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SUMMARY

1. The findings of the Farm Scale Evaluations of spring sown genetically modified crops are now published in a special issue of the Philosophical Transactions of the Royal Society. Here, we bring together elements of these findings to assess the potential implications of large scale growing of GMHT crops on farmland biodiversity.

2. Effects of genetically modified herbicide-tolerant (GMHT) beet, maize and spring oilseed rape crops on weeds and invertebrates were investigated across Great Britain during 2000-02.

3. In beet and spring oilseed rape before post-emergence herbicides were applied, there were more weeds in GMHT crops than in conventional crops. Following herbicide applications to GMHT beet and spring oilseed rape crops, weed biomass and seed rain were one third or less than corresponding amounts in conventional crops, resulting in smaller seedbanks. In maize, numbers, biomass and seed rain of dicot weeds were higher in GMHT treatments throughout the season; there was little evidence of effects on seedbanks. Bees, butterflies, common seed-eating carabids and detritivorous invertebrates were found in larger numbers in treatments and crops where there were more forage resources.

4. There were few treatment effects on species diversity and consumer / resource ratios.

5. Differences in mean plant and invertebrate abundance between different conventional crop species were as great as that observed between GMHT and conventional varieties of each crop. In general conventional oilseed rape and beet fields were the richest in flora and fauna, with conventional maize crops the poorest.

6. For each crop, treatment effects could all be explained by the different herbicide regimes, and were consistent between sites, farms, years and different initial levels of weeds.

7. If these trends are maintained under widespread GMHT cropping, then the present herbicide regimes associated with GMHT beet and spring oilseed rape might exacerbate long-term declines of dicot weeds, that include species that are important food resources for many invertebrate, small mammal and bird species. By contrast, these same weeds might increase in abundance following a shift from conventional to GMHT maize cropping, due to the greater weed control exerted by conventional herbicide regimes compared to those used with the GMHT crops.

8. Major sources of variation in potential impacts arise from probable changes in herbicide regimes, tillage systems and crop rotations and from possible long-term interactions between weed and invertebrate populations. All of these potential effects depend greatly upon the management of the crops, the rotations, and upon the provision of forage and habitat resources across the entire farmed landscape.

INTRODUCTION

Arable weeds can cause economic losses to farmers because of reductions in crop yield, quality and production efficiency (e.g. Cousens & Mortimer 1995), and so it is not surprising that farmers have sought to reduce their numbers. Indeed, weed abundance and diversity fell in Great Britain (GB) during the 20th Century (Firbank 1999) as farmers adopted a range of technologies and practices, including the use of herbicides. The effectiveness of weed control using herbicides varies considerably between crops, not least because the crops themselves are susceptible to some herbicides but not others. Modern herbicides tend to have a narrow spectrum of activity, and often need to be applied in cocktails to control the wide range of weeds present in arable fields. Herbicide-tolerant crops were developed to reduce this problem, by allowing farmers to use herbicides that act upon a wide range of weed species and plant sizes. Weed control is potentially more efficient and easier for the farmer using such broad-spectrum herbicides.

However, many weed species are also important food sources for a range of invertebrates, birds and mammals, and as these weed populations have declined, so have populations of many species that inhabit arable land. In particular, there is now a Government target to reverse the declines of farmland birds such as skylark (*Alauda arvensis*) and corn bunting (*Miliaria calandra*). It has been suggested that the widespread use of herbicide-tolerant crops will reduce still further populations of arable weeds, exacerbating declines in birds that feed on weed seeds in the autumn and winter (Watkinson *et al.* 2000). This risk to wildlife populations needs to be taken into account when assessing the impacts of growing these crops. By contrast, it is also possible that the use of broad-spectrum herbicides may benefit farmland wildlife, since they may be less persistent and toxic than the herbicides they might replace (Squire *et al.* 2003), and also because they can be applied later in the season to allow more time for weeds to grow and be used as food and habitat within the fields (Strandberg & Bruus Pedersen 2002; Dewar *et al.* 2003; Firbank *et al.* 2003*a*).

The Farm Scale Evaluations (FSE) were established to compare the effects on farmland wildlife of the weed management of herbicide-tolerant crops compared with that of comparable conventional varieties. The crops under study have been genetically modified to be tolerant to particular broad-spectrum herbicides, and have been selected for study in order to inform decisions about their possible commercialisation in the United Kingdom (Firbank *et al.* 1999; Firbank *et al.* 2003*a*). Three of these genetically modified herbicide-tolerant (GMHT) crops are tolerant to the herbicide glufosinate-ammonium, namely maize, *Zea mays* L., spring oilseed rape and winter oilseed rape, *Brassica napus* L. subsp. *oleifera* (DC.) Metzger, while the fourth crop, beet, *Beta vulgaris* L. subsp. *vulgaris*, is tolerant to glyphosate. These crops were considered within separate experiments, each designed to test the null hypothesis of no difference between the management of GMHT varieties and that of comparable conventional varieties in their effect on selected indicators of wildlife abundance and diversity. The FSE was also designed to estimate the magnitudes and consider the implications of any differences that are found (Firbank *et al.* 2003*a*; Perry *et al.* 2003). While the FSE has attracted considerable public attention because the crops have been genetically modified, the way in which the varