB to obtain estimates (using published yield-loss relationships) of yield losses associated with reducing or omitting specific pesticide inputs applied against weed, pest or disease targets. These estimates are supported with field observations on the abundance of the target species before and after treatment. The following sections of this chapter discuss the observed yield effects of reduced pesticide use in SCARAB, but it must be borne in mind that these effects are the result of the combined pesticide programme applied to each crop in question and, as such, must be interpreted with care.

Pests and diseases were monitored throughout the life of each crop to determine the need for pesticide treatment. Assessments were made after fungicide and insecticide applications in order to determine the level of control achieved. Frequent and detailed observations of weed populations were made regularly at a range of distances from the field boundary, to determine the impact of the Current Farm Practice (CFP) and the Reduced Input Approach (RIA) regimes on the distribution and frequency of weed flora within each field. There were no baseline assessments of pests, diseases or weeds in the pre-treatment year.

The crucial differences between the two pesticide regimes were the lack of insecticide and the substantial reductions in herbicide and fungicide use (Chapter 3.1). RIA was designed to contrast strongly with CFP, thus providing the differential in pesticide applications required to assess the potential effects of pesticides on non-target organisms. The complete absence of insecticides (including molluscicides and nematicides) in RIA inevitably gave rise to a commercial disadvantage, the economic details of which are discussed in Chapter 3.6.

Weed control

Herbicide use

The herbicides used in SCARAB were specific to each site and the spectrum of weeds present, were influenced by soil type and geographical area, and were among those most widely used by UK farmers, as shown in the MAFF Pesticide Usage Survey Reports (e.g. Davies *et al.*, 1993). Where possible, action thresholds were used as an aid to decision-making for herbicide treatments. Thirty-six different herbicide active ingredients were used on the nine crop types in SCARAB. The target reduction for herbicides in RIA was 50% or less than that used in CFP. However, a reduction of only 43% was achieved because of problem weeds at Gleadthorpe and High Mowthorpe. On most occasions, the dose of herbicides was

Reducing Agrochemical use on the Arable Farm: The TALISMAN and SCARAB Projects.

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reduced in RIA, rather than omitting applications altogether. There were two exceptions to this: firstly, the sugar beet crops at Gleadthorpe received full-rate herbicides in both CFP and RIA because of the poor competitive nature of sugar beet; secondly, full rate herbicides were also used in the CFP and RIA regimes of winter oilseed rape at High Mowthorpe in 1994, because of problems with poppies (*Papaver rhoeas*) and cleavers (*Galium aparine*) in previous crops.

At Drayton, the grass-wheat-grass rotation was effective in controlling weeds, with the greatest use of herbicide occurring in the second-year wheat crops. Herbicide programmes for both first and second wheats were based on diflufenican/isoproturon mixtures and supplemented by contact herbicides (e.g. fenoxaprop-P-ethyl and fluroxypyr) to control wild oats (*Avena fatua*) and cleavers. In total, only seven herbicide active ingredients were used in the wheat and grass crops at Drayton.

Of the three sites, herbicide use was greatest at Gleadthorpe. Cropping patterns at this site were diverse, with rotations containing winter and spring cereals, potatoes, spring beans and sugar beet. In total, 24 different herbicide active ingredients were used to control weeds at Gleadthorpe. Many of these were used in sugar beet, which is very susceptible to weed competition in the first 10 weeks following establishment. Several applications of multiple low-dose herbicide tank-mixes are normally applied to sugar beet to achieve optimum control of weeds. Analysis of the major crop groups of cereals and non-cereals, showed that the greatest number of herbicide units was applied to CFP in cereals (**Table 3.5.1**). The amount applied to the CFP in the non-cereal group was less, but only by 7%. This is less than the equivalent reduction achieved in TALISMAN and is due primarily to the high level of herbicide applied to SCARAB sugar beet and potato crops.

The High Mowthorpe rotation was based predominantly on winter cereals, with winter oilseed rape and spring bean break crops. With a weed spectrum of mostly broad-leaved weeds with some wild oats, the most commonly used herbicides in winter cereals were diflufenican and isoproturon, applied as a tank-mix in the autumn. Where necessary, spring applied herbicides such as metsulfuron-methyl and fluroxypyr were applied to control poppy and cleavers, respectively. Spring cereals received contact herbicides only (e.g. bromoxynil, ioxynil and mecoprop), and all break crops received at least one residual herbicide (e.g. propyzamide in oilseed rape). In total, 12 herbicide active ingredients were used on the range of crops grown at High Mowthorpe.

Weed species and diversity

The various weed flora occurring on arable soils are the result of selection pressure from the type of crops grown in the rotation and the pattern of herbicide use. Each of the SCARAB sites possessed a unique weed spectrum of broad-leaved and grass weeds which had evolved over the past 30 years of intensive crop production. Most of the herbicides used previously at these sites were applied at, or near to, full label-recommended rates, and weed resistance to herbicides was not thought to have contributed to the dominance of any particular weed species. Weed numbers and species were assessed in three field areas of each SCARAB plot (Chapter 3.1). These included the field-crop margin (adjacent to the field boundary), the crop headland (first 10 m of crop adjacent to the boundary) and the within-field area (crop area 40 m to 120 m out from the boundary).

Grasses

The greatest number of grass species (12) was found at High Mowthorpe, with most of them occurring in the crop margin (**Table 3.5.2**). Of the grasses found, wild oats, meadow fescue (*Festuca pratensis*), annual meadow grass (*Poa annua*), volunteer wheat and barley occurred in all three field areas. Only five grass weed species were found at Drayton. Italian ryegrass (*Lolium perenne* ssp. *multiflorum*), annual meadow grass and rough-stalked meadow grasses (*Poa trivialis*) were found only in the margin. Three species of economic importance, black-grass (*Alopecurus myosuroides*), wild oats and couch (*Elytrigia repens*) were all found in the headland area and black-grass was also recorded in the field area. Volunteer wheat was not found in any area due to the good suppressive ability of the grass crop which comprised the majority of the Drayton rotation. A total of 10 grass species was found at Gleadthorpe, again mostly in the field margin area. Volunteer wheat and barley and annual meadow grass were found in all areas, whilst wild oats, sterile brome (*Anisantha sterilis*) and couch were found in the margin area only.

Broad-leaved weeds

A total of 48 broad-leaved weed species was found over the three sites (**Table 3.5.3**). All three sites had a similar number of weed species present in the headland and field areas, but Gleadthorpe had slightly more weed species in the margin area. There was a greater diversity of broad-leaved weeds than grasses in SCARAB, and each site supported a unique weed flora.

Some weeds were found only at a single site in a single area:

- bugloss (*Anchusa arvensis*) and plantain (*Plantago media*) in the margin at Gleadthorpe;
- hogweed (*Heracleum sphondylium*) in the margin at High Mowthorpe;
- buttercup (*Ranunculus repens*) in the margin at Drayton.

Other weeds such as pineapple weed (*Matricaria discoidea*) were found in the headland area only at High Mowthorpe and Gleadthorpe. Fat hen (*Chenopodium album*) was recorded only in the field area at High Mowthorpe, but was found in all areas at Gleadthorpe where fat hen is considered a major weed on the sandy soil of that site. Other weeds such as orache (*Atriplex patula*), hedge mustard (*Sisymbrium officinale*) and field pansy (*Viola arvensis*) could be found in all areas at Gleadthorpe, but at no other site. The same was true for red dead-nettle (*Lamium purpureum*) at High Mowthorpe, and scarlet pimpernel (*Anagallis arvensis*), spear thistle (*Cirsium vulgare*) and round-leaved fluellen (*Kickxia spuria*) at Drayton. Weeds such as cleavers, knotgrass (*Polygonum aviculare*), creeping thistle (*Cirsium arvense*) and chickweed (*Stellaria media*) were found in all areas at all three sites.

Because of the intensive floral monitoring in SCARAB, it has been possible to identify weeds which were not present at the beginning of the study, but were recorded during the latter years. These included:

- wild radish (*Raphanus raphanistrum*) which was first recorded at Gleadthorpe in 1994 and then again in 1996;
- spear thistle, which was not recorded at Drayton until 1993, then annually thereafter;
- small toadflax (*Chaenorhinum minus*), willowherb (*Chamerion angustifolium*) and round-leaved fluellen recorded at Drayton in 1993 only;
- willowherb and redshank (*Persicaria maculosa*) at Gleadthorpe in 1994 and 1995 only;
- many-seeded goosefoot (*Chenopodium polyspermum*) and plantain were only recorded at Drayton in 1996.

These results from SCARAB appear to mirror the results found in the Boxworth Project, where plant diversity was shown to be greatest in the first metre of cultivated ground from the field edge and where field species predominated (Marshall, 1992). The major implication of the Boxworth Project results was that most field-boundary plants did not constitute a threat as field weeds. Data from SCARAB flora assessments support this conclusion, as many of the weed species identified, especially grasses, were confined to the crop margin area.

Weed numbers

For the majority of crops in SCARAB, reduced rates of herbicides were applied to RIA and weed numbers increased as a result. In a few cases, where yield was likely to be seriously threatened by weed competition (e.g. potatoes, sugar beet and oilseed rape), full rate herbicides were used in both RIA and CFP, and weeds were suppressed. The efficacy of the half-rate herbicide programmes employed in the RIA varied from effective to inadequate (**Table 3.5.4**). Weed control was generally poorer in the oilseed rape and bean crops, where broad-leaved weeds predominated, and these were not well-controlled by the herbicides available. Weed control in potatoes and sugar beet was considered critical, so levels of herbicide were generally maintained at the same level in RIA as CFP to protect yield.

By looking at the combined data for all three sites across the six years of the SCARAB study, it can be seen that weed numbers in RIA were always higher than in CFP (**Fig. 3.5.1**). The level of weed control in CFP was relatively consistent, but it is worth noting that although CFP received full-rate herbicide, weeds were not completely eliminated in any year and weed seeds were returned to the soil seedbank.

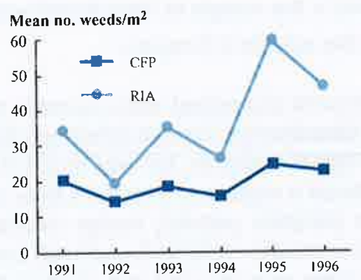

Figure 3.5.1. Mean numbers of weeds in the SCARAB pesticide regimes, 1991–1996. Data shown are means of all three sites, across all crops.

The peaks in weed numbers in RIA in 1993 and 1995 were due to specific weed problems at Gleadthorpe and High Mowthorpe. The problems of poor overall weed control in some crops in 1991 and 1993 were accentuated as a result of subsequent cultivation practices. Weeds and crop stubbles were ploughed down prior to sowing of the following crop, and then ploughed back up to the surface prior to drilling of subsequent crops.

Site-specific weed populations

Drayton

Although there were 26 weed species recorded at Drayton, many were located in the field margins, and numbers of weeds in the main field areas were low in both CFP and RIA. Numbers increased up to 40/m² in the first grass crop after wheat in 'Field 1' but subsequently declined to virtually zero as the grass ley became established over the following three years (**Fig. 3.5.2**). In 'Field 5', numbers of weeds increased up to 53/m² in the first wheat crop after grass but again declined to very low numbers through the rest of the rotation. Differences between CFP and RIA in both fields were small, and are unlikely to be responsible for yield loss as a result of weed competition.

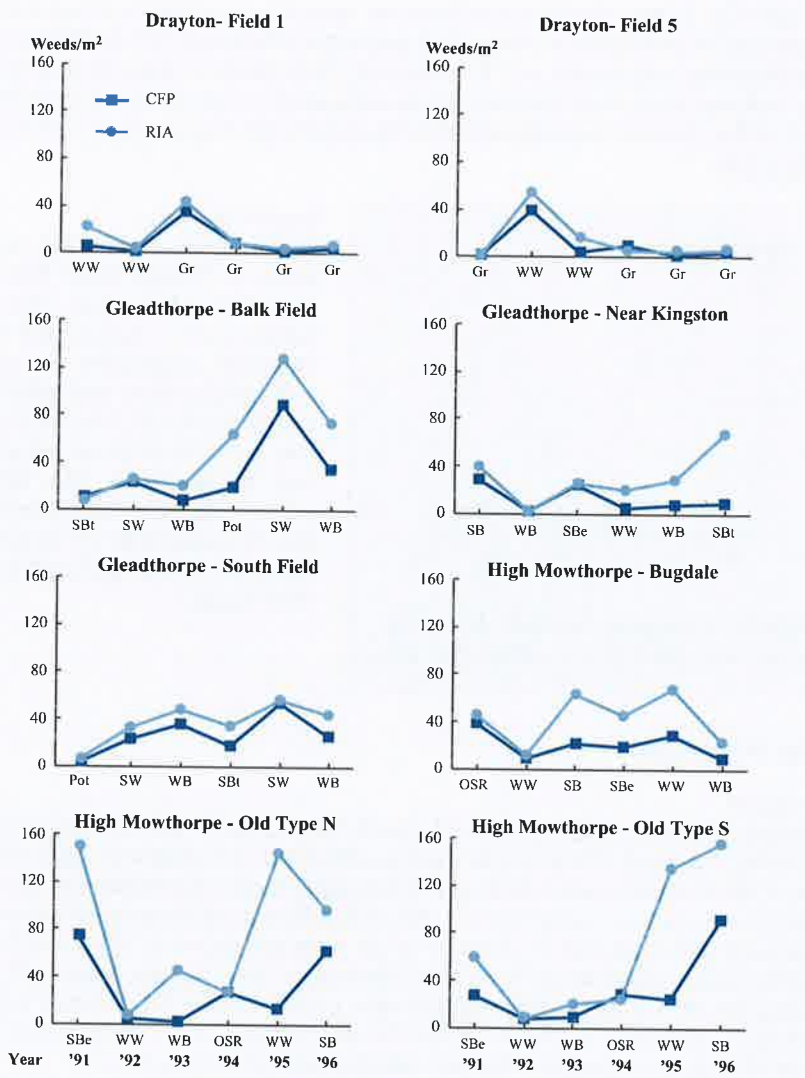

Figure 3.5.2. Weed populations in SCARAB fields, 1991–1996, in CFP and RIA pesticide regimes (weeds/m²). Key to crops: WW - winter wheat; Gr - grass; SBt - sugar beet; SW - spring wheat; WB - winter barley; Pot - potatoes; SB - spring barley; SBe - spring beans; OSR - winter oilseed rape.

Gleadthorpe

'Balk Field'

Because of anticipated yield penalties from reduced rate herbicide use, a full rate programme was used in the sugar beet crop in 1991. Thereafter, the herbicide programme was reduced to half-rate in the following two cereal crops, and weed numbers increased marginally in RIA under winter barley by 10 weeds/m². Herbicide rates were only partly reduced in RIA for the potato crop in 1994, as potatoes are very sensitive to weed competition. Weed numbers in RIA increased further under potatoes, and were 45% higher in RIA than CFP in the following spring wheat in 1995 and 80% higher in the final crop of winter barley in 1996 (**Fig. 3.5.2**). Shepherd's purse (*Capsella bursa-pastoris*) and knotgrass both increased in number between 1992 and 1995 as a result of reduced herbicide applications to RIA, and knotgrass in particular showed a six-fold increase in numbers in RIA between 1993 and 1995 (**Fig. 3.5.3**). The high weed numbers in the spring wheat crop in 1995 were possibly a result of reduced crop competitiveness in the very dry summer conditions.

'Near Kingston'
All the crops in 'Near Kingston' field received reduced rate herbicide inputs in RIA. There was little difference in the weed populations between CFP and RIA in the first three years up to 1994 and, from then on, the treatments began to diverge. In the final year, 1996, there were almost 60 more weeds/m² in RIA in the sugar beet crop, although weed populations did not increase to the levels seen in 'Balk Field' (**Fig. 3.5.2**).

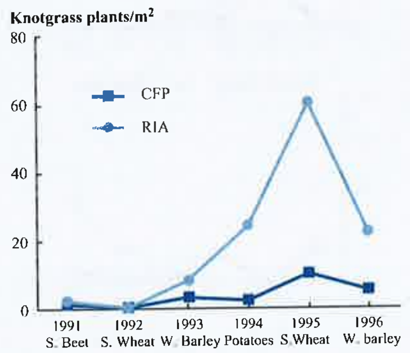

Figure 3.5.3. Knotgrass populations in the SCARAB pesticide regimes, 'Balk Field', Gleadthorpe, 1991–1996.

'South Field'
Weed numbers were also much lower in 'South Field' than in 'Balk Field' (**Fig. 3.5.2**). The RIA potato crop received a full-rate herbicide programme in 1991, and weed control was effective and similar to CFP. The remaining five crops all received reduced-rate herbicides in RIA. Weed control was marginally poorer in RIA compared with CFP in winter barley (1993 and 1996) and sugar beet (1994).

High Mowthorpe

'Bugdale'
Weed populations remained similar for both CFP and RIA for the first two years of SCARAB (**Fig. 3.5.2**). Weed control was less effective in spring barley (1993), where use of reduced rate contact herbicides (bromoxynil, ioxynil and mecoprop) allowed weed numbers to increase more in RIA. This difference was perpetuated in the following two crops with an average of 40 more weeds/m² in RIA, comprising mainly broad-leaved weeds such as chickweed, cleavers, poppy, speedwell and knotgrass. Annual meadow grass was also present. In the final crop of winter barley, the difference between CFP and RIA was reduced back to 13 weeds/m² as a result of good control from half-rate diflufenican and isoproturon.

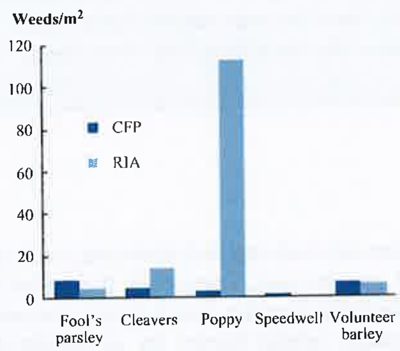

Figure 3.5.4. Number of weeds by species in the SCARAB pesticide regimes in 'Old Type', High Mowthorpe, 1995.

'Old Type N & S'
Poor control in the first year crop of spring beans led to a doubling of weeds in RIA, compared with CFP, especially in the north half of the field (**Fig. 3.5.2**). However, the half-rate autumn residual herbicides (diflufenican and isoproturon) applied to RIA in winter wheat in the following year (1992) gave very effective control of all weeds, and numbers in both RIA and CFP were low. The difference in weed numbers between CFP and RIA was re-established in winter barley in 1993, when the weed seeds deposited in the spring beans were returned to the surface layers by ploughing. Because of the heavy burden of weeds that was established in Old Type, full-rate herbicide was applied to RIA in winter oilseed rape, which gave effective weed control. However, a reduced rate herbicide programme in the following winter wheat (1995) resulted in a large increase in weed numbers, allowing a difference of 120 weeds/m² to develop in RIA compared with CFP. These

weeds comprised mainly poppy and cleavers (**Fig. 3.5.4**). Increasing numbers of wild oats also appeared in the crop, although not in the fixed-point assessment areas. In the final crop of spring barley, weed populations increased in both CFP and RIA and remained over 60% higher in RIA compared with CFP.

Crop equivalents

Although no direct measure was possible of the impact on yield of the increase in weed numbers in RIA at these sites, use of 'crop equivalents' presents an opportunity to estimate this impact. Work by Wilson & Wright (1990) defined a competitive index for a range of weed species in winter wheat. This index provided a measure of the impact on crop yield of key weed species, and defined the 'crop equivalent' unit as the numbers of a given weed species expected to produce a yield reduction of 2%.

Cleavers are an important arable weed, and much time and money is currently spent on controlling them. Very few cleavers/m^2 are required to cause major losses in crop yield. For example, in winter wheat, 1.6 cleavers/m^2 would be expected to give a yield loss of 2% (Wilson & Wright, 1990). In oilseed rape, 2.7 cleavers/m^2 would be expected to give a 5% yield loss (Lutman *et al.*, 1995). In 'Old Type' field at High Mowthorpe, the difference in the number of cleavers between CFP and RIA increased between 1992 and 1995, reaching nine cleavers/m^2 more in RIA than CFP in winter wheat in 1995. Using the crop equivalent of 1.6 cleavers/m^2, a loss in crop yield in the order of 11% could have been expected.

Poppy was the other site-specific weed to show a large increase in numbers under RIA over the six-year study, in the same field. At the peak in 1995, RIA had 109 poppies/m^2 more than CFP. Using a crop equivalent of 21 poppies/m^2 required to achieve a 2% reduction in crop yield, the poppy population in RIA was estimated to have caused a yield reduction of around 10% in winter wheat. The observed yield loss in the RIA of 'Old Type' in 1995 averaged 1.47 t/ha or 17%, compared with the combined calculated yield loss of 21% from the cleavers and poppy infestations.

Invertebrate pest control

Insecticide use

The insecticides (including nematicides) applied in SCARAB reflected those most commonly in use by farmers at the time, as indicated by the MAFF Pesticide Usage Survey Reports produced in 1991, 1993 and 1995 (e.g. Davies *et al.*, 1993). Unlike fungicides, there was little change in the range of insecticide products available and used during the SCARAB study. Crops were monitored regularly during the growing season, and assessed at key crop growth stages to determine the need for insecticide treatment. Insecticides were not applied in the RIA regime. In order to meet the demands of the ecological studies, it was, on occasions, necessary to apply an insecticide to the CFP regime against a particular invertebrate pest problem even though the normal action threshold against that particular pest may not have been exceeded in the field (Chapter 3.1). Pest populations were assessed before and after each insecticide application to CFP. This gave data to allow the level of pest control achieved to be compared with the nil-insecticide RIA treatment. In total, 31 applications of insecticide were made to CFP in cereals and 18 applications to CFP in non-cereals. These insecticides were targeted at a wide range of pests as detailed in **Tables 3.1.7, 3.1.8 & 3.1.9** in Chapter 3.1.

Invertebrate pest action thresholds were reached or exceeded in 13 out of 28 cereal crops, and in 10 out of 20 non-cereal crops. However, in over 70% of the insecticide applications, the levels of pest incidence and damage in the nil-insecticide RIA were found to be similar to the treated CFP. Slugs were not found at damaging levels in any of the SCARAB crops throughout the duration of the study and, consequently, no molluscicides were applied to any of the crops.

Pests in cereals

Wheat bulb fly (*Delia coarctata*) was a particular problem at Gleadthorpe, where potatoes and sugar beet were included in the rotation. Bare soil beneath the canopy of these root crops provided suitable egg-laying sites for wheat bulb fly during July and August. A variable egg count of up to 1.0 million eggs/ha was recorded for 'Balk Field' at Gleadthorpe in autumn 1994. Fonofos seed treatment was subsequently applied to the CFP spring wheat sown in late December, but not to RIA. Crop damage was subsequently assessed in April 1995, and the percentage of plants showing symptoms of attack (deadhearts) reached 3% on CFP and 11% on RIA. The RIA plot yielded 0.9 t/ha less than CFP in this field but it is unlikely that the wheat bulb fly damage seen would have resulted in this level of loss. Other factors including higher weed numbers and aphid populations on RIA were also implicated. In the same year, low numbers of 0.3 million eggs/ha were found in 'South Field' at Gleadthorpe. No seed treatment was used in CFP but owing to the level of wheat bulb fly damage which became visible in March, a dimethoate spray was applied to the CFP of 'South Field'. However, the numbers of deadhearts continued to rise after the spray was applied, so there was little difference in the final damage levels between CFP and RIA.

Summer infestations of cereal aphids, including grain aphid (*Sitobion avenae*) and rose-grain aphid (*Metopolophium dirhodum*), gave rise to most of the pest problems in cereal crops at all SCARAB sites. Of the 28 cereal crops grown, four spring wheat and five winter wheat crops exceeded the cereal aphid treatment threshold, which was defined as at least 66% of tillers infested between the start of flowering and the late milky-ripe growth stages. When aphid numbers exceeded threshold, a single application of an insecticide (e.g. dimethoate or pirimicarb) was immediately applied to the CFP only. Numbers of aphids were typically reduced in CFP from over 90% tillers infested to around 5% tillers infested but remained high in RIA for a period of up to two weeks after the sprays were applied to CFP. Aphid numbers then declined in RIA as a result of natural causes such as predation. It is of interest to note that in several of the crops (e.g. spring wheat at Gleadthorpe in 1995), aphid numbers increased in CFP as numbers in RIA were declining, and were generally found to be at higher levels in CFP than in RIA by the last assessment date (**Table 3.5.5**). This observation may reflect higher levels of activity of predatory insects and spiders in the insecticide untreated RIA plots.

Previous research into aphid/yield loss relationships (Oakley & Walters, 1994; Oakley *et al.*, 1998) predicted the potential yield loss from increasing, stable or declining aphid populations in winter wheat. Where numbers of tillers infested with aphids were above threshold at growth stage (GS) 61 (flowering), a yield reduction of 0.26 t/ha could be expected if the aphids were not controlled subsequently. Control of above threshold aphid numbers at GS 73 (milky ripe) gave a lower potential yield response to treatment of 0.1 t/ha. Based on these data, in the SCARAB winter wheat crops previously described, where the aphids remained at high levels in RIA from GS 59 to GS 83, a yield reduction of at least 0.26 t/ha could have occurred. At £85/t, this could have resulted in a reduction in output of £22/ha, compared with typical current insecticide costs of £2.50/ha for dimethoate. The actual yield losses observed in these crops ranged from 0.5 t/ha to 0.8 t/ha, but it should be understood that some of these losses represent the combined effect of the RIA regime, including possible effects on the control of weeds and disease resulting from reducing inputs of herbicides and fungicides.

As a consequence of uncontrolled aphid numbers in the RIA of winter wheat at High Mowthorpe in 1995, a visible difference in sooty mould (*Cladosporium* spp.) infection developed as a result of higher levels of aphid honeydew deposited on the ears and flag leaves. Thirteen per cent more ears were affected with sooty moulds in RIA, compared with CFP, even though RIA received a reduced-rate fungicide (propiconazole) at ear emergence. The observed differences in the levels of sooty mould infection between CFP and RIA may have contributed to some loss in yield, as thousand seed weights and specific weights were lower on RIA.

The insecticide cypermethrin was applied in the autumn to CFP of all nine winter barley crops, to control the aphid vectors of barley yellow dwarf virus (BYDV). Aphids were found only in three crops, with high levels in two of them. However, no BYDV symptoms were observed in any of the RIA or CFP plots. The low cost of insecticides (usually synthetic pyrethroid sprays), combined with the threat of serious yield losses (Vickerman & Wratten, 1979) in high-risk years, has resulted in the preventive control of BYDV becoming a widespread and routine commercial practice.

In the four crops of spring barley in SCARAB, none of the pests present reached insecticide treatment thresholds. Wheat bulb fly and cereal aphids were found at Gleadthorpe in 1991 and cereal aphids at High Mowthorpe in 1993 and 1996. These crops received an insecticide spray to establish a difference between CFP and RIA for the purposes of the ecological studies. However, in commercial practice, these sprays would not have been justified.

Pests in spring beans and winter oilseed rape

Pest populations exceeded insecticide treatment thresholds in two of the four crops of spring beans in the SCARAB study. Black bean aphid (*Aphis fabae*) attacked the crops of spring beans in 'Old Type N & S' at High Mowthorpe in early July (post-flowering) in 1991. Although pirimicarb was applied to CFP, aphid numbers remained at a similar level to the untreated RIA due to re-invasion by the pest. Numbers on both treatments declined naturally during August. All other bean crops received an insecticide spray to establish a difference between CFP and RIA, but in practice, these sprays would probably have been uneconomic to apply.

In winter oilseed rape, cabbage seed weevil (*Ceutorhynchus assimilis*) exceeded the threshold of 0.5 weevils per plant at High Mowthorpe in early June 1991 and triazophos was applied shortly afterwards (post-flowering). Yields of oilseed rape were 0.6 t/ha (20%) lower in RIA than in CFP, with similar numbers of weeds and levels of disease in each regime. Therefore, the observed yield difference may be attributable in part to the cabbage seed weevil population observed in this crop, although yield losses from this pest are more typically in the region of five to seven per cent (Ward *et al.*, 1985). In 1994, seed weevil did not reach threshold numbers in either crop of oilseed rape at High Mowthorpe, which may have been due to increasing levels of parasitism by *Trichomalus perfectus* (an ectoparasitic pteromalid wasp), the incidence of which had been monitored elsewhere on this farm and was found to be increasing (Alford *et al.*, 1995).

Pests in sugar beet

In all three sugar beet crops grown in SCARAB, populations of migratory nematodes (including *Trichodorus* spp. and *Longidorus* spp.) were found to exceed the treatment guideline of 200 nematodes per litre of soil. The granular nematicide, aldicarb, was subsequently applied as a soil treatment to CFP. Aphids were also recorded in high numbers in both CFP and RIA in 1991 and 1994. Few aphids appeared until late June. Thereafter, numbers of peach-potato aphid (*Myzus persicae*) increased rapidly but declined quickly in late July. Black bean aphid populations developed more slowly and were sustained for a longer period into early August. Pirimicarb was applied to CFP in mid-July in 1991 but, in 1994, the aphid populations declined naturally and no insecticide was required.

Silver y moth (*Autographa gamma*) caterpillars attacked the sugar beet crop at Gleadthorpe in 1996, reflecting a high national incidence of this pest observed during that summer. In the RIA, 98% of the plants were attacked and the damaged plants were estimated to have lost an average of 38% of their leaf area to caterpillar feeding. Cypermethrin was subsequently applied to the CFP, which reduced the proportion of plants attacked to 88% and limited the loss in leaf area to 12%. Although a large proportion of the 9.9 t/ha yield depression observed in RIA, compared with CFP, may be attributed to attack by migratory nematodes and silver y moth, poor weed control may also have contributed to the lower yield of the reduced input regime.

Pests in potatoes

Aphids (primarily *Macrosiphum euphorbiae*) were a particular problem at Gleadthorpe in the cultivar Record in 1991 and 1994. This cultivar is known to be susceptible to direct feeding damage by aphids. In severe cases, a symptom known as 'false top roll' may occur, when the upper leaves of the plant curl up and wither in response to the physiological stress of aphid attack. Assessments of the proportion of plants infested with potato aphids were done in mid-July in 1991, and in early and late June 1994. The assessments made in 1994 showed that the proportion of plants infested on both treatments increased up to 70% during June. The equivalent populations observed in 1991 were lower and approximately half of those observed in 1994. In both years, the observed increases in aphid populations were sufficient to trigger aphicide treatments to the CFP.

Following the application of pirimicarb in 1994, aphid numbers were reduced to zero in CFP in both years. However, the numbers of potato aphid continued to increase in RIA and 91% of plants were infested by mid-July. Within approximately two weeks of insecticide application to the CFP, the aphid populations in the untreated RIA declined to low numbers due to natural causes such as predation and disease. Until recently, the standard advice to growers in the UK was to apply insecticides to control aphids on ware potatoes at the relatively low population density of five aphids per compound leaf (Gratwick, 1989). This was based on research carried out in the 1960s and 1970s (Carden, 1965; Southall & Sly, 1976) and yield losses ranged from 1.5 up to 4.5 t/ha depending on the number and species of aphids. Field experiments done in the period 1986–1993 by ADAS on a range of varieties suggested that even high populations (30 per compound leaf) did not cause direct yield loss in the absence of false top roll. The observed yield losses in RIA, compared with CFP, were 5.2 t/ha (13.7%) in the 38 t/ha ware crop of cv. Record in 1991 and 8.3 t/ha (16.3%) in the 50.9 t/ha crop of cv. Record in 1994. It is believed that a large element of the RIA yield losses was caused by the restriction of tuber bulking resulting from direct feeding by aphids as no other problems were apparent, although this is not supported by the previous studies discussed.

Pests in grass

Populations of leatherjackets (*Tipula paludosa*) exceeded the treatment threshold of 130 leatherjackets/m^2 in a fourth grass crop at Drayton in December 1991. At that time, their numbers were estimated to be 610/m^2 in CFP and 1010/m^2 in RIA. Chlorpyrifos was applied to CFP at full-rate at the end of January 1992 and numbers of leatherjackets were subsequently reduced to zero but remained above threshold in RIA at 443/m^2. By late March 1993, no leatherjackets were found surviving in the CFP and numbers had declined naturally to 200/m^2 in RIA.

Work by Blackshaw (1985) suggests that losses of 0.23 to 0.31 t/ha of grass herbage may have occurred in the RIA owing to the uncontrolled leatherjackets. The actual yield difference measured between CFP and RIA was 1.8 t/ha, suggesting that other factors may well have been implicated.

Disease control

The design of SCARAB did not allow yield losses to be directly ascribed to the reduction or omission of individual fungicides. However, there have been occasions in the study where notable differences occurred in the levels of disease control between CFP and RIA. Some yield loss equations exist to calculate potential yield losses from given levels of disease infection. Of the 48 crops grown in SCARAB, 16 crops had a level of disease on RIA which may have been implicated in yield losses, especially on winter and spring wheat and spring beans. In the majority of other crops, low or nil fungicide use in RIA gave very similar levels of disease to those achieved in CFP.

Fungicide use

The fungicides applied in SCARAB reflected those most commonly in use by farmers at the time, as indicated by the MAFF Pesticide Usage Survey Reports produced in 1991, 1993 and 1995 (e.g. Davies *et al.*, 1993). The new and novel group of fungicides, known as the strobilurins, were not widely used by farmers until after the end of the Project, so they were not used on CFP or RIA. Crops in SCARAB were monitored regularly during the growing season, and assessed at key crop growth stages to determine the need for fungicide treatment. Fungicides were consistently applied at reduced rates in RIA, apart from in the potato crops at Gleadthorpe where full rates (or just less than full rates) were applied, owing to the risk of serious yield loss from potato blight (*Phytophthora infestans*).

Diseases in cereals

Septoria tritici was the most common disease in the winter wheat crops in SCARAB, and the potential yield loss from this disease can be described by the following disease/yield loss relationship (Thomas *et al.*, 1989):

% yield loss = % *S. tritici* on Leaf 2 x 0.42.

Wheat powdery mildew (*Blumeria graminis*) is generally regarded as less important than *S. tritici*, but can still cause significant yield loss which can be calculated using the following relationship (Cook *et al.*, 1991):

% yield loss = % powdery mildew on Leaf 2 x 0.35

The potential for yield loss due to the higher levels of foliar disease on Leaf 2 of RIA, compared with CFP, occurred in only six of the 20 winter cereal crops grown (**Table 3.5.6**). The potential yield losses resulting from the observed levels of disease were calculated using the above formulae, using typical yields of winter wheat and winter barley. For example, in a hypothetical first-year crop of winter wheat yielding 10 t/ha, the predicted combined yield loss due to the observed incidence of *S. tritici* and powdery mildew associated with reduced fungicide use in SCARAB was 0.39 t/ha. In contrast, the observed overall yield reduction of the RIA of first-year winter wheat crops in SCARAB was 0.66 t/ha, compared with CFP. The additional loss of the observed, compared with predicted, yield may have been a result of the greater weed competition and invertebrate pest populations that occurred in many RIA plots.

In the feed-grade, second-year wheat crops at Drayton, the potential yield loss was calculated as 0.37 t/ha for a 10 t/ha crop, whereas the observed mean yield reduction in RIA, compared with CFP, was 1.13 t/ha. Severe crop lodging was also believed to have contributed to the observed reductions in the RIA yield of second-year wheat crops at Drayton in 1992.

Foliar disease also played a minor role in the four spring wheat crops grown at Gleadthorpe. Similar levels of powdery mildew were recorded in the springs of 1992 and 1995 in both CFP and RIA, prior to fungicide applications. The fungicides applied, typically based on tebuconazole, were very effective in controlling disease and further disease development was normally limited to trace or low levels (< 10%) on the lower leaves.

Moderate levels of powdery mildew were present in only two of the nine winter barley crops in SCARAB. There are no established formulae to describe the yield-loss relationship of powdery mildew in winter barley. However, it is believed to be a damaging foliar disease in that crop. Where powdery mildew was most prevalent, an estimate of the potential yield loss (made using the yield-loss equation for winter wheat) suggested that the yield loss from moderate mildew in RIA would have been around 1.4% or 0.08 t/ha. The observed yield differences between RIA and CFP associated with the two affected crops ranged from a reduction of 0.5t/ha to an increase of 0.9 t/ha on RIA and may have been influenced by other factors such as weed and pest control.

Very little disease was found in the four crops of spring barley grown in the SCARAB study. Typically, the levels of powdery mildew were moderate on leaf three in both CFP (4%) and RIA (8%), but absent on leaves one and two. Levels declined on all leaves following fungicide application. According to the established yield loss relationship for powdery mildew in spring barley (Priestley & Bayles, 1988), the observed level of mildew in RIA could have been expected to result in a yield loss of about 0.3 t/ha. However, the observed yield differences in RIA, compared with CFP, ranged from +0.3t/ha to -0.4t/ha and were believed to be more influenced by differences in weed numbers than disease control.

Diseases in non-cereal crops

Very little disease was found in the three crops of winter oilseed rape grown in the SCARAB rotation at High Mowthorpe. Levels of downy mildew (*Peronospora parasitica*), light leaf spot (*Pyrenopeziza brassicae*), sclerotinia (*Sclerotinia sclerotiorum*) and alternaria (*Alternaria brassicae*) were all well below treatment thresholds in the oilseed rape. In two crops of rape, no fungicides were applied to either CFP or RIA regimes.

Sugar beet crops are not normally treated with fungicides, unless there is a late infection of mildew (*Erysiphe betae*) or rust (*Uromyces betae*). Little disease was found in either CFP or RIA in the three sugar beet crops grown at Gleadthorpe, and consequently, no fungicides were used, which reflected industry practice at that time.

The potato crops in SCARAB were grown to commercial contract standards for crisping, and as such, little or no foliar or tuber disease could be accepted. The variety Record was grown in 'South Field' at Gleadthorpe in 1991 with full irrigation, and received a full-rate, prophylactic blight fungicide programme of cymoxanil, mancozeb, oxadixyl, fentin hydroxide, fentin acetate and maneb to CFP, which was reduced by 25% when applied to RIA. There was no blight recorded in either CFP or RIA. The same variety was grown in 'Balk Field' in 1994, and a full fungicide programme of cymoxanil, mancozeb and oxadixyl was applied to both CFP and RIA, and no blight was recorded.

Grass crops are not normally treated with fungicides, unless there is a serious infection of mildew (*Blumeria graminis*) or crown rust (*Puccinia coronata*). Little disease was found in either CFP or RIA in the eight grass crops grown at Drayton. Propiconazole was applied to CFP in five crops to represent situations in which commercial farmers might apply a pesticide to grass. However, it is unlikely that these sprays would form part of current practice and should be viewed accordingly. Disease levels were generally very low, and higher levels in the absence of fungicide on RIA were only found in 'Field 1' in 1994.

Occasions where disease control in RIA equalled that of CFP

Intensive assessment of disease levels, both before and after fungicide treatment, enabled the occasions of similar disease control in RIA and CFP to be determined. In total, 30 reduced-rate applications out of 77 RIA fungicide applications resulted in disease control at least as good as that achieved by full-rate applications in CFP. These fungicides were targeted at septoria (*S. tritici* & *S. nodorum*), powdery mildew, eyespot (*Tapesia* spp.) and sooty moulds (*Cladosporium* spp. & *Alternaria* spp.) in winter and spring wheat; rhynchosporium (*Rhynchosporium secalis*), net blotch (*Pyrenophora teres*), powdery mildew, brown rust (*Puccinia hordei*) and eyespot in winter and spring barley; and crown rust and powdery mildew in grass. The diseases were above current treatment thresholds when assessed and so treatment to CFP was justified. Most of the winter wheats where reduced-rate fungicide gave similar responses to full-rate fungicide were first wheats, indicating the importance of minimising disease carry-over between winter cereals.

Discussion

The effects of reducing pesticide inputs to control weeds, pests and diseases in SCARAB were variable and were influenced by the site and rotation, weather conditions and seasonal fluctuations in pest and disease problems. Overall, weed numbers tended to be higher under the low-input regime, especially in the combinable crop rotation at High Mowthorpe. At this site, the effects of poor control of poppies and cleavers in RIA in the spring bean crop at the start of the study were noticed throughout the rest of the rotation. Cultivations played a part in determining whether shed seed posed a problem to the new crop or the following crop depending on whether the seed was buried or re-exposed to the soil surface after ploughing. Reducing herbicide inputs in the presence of potentially high weed numbers resulted in exacerbated weed problems. Weed numbers and the weed seedbank also increased under the low-input regime in TALISMAN (Chapters 2.3 & 2.4), with similar problems experienced on the High Mowthorpe SCARAB and TALISMAN trial sites, which had the same rotation.

The grass leys in the rotation at Drayton appeared to have a smothering effect on arable weed numbers, once the ley was established and the cutting/grazing regime implemented. Weed numbers were mostly contained within the combinable/root crop rotation at Gleadthorpe, as full-rate herbicides were used on RIA in some of the root crops, because of known problems with weed control and yield loss in the high value potato and sugar beet crops.

The floral species diversity in each of the SCARAB fields was influenced by the previous cropping history and mostly comprised grass and broad-leaved species associated with arable cropping. Species diversity was greatest in the crop margin area, as was found in the Boxworth Project (Marshall, 1992). Reducing herbicide inputs over the six-year period in SCARAB did not result in increased diversity of weed species, but it did allow populations of 'aggressive' and 'opportunistic' arable cropping weeds like poppy, cleavers and knotgrass to proliferate.

Although the CFP regime was never entirely free of weeds, the return of weed seeds to the soil remained greater in RIA, which ultimately led to the build up of unacceptable weed populations. SCARAB has indicated that, in some instances, the impact of reduced rate herbicide programmes can be tolerated in the short-term. However, there is a risk of creating longer-term weed problems, which are likely to require the intervention of full rate herbicides in order to maintain economically acceptable weed populations.

Pest thresholds were reached in 48% of the crops in SCARAB and insecticides were applied to CFP. Pest numbers often reached high levels in RIA where no insecticide was applied, but the difference in the level of pest damage between CFP and RIA was often slight. However, the omission of insecticides in RIA is thought to have contributed to yield loss in the crops where thresholds were reached, especially for aphids in cereals, potatoes and sugar beet, migratory nematodes in sugar beet and wheat bulb fly in spring wheat. The remaining 52% of the insecticide treatments applied to CFP were to create contrasting treatment differences for the purposes of the ecological studies in SCARAB. Although these experimental applications were not strictly justified on economic grounds, they remained commercially realistic.

There was some evidence that a range of natural predators was successful in eventually reducing aphid populations in cereals, potatoes and sugar beet to harmless levels in RIA but this did not occur until after the critical growth stages of the crop. Consequently, both yield and quality may have suffered as a result. Aphid numbers were also seen to increase in CFP several weeks after broad-spectrum insecticides had been applied, suggesting that the aphid-regulating capacity of certain beneficial insects and spiders may have been adversely affected by these treatments.

Results from SCARAB have shown that higher levels of disease were present in cereals following the use of reduced rate fungicides in RIA, compared with full rates in CFP. However, in only 30% of the winter cereal crops were the differences in disease incidence likely to have resulted in economically important yield losses. *S. tritici* was found to be around 6.9% higher in RIA in four out of 11 winter wheat crops and was estimated to have caused a yield loss of 2.9%. Similarly, but to a lesser extent in winter barley, 4% more powdery mildew in RIA of two out of nine crops could have reduced yield by 1.4%, compared with an observed average yield increase of 3.6% in RIA. However, in the majority of crops, the effect of reduced rate fungicide use in RIA did not lead to major differences in disease levels between CFP and RIA. Little or no difference in disease development was seen in spring barley, spring wheat, oilseed rape, beans or grass from the adoption of a reduced-rate fungicide strategy. This clearly indicates the potential to successfully reduce the amount of fungicide currently used in these crops.

Results from SCARAB have demonstrated that pesticide use can be reduced, and in many cases it is profitable to do so. However, it is necessary to identify and understand areas of potential risk on the farm, where reducing pesticide use would incur major losses without careful pesticide management.

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Table 3.5.1. Mean herbicide units applied per crop in SCARAB and percentage reduction in RIA compared with CFP (1991–1996).

	Cereals			Non-cereals	
Site	**System**	**Total units* applied/ha**	**Site**	**System**	**Total units* applied/ha**
Drayton	CFP	4.25	Drayton	CFP	0.25
(4 crops)	RIA	2.00	(8 crops)	RIA	0.06
	% reduction	52.9		% reduction	76.00
Gleadthorpe	CFP	1.75	Gleadthorpe	CFP	6.11
(12 crops)	RIA	0.88	(6 crops)	RIA	4.11
	% reduction	50.0		% reduction	32.70
H. Mowthorpe	CFP	2.83	H. Mowthorpe	CFP	1.50
(12 crops)	RIA	1.58	(6 crops)	RIA	0.92
	% reduction	44.0		% reduction	38.7
All sites	CFP	2.57	All sites	CFP	2.38
(28 crops)	RIA	1.34	(20 crops)	RIA	1.53
	% reduction	47.9		% reduction	35.70

* One unit is defined as one full label-rate application of a single active ingredient.

Table 3.5.2. Occurrence and distribution of grass weed species in SCARAB (1991–1996).

Grass species		**Site**	
	Drayton	**Gleadthorpe**	**High Mowthorpe**
Agrostis stonolifera	-	-	MH
Alopecurus mysuroides	HF	-	-
Arrhenatherum elatius	-	M	M
Anisantha sterilis	-	M	MF
Avena fatua	H	M	MHF
Elytrigia repens	MH	M	M
Festuca pratensis	-	-	MHF
Hordeum sativum	-	-	MHF
Lolium multiflorum	M	-	MHF
Lolium perenne	-	-	MHF
Poa annua	MHF	MHF	M
Poa pratensis	M	-	MHF
Poa trivialis	M	MHF	-
Triticum aestivum	MHF	-	-
Triticum durum	-	-	MHF

M = margin of crop; H = 2.5 to 10 m into crop; F = 40 to 120 m into crop.

Table 3.5.3. Occurrence and distribution of broad-leaved weed species in SCARAB, 1991–1996.

Broad leaved species	Site*			Broad leaved species	Site*		
	DT	GT	HM		DT	GT	HM
Aethusa cynapium	MHF	MH	MH	*Papaver rhoeas*	-	F	MHF
Anagallis arvensis	MHF	-	-	*Persicaria maculosa*	-	HF	-
Anchusa arvensis	-	M	-	*Plantago media*	-	M	-
Atriplex patula	-	MHF	-	*Polygonum aviculare*	MHF	MHF	MHF
Brassica napus	-	MHF	MHF	*Prunus spinosa*	M	-	-
Capsella bursa-pastoris	-	MHF	MHF	*Ranunculus repens*	M	-	-
Chaenorhinum minus	MH	-	-	*Raphanus raphanistrum*	-	MHF	H
Chamerion angustifolium	MF	M	-	*Rubus fruticosa*	M	M	-
Chenopodium album	-	MHF	F	*Rumex* spp.	-	M	M
Chenopodium polyspermum	H	-	-	*Senecio vulgaris*	H	MHF	HF
Cirsium arvense	MHF	MHF	-	*Sinapis arvensis*	F	-	HF
Cirsium vulgare	MHF	-	-	*Sisymbrium officinale*	-	MHF	-
Convolvulus arvensis	MF	-	-	*Solanum tuberosum*	-	MHF	HF
Euphorbia spp.	HF	-	-	*Sonchus* spp.	MHF	MHF	MHF
Fallopia convolvulus	MHF	MHF	HF	*Stellaria media*	MHF	MHF	MHF
Fumaria officinalis	-	MH	MHF	*Taraxacum* sect. *ruderalia*	F	-	H
Galium aparine	MHF	MHF	MHF	*Torilis nodosa*	-	-	M
Geranium spp.	F	M	-	*Tripleurospermum indorum*	-	MHF	MHF
Heracleum sphondylium	-	-	M	*Urtica urens*	M	MHF	MHF
Kickxia spuria	MHF	-	-	*Urtica dioica*	-	-	M
Lamium amplexicaule	M	-	HF	*Veronica persica*	MHF	-	MHF
Lamium purpureum	-	-	MHF	*Vicia faba*	-	HF	HF
Matricaria discoidea	-	H	H	*Vicia tetrasperma*	MH	-	-
Myosotis arvensis	-	MHF	MHF	*Viola arvensis*	-	MHF	-

* DT = Drayton; GT = Gleadthorpe; HM = High Mowthorpe.
M = margin of crop; H = 2.5 to 10 m into crop; F = 40 to 120 m into crop.

Table 3.5.4. Mean weed populations (weeds/m^2) in cereals and non-cereal crops in the SCARAB treatment regimes across all years (1991–1996).

Site	Crop	Regime CFP	RIA	Difference*
Drayton	Cereals (4 crops)	12	24	+12
	Non-cereal (8 crops)	7	9	+2
Gleadthorpe	Cereals (12 crops)	27	42	+15
	Non-cereal (6 crops)	13	33	+20
High Mowthorpe	Cereals (12 crops)	21	58	+37
	Non-cereal (6 crops)	33	54	+21

* The difference in mean weed population in RIA, compared with CFP.

Table 3.5.5. Grain aphid numbers on spring wheat in the CFP (dimethoate applied) and RIA regimes at Gleadthorpe in 1995 (% tillers infested).

Assessment dates	CFP (% tillers infested)	RIA (% tillers infested)
23 June	76	84
28 June (dimethoate applied)	4	96
7 July	5	82
14 July	21	2

Table 3.5.6. Estimated effects on yield of the higher levels of foliar diseases on cereals in the RIA treatment regime in SCARAB.

Crop	Disease	Difference in disease on Leaf 2 of RIA* (%)	Estimated yield loss (t/ha)
First winter wheat (1 crop)	*Septoria tritici*	+2.8	1.2
Second winter wheat (2 crops)	*Septoria tritici*	+8.9	3.7
First winter wheat (1 crop)	Powdery mildew	+7.7	2.7
Winter barley (2 crops)	Powdery mildew	+4.0	1.4**

* Difference in disease incidence in RIA compared with CFP.
** Value calculated using wheat mildew disease relationship.

THE IMPACT OF REDUCED INPUT PESTICIDE USE ON CROP YIELDS AND ECONOMICS IN SCARAB

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Introduction

The main objective of the SCARAB Project was to determine the ecological effects of pesticides in current commercial use, as described in Chapter 3.1 (Cooper, 1990). In particular, insecticides were totally excluded from the Reduced Input Approach (RIA) treatment, with the exception of one insecticide seed treatment applied to one out of 48 crops. Herbicides and fungicides were mostly applied to RIA crops at reduced rates. Decisions on pesticide inputs were primarily influenced by the need to reduce the pesticide loading on the environment whilst maintaining a comparable crop habitat to the Current Farm Practice (CFP) treatment. Crop yields and economic considerations were of secondary importance.

The large-scale, split-field design of the Project was developed to enable ecological assessments, especially of the mobile arthropods, to be carried out in a field situation. Such a design does not lend itself to accurate statistical analysis of conventional parameters such as yields and gross margins because of the lack of replication. However, where possible, data have been subjected to a paired two-tail t-test, to give some indication of statistical difference between the CFP and RIA treatments. The more formal replicated small plot design of TALISMAN was chosen to provide robust data on the impact of low-input nitrogen and pesticide use on crop yield and economics (Chapters 2.1 and 2.8).

Yields were measured in the SCARAB fields from the whole-plot monitoring areas for combinable crops (approximately 1.25 ha per split field), and from sub-samples of plots for potatoes, sugar beet and grass. Gross margins were also calculated for each crop, on the same basis as the TALISMAN crops, as described in Chapter 2.8. Arable Area Payments (AAPs) were included for appropriate crops from 1993 to 1996. There were no AAPs for sugar beet, potatoes or grass in these calculations. Gross margins for the grass crops at Drayton were calculated on a different basis to the combinable and root crops. Standard figures of £80/t at 100% d.m. and £180/ha for variable costs (excluding sprays) were used for all the grass crops. However, pesticide treatments applied to grass were costed in at actual prices.

This chapter deals with the yields and gross margins from all crops at the three sites. Unlike TALISMAN, there is no scope within the data collected in SCARAB to determine exactly which pesticide, or group of pesticides, had a direct effect on yield. Any effects seen are the result of the overall pesticide regime used on each plot. However, attempts have been made in Chapter 3.5 to link yield effects to observed pest, disease or weed problems based on prior knowledge, economic thresholds from other research, and where appropriate, references to yield effects seen in relevant TALISMAN crops in the same year.

The impact of reduced pesticide use on yields and gross margins

The overall effect of omitting insecticide use and reducing herbicide and fungicide use, by 43% and 52% respectively in SCARAB, was a significant yield reduction of 1.47 t/ha or 12% ($P < 0.001$) and a significant reduction in gross margin of £47/ha or 5.5% ($P < 0.01$) (**Tables 3.6.1 & 3.6.2; Fig. 3.6.1**). The effects on yield and gross

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Young J E B, Griffin M J, Alford D V, Ogilvy S E. [*eds*] 2001. London: DEFRA.

margin varied between the 48 comparisons between CFP and RIA. To give an indication of the variability, paired data from the CFP and RIA plots from each SCARAB field for each crop and year have been plotted so that each pair forms a co-ordinate point on a chart **(Figs 3.6.2 & 3.6.3)**. Points on the diagonal line indicate equal yields or gross margins from both treatments, points below the line indicate a higher yield or gross margin from CFP in the comparison, and points above the line indicate a higher yield or gross margin from RIA.

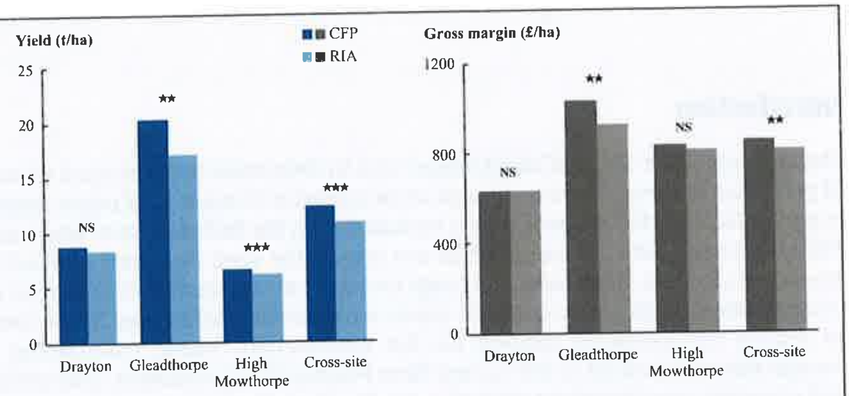

Figure 3.6.1. The effect of the pesticide regime on mean yields and gross margins of all crops in SCARAB. NS = not significant; ** $P < 0.01$; *** $P < 0.001$, based on the P (T † t) two-tail test.

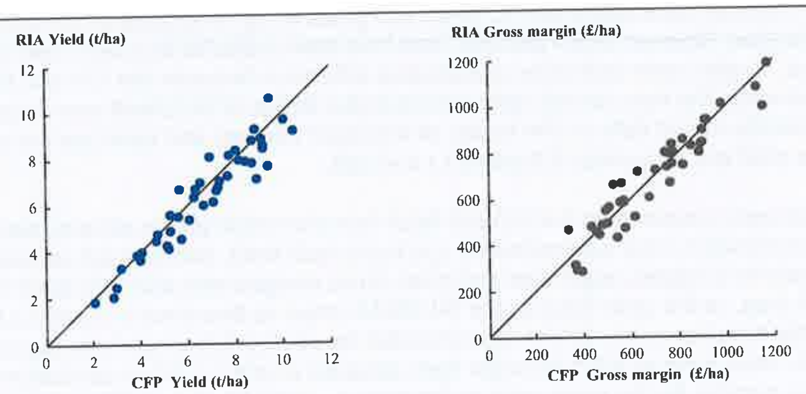

Figure 3.6.2. Yields and gross margins of all crops (excluding sugar beet and potatoes) in the RIA pesticide regime compared with the CFP pesticide regime. The diagonal line represents equal values from the two treatments.

For the combinable and grass crops (43 comparisons), yields were equal between CFP and RIA for three (7%) comparisons; 31 (72%) had lower yields on RIA with a range from -0.1 to -1.91 t/ha, average 0.73 t/ha; and nine (21%) had higher yields on RIA with a range from 0.2 to 1.0 t/ha, average 0.49 t/ha. In contrast with the gross margins, savings in variable costs made up for some of the yield losses; three comparisons were still equal for CFP and RIA; 20 (46%) had lower gross margins on RIA with a range from -£7/ha to -£164/ha, average -£70/ha; and 20 (46%) had higher gross margins on RIA with a range from £8/ha to £128/ha, average £43/ha.

The comparisons between CFP and RIA for sugar beet and potatoes are shown in **Fig. 3.6.3**, and in all five cases, RIA had a lower yield and gross margin than CFP. Reductions in variable costs did not compensate for the losses in yield for these crops.

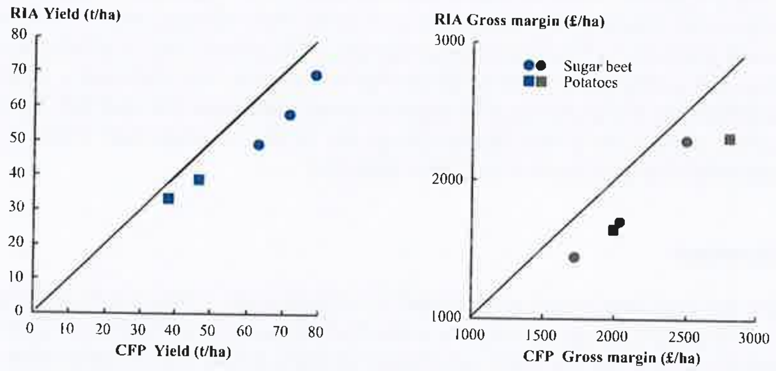

Figure 3.6.3. Yields and gross margins of sugar beet and potatoes in the RIA pesticide regime compared with the CFP pesticide regime. The diagonal line represents equal values from the two treatments.

The effects of RIA on yields and gross margins at a site level are shown in **Tables 3.6.1 & 3.6.2** and **Figs 3.6.1, 3.6.4 & 3.6.5**, and are described below.

Drayton

Grass leys and winter wheat were the main crops at Drayton. Overall at this site, there was no significant effect of the RIA treatment on yields or gross margins; the average yield was 3.7% lower on RIA but gross margins were equal for the two treatments.

Gleadthorpe

The mixed rotation at Gleadthorpe included the high yield and high value sugar beet and potato crops, as well as combinable cereals and legumes. Overall yield and gross margins were significantly lower on RIA ($P < 0.01$) by 16.1% and 10.3% respectively, mainly as a result of the effects on sugar beet and potatoes, which are discussed in more detail below.

High Mowthorpe

The rotation at High Mowthorpe was a combination of cereals, oilseeds and legumes. Overall yield was significantly lower on RIA ($P < 0.001$) at this site by 6.6%, but savings in variable costs made up for most of the lost revenue, and there was no significant difference in the overall gross margins between CFP and RIA.

Statistical analysis of yields and gross margins at the crop level is limited by the number of crops in each comparison, from a maximum of 11 winter wheat crops to only two potato crops (**Tables 3.6.3 & 3.6.4**). In some cases, quite large differences between treatments do not appear to be significant because of the lack of replication; therefore, the interpretation of these results needs to be treated with some caution.

Winter wheat

Overall wheat yields were significantly lower in RIA by 0.74 t/ha or 8.8% ($P < 0.001$) (**Table 3.6.3**). Nine out of the 11 crops had lower yields in RIA, ranging from -0.5 to -1.91 t/ha, with the greatest loss of 1.91 t/ha occurring in 'Old Type North' field at High Mowthorpe in 1995. This effect was probably the result of the very high poppy (*Papaver rhoeas*), cleavers (*Galium aparine*) and wild-oat (*Avena* spp.) populations in RIA that year (**Table 3.6.5**). The nine lower-yielding wheat crops had more disease in RIA and less green leaf area; five crops reached the threshold for summer aphids (*Sitobion avenae* and *Metopolophium dirhodum*) and RIA crops were left untreated; weed numbers were also higher on eight RIA crops; and one crop had more lodging. The main diseases were *Septoria* spp., powdery mildew (*Blumeria graminis*) and eyespot (*Tapesia* spp.). The overall loss in yield and crop revenue was partly compensated for by the reduction in variable costs, as there was a difference of £35/ha (3.8%) in gross margin between CFP and RIA, but this was not a significant effect (**Table 3.6.4**). Six of the 11 crops had lower gross margins which ranged from -£54/ha to -£164/ha.

Spring wheat

All four spring wheat crops were grown at Gleadthorpe. Yields on all plots were very low in 1995 (average 2.2 t/ha) as a result of the summer drought conditions on this light land site. All the crops were lower-yielding in RIA, with a range from -0.3 t/ha to -1.0 t/ha, and on average yielded significantly less ($P < 0.01$) by 0.85 t/ha or 22.1% (**Table 3.6.3**). The main problems appeared to be associated with summer aphids which were higher on all four RIA crops compared with CFP (**Table 3.6.5**). Wheat bulb fly (*Delia coarctata*) was a problem in two crops which may have contributed to the lower fertile tiller numbers in the untreated RIA crops. Disease levels were very low in the spring wheat crops, although green leaf area was lower in two RIA crops. Weed numbers were also higher in two RIA crops. Gross margins were also lower in RIA by £78/ha or 17.3% (range -£3/ha to -£119/ha) but this effect was not significant (**Table 3.6.4**).

Winter and spring barley

The barley crops grown at Gleadthorpe and High Mowthorpe were less affected by the lower pesticide use on RIA, and there were no significant overall effects on yield or gross margin (**Tables 3.6.3 & 3.6.4**). Nine of the 13 barley crops were lower-yielding in RIA, with losses ranging from -0.05 t/ha to -1.3 t/ha (**Table 3.6.5**). Weed numbers were higher in RIA in eight crops; autumn aphids (*Rhopalosiphum padi* and *Sitobion avenae*), as vectors of barley yellow dwarf virus, were present on two winter crops and summer aphids reached treatment threshold on one winter crop; disease levels were only higher on two crops; fertile tiller numbers were lower in two crops; and a higher proportion of stem brackling (collapse) affected two RIA crops. On average, yields were 0.4 t/ha (6%) and 0.02 t/ha (0.3%) lower in RIA than in CFP for the winter and spring crops respectively, whereas gross margins were £9/ha (1.3%) and £28/ha (4%) higher respectively. The greatest yield differences were seen at Gleadthorpe, but the effects on gross margins were the same at each site (**Fig. 3.6.4**).

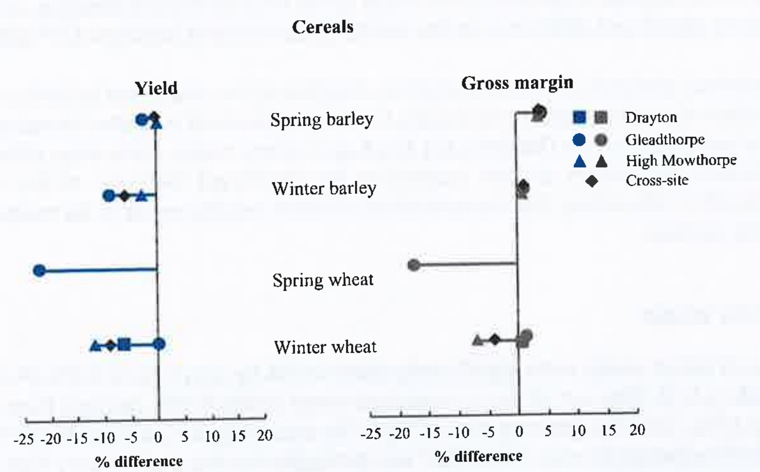

Figure 3.6.4. The effect of the RIA pesticide regime on mean yields and gross margins of the SCARAB cereal crops, shown as percentage difference of the RIA from the CFP pesticide regimes.

Spring beans

Four crops of spring beans were grown, one at Gleadthorpe and three at High Mowthorpe. All of the crops were lower-yielding in RIA, with a range from -0.1 t/ha to -0.4 t/ha (**Table 3.6.6**). Weed numbers were higher in all four RIA crops; black bean aphid (*Aphis fabae*) was a problem on two crops and pea and bean weevil (*Sitona lineatus*) on one; chocolate spot (*Botrytis* spp.) and downy mildew (*Peronospora viciae*) were more evident on three RIA crops. Overall yield was significantly lower in RIA ($P < 0.05$) by 0.25 t/ha (5.7%) (**Table 3.6.3**), but the positive effect on gross margin, of £18/ha or 3.2%, was not statistically significant (**Table 3.6.4**). Effects were similar at both sites (**Fig. 3.6.5**).

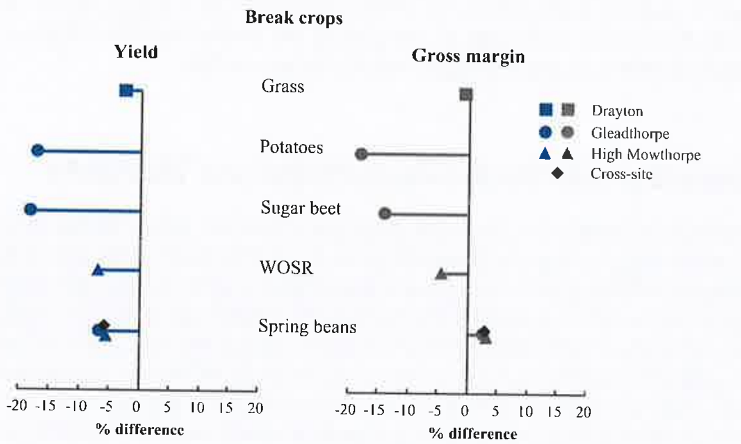

Figure 3.6.5. The effect of the RIA pesticide regime on mean yields and gross margins of the SCARAB break crops, shown as percentage difference of the RIA from the CFP pesticide regimes.

Winter oilseed rape

Only three crops of oilseed rape were grown in total, and these were all at High Mowthorpe. Two of the three crops were lower-yielding in RIA, and the largest loss of 0.6 t/ha may have been associated with above threshold numbers of cabbage seed weevil (*Ceutorhynchus assimilis*), which were untreated in RIA (**Table 3.6.6**). Yields and gross margins were on average 0.23 t/ha (6.8%) and £32/ha (4.2%) lower in RIA respectively, but the differences were not significant (**Tables 3.6.3 & 3.6.4**).

Sugar beet

Three sugar beet crops were grown at Gleadthorpe. Yields were significantly reduced in all three crops by 12.8 t/ha or 18% on average ($P < 0.01$) (**Table 3.6.3**). The losses in yield varied from -9.9 t/ha to -14.3 t/ha and may have been associated with untreated pest problems in RIA which involved migratory nematodes (e.g. *Trichodorus* spp.) in all three crops, aphids (e.g. *Myzus persicae*) in two crops and silver y moth (*Autographa gamma*) in one crop (**Table 3.6.6**). Weed numbers were also higher in RIA in two crops. Gross margins were also significantly affected by £286/ha or 13.7% ($P < 0.01$)(**Table 3.6.4**).

Potatoes

Only two crops of potatoes were grown at Gleadthorpe which limits the interpretation of the results. Yields were on average 6.75 t/ha or 15.9% lower in RIA, and corresponding gross margins were £426/ha or 17.8% lower (**Tables 3.6.3 & 3.6.4**). These results were not significant because of the small sample size. The yield losses may have been caused by aphid (e.g. *Macrosiphum euphorbiae*) populations, the numbers of which exceeded the treatment threshold and remained untreated in both RIA crops (**Table 3.6.6**).

Grass

All eight grass crops were grown in the ley/wheat rotation at Drayton. There were no significant effects on yields or gross margins (**Tables 3.6.3 & 3.6.4**). Yield responses were more variable in this crop and ranged from a loss of 1.8 t/ha to an increase of 1.0 t/ha, with an average of 0.19 t/ha less in RIA. Four of the eight RIA grass crops yielded less than CFP (**Table 3.6.6**). The losses were difficult to assign to specific crop effects or problems, except for 'Field 5' in 1991. 'Field 5' contained above threshold populations of leatherjackets (*Tipula* spp.), which may have contributed to the yield loss of 1.8 t/ha in the untreated RIA. Effects on gross margins were small and averaged only £5/ha less in RIA.

Comparison with the Boxworth Project and TALISMAN

The effects of adopting a low-input pesticide regime on overall winter wheat yields and gross margins from the three Projects, Boxworth, TALISMAN and SCARAB, are presented in **Table 3.6.7**. It is not possible to do a straight comparison between the gross margins for the Boxworth Project and TALISMAN and SCARAB, because AAPs were not in place when the Boxworth Project was carried out. AAPs between 1993 and 1996 for cereal crops ranged from £141/ha to £269/ha and averaged £218/ha, so this figure could be added to the Boxworth gross margins for comparative purposes. Wheat yields of the full-input pesticide treatments were higher in SCARAB (8.38 t/ha) and TALISMAN (8.13 t/ha) compared with the full insurance pesticide regime in the Boxworth Project (7.74 t/ha) (Greig-Smith *et al.*, 1992). Yield reductions from adopting the lower pesticide regimes were 0.74 t/ha (8.8%), 0.54 t/ha (6.6%) and 0.92 t/ha (11.9%) less than the corresponding commercial full-input regimes in SCARAB, TALISMAN and Boxworth respectively. Gross margins were much less affected by the lower inputs, with losses of £35/ha (3.8%) and £2/ha (0.2%) in SCARAB and TALISMAN, and an increase of £23/ha (5.1%) in the Boxworth Project.

Conclusions

The reduction of pesticides and the omission of insecticides and nematicides in the SCARAB reduced input treatment was used to create an ecological difference between the treatments to monitor the impact of commercial pesticide use (Cooper, 1990). This resulted in a high proportion of yield losses, although, in some cases, the loss in revenue was counteracted by reductions in variable costs. Untreated pest problems in RIA were probably the main cause of yield loss, although this cannot be confirmed because of the limitations of the design of the large-scale, split-field project. Aphids reached economic threshold levels in many of the cereal crops and on both the potato crops. Untreated migratory nematodes probably contributed to the large yield losses experienced in the RIA sugar beet crops. Weed numbers were also generally higher on RIA plots, which would also have contributed to the lower yields. Although disease levels were higher on some crops, levels did not appear to cause large yield losses. This supports the results from the TALISMAN Project (Chapter 2.8) and the Integrated Farming System (IFS) research projects (Anon., 1998; Ogilvy, 2000), in which reductions in fungicide use were easier to achieve without yield loss, compared with reductions in herbicide or insecticide use.

Reducing herbicide use over the rotations in SCARAB generally resulted in increased weed numbers, which are likely to lead to large increases in the weed seedbank, as shown in TALISMAN (Chapter 2.4). The increased long-term weed problems would probably require remedial herbicide use in the future unless cultural measures were also adopted as in an integrated farming system (Ogilvy, 2000).

Omitting insecticide use can have short-term effects, resulting in sporadic pest damage to crops and associated yield losses. Long-term problems may arise if populations of some soil-borne pests, e.g. potato cyst nematodes (*Globodera* spp.) and migratory nematodes, are allowed to build up to damaging levels. In such situations, resistant varieties and rotations need to be used to manage pest problems by extending intervals between susceptible crops to allow populations to decline.

Although, it is possible to achieve reductions in pesticide use and maintain profitability (Anon., 1998) by adjusting husbandry techniques, the benefits to the environment need to be assessed. Whilst it appears to be easiest to reduce fungicide inputs, these inputs (as a group) probably have less impact on non-target species in the environment than insecticides (including molluscicides and nematicides) and herbicides (Greig-Smith *et al.*, 1992).

SCARAB has indicated that low-input pesticide use is not without economic risk. The enforced omission of insecticides and nematicides in the reduced input regime, to fulfil the ecological objectives of the study, gave an immediate commercial disadvantage. Uncontrolled pest problems, together with a build-up in weed populations, were the main factors associated with loss in revenue in SCARAB. However, as in TALISMAN, carefully managed reductions in fungicide use appeared to offer financial benefits without compromising yield or income. In practice, a more flexible and integrated approach than that used in SCARAB would be adopted to achieve reductions in pesticide use, without compromising farm profitability.

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Ogilvy S E. 2000. LINK Integrated Farming Systems (a field-scale comparison of arable rotations). Volume I: Experimental Work. *HGCA Project Report No. 173.* London: HGCA.

Table 3.6.1. The effect of SCARAB pesticide use on the mean yields of all crops at each site, 1991–1996 (t/ha at the appropriate d.m. percentage).

Site	Yield (t/ha)		Two-tail t-test	Significance
	CFP	RIA	$P(T \leq t)$	
Drayton	8.65	8.33	0.234	NS
Gleadthorpe	20.24	16.98	0.013	**
High Mowthorpe	6.54	6.11	0.002	***
Cross-site	12.21	10.74	0.004	***

** $P < 0.01$.
*** $P < 0.001$.
NS Not significant.

Table 3.6.2. The effect of SCARAB pesticide use on the gross margins of all crops at each site, 1991–1996 (£/ha, including appropriate area payments).

Site	Gross margin (£/ha)		Two-tail t-test	Significance
	CFP	RIA	$P(T \leq t)$	
Drayton	629	629	0.994	NS
Gleadthorpe	1027	921	0.016	**
High Mowthorpe	829	809	0.174	NS
Cross-site	853	806	0.011	**

** $P < 0.01$.
NS Not significant.

Table 3.6.3. The effect of SCARAB pesticide use on the yields of individual crops, meaned across sites, 1991–1996 (t/ha at the appropriate d.m. percentage).

Crop (no. grown)	Yield (t/ha) CFP	RIA	RIA as % of CFP	Two-tail t-test *P* (T ≤ t)	Significance
Winter wheat (11)	8.38	7.64	91.2	0.002	***
Spring wheat (4)	3.85	3.00	77.9	0.021	**
Winter barley (9)	6.68	6.28	94.0	0.130	NS
Spring barley (4)	6.51	6.49	99.7	0.943	NS
Spring beans (4)	4.40	4.15	94.3	0.030	*
Winter oilseed rape (3)	3.38	3.15	93.2	0.355	NS
Sugar beet (3)	71.17	58.33	82.0	0.013	**
Potatoes (2)	42.39	35.64	84.1	0.143	NS
Grass (8)	8.28	8.09	97.7	0.608	NS
Mean (48)	12.21	10.74	88.0	0.004	***

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
NS Not significant.

Table 3.6.4. The effect of SCARAB pesticide use on the gross margins of individual crops, meaned across sites, 1991–1996 (£/ha, including appropriate area payments).

Crop (no. grown)	Gross margin (£/ha) CFP	RIA	RIA as % of CFP	Two-tail t-test *P* (T ≤ t)	Significance
Winter wheat (11)	927	892	96.2	0.124	NS
Spring wheat (4)	451	373	82.7	0.057	NS
Winter barley (9)	684	693	101.3	0.676	NS
Spring barley (4)	706	734	104.0	0.203	NS
Spring beans (4)	566	584	103.2	0.178	NS
Winter oilseed rape (3)	768	736	95.8	0.474	NS
Sugar beet (3)	2089	1803	86.3	0.016	**
Potatoes (2)	2400	1974	82.2	0.099	NS
Grass (8)	543	539	99.3	0.920	NS
Mean (48)	853	806	94.5	0.011	**

** $P < 0.01$.
NS Not significant.

Table 3.6.5. Factors contributing to yield losses in RIA cereal crops compared with CFP (t/ha).

Crop and Site	Field	Year	Yield loss	Weeds	Pests	Diseases	Crop morphology
Winter wheat							
Drayton	Field 1	1991	0.5	✓	✓aut. aphid	✓✓S/M/<G	-
		1992	1.4	✓	-	✓ S/ <G	>lodging
	Field 5	1993	0.8	✓	✓ aphids	✓ <G	-
H. Mowthorpe	Bugdale	1992	0.6	-	✓ aphids	✓ S/<G	-
		1995	0.7	✓	✓ aphids	✓ SN	-
	Old Type N	1992	0.8	✓	✓ aphids	✓ S/M/<G	-
		1995	1.9	✓✓	-	✓ SN	<fertile tillers
	Old Type S	1992	0.7	✓	✓ aphids	✓ S/M/<G	-
		1995	1.0	✓	-	✓ SN	<fertile tillers
Spring wheat							
Gleadthorpe	Balk Field	1992	0.6	-	✓ aphids	✓ <G	-
		1995	0.9	✓	✓ WBF/aph.	-	<fertile tillers
	South Field	1992	1.0	✓	✓ aphids	✓ <G	-
		1995	0.3	-	✓ WBF/aph.	-	<fertile tillers
Winter barley							
Gleadthorpe	Balk Field	1993	0.5	✓	-	✓ M/<G	<fertile tillers
		1996	1.3	✓	✓ aut. aphid	-	-
	Near Kingston	1995	0.8	✓	✓ aphids	-	-
	South Field	1996	1.3	✓	✓ aut. aphid	-	-
H. Mowthorpe	Bugdale	1996	0.3	✓	-	-	-
	Old Type N	1993	0.4	✓	-	-	>brackling
	Old Type S	1993	0.05	✓	-	-	>brackling
Spring barley							
Gleadthorpe	Near Kingston	1991	0.15	-	-	✓ M/E/F	-
H. Mowthorpe	Bugdale	1993	0.4	✓	-	-	<fertile tillers

Abbreviations:
aut. aphid = autumn aphids (as vectors of barley yellow dwarf virus);
aph. = summer aphids;
WBF = wheat bulb fly;
S = *Septoria tritici;*
SN = *Septoria nodorum*;
M = powdery mildew;
<G = less green leaf area (GLA);
E = sharp eyespot (*Rhizoctonia cerealis*);
F = fusarium (*Fusarium* spp.).

Table 3.6.6. Factors contributing to yield losses in RIA break crops compared with CFP (t/ha).

Crop and Site	Field	Year	Yield loss	Weeds	Pests	Diseases	Crop morphology
Spring beans							
Gleadthorpe	Near Kingston	1993	0.3	✓	-	✓ choc.	-
H. Mowthorpe	Bugdale	1994	0.1	✓	✓ weevil	-	<plants
	Old Type N	1991	0.4	✓	✓ aphids	✓ choc./DM	<plants
	Old Type S	1991	0.2	✓	✓ aphids	✓ choc./DM	<plants
W. oilseed rape							
H. Mowthorpe	Bugdale	1991	0.6	-	✓ seed weevil	-	<plants
	Old Type S	1994	0.1	✓	-	-	-
Sugar beet							
Gleadthorpe	Balk Field	1991	14.3	-	✓ MN/aphids	-	-
	Near Kingston	1996	9.9	✓	✓ MN/silv. y	-	-
	South Field	1994	14.3	✓	✓ MN/aphids	-	-
Potatoes							
Gleadthorpe	Balk	1994	8.3	-	✓ aphids	-	-
	South	1991	5.21	-	✓ aphids	-	-
Grass							
Drayton	Field 1	1995	0.7	-	-	-	-
		1996	0.5	✓	-	-	-
	Field 5	1991	1.8	-	✓ leatherj.	-	-
		1994	1.0	-	-	-	-

Abbreviations:
MN = migratory nematodes;
silv. y = silver y moth;
leatherj. = leatherjackets;
choc. = chocolate spot;
DM = downy mildew.

Table 3.6.7. Effects of the low pesticide regime on yields and gross margins of winter wheat in the Boxworth, TALISMAN and SCARAB Projects (t/ha and £/ha).

Regime	Boxworth Project			TALISMAN[1]			SCARAB		
	Units*	Yield	GM**	Units	Yield	GM	Units	Yield	GM
High pesticide	14.4	7.74	454	8.5	8.13	878	8.3	8.38	927
Low pesticide	6.8	6.82	477	3.6	7.59	876	3.0	7.64	892
Integrated	6.1	6.39	423						

* Units of pesticide product applied in the Boxworth Project, units of active ingredient applied in TALISMAN and SCARAB.
** Gross margins for wheat in the Boxworth Project do not include Arable Area Payments.
1 Data from TALISMAN are at the CCP nitrogen rate.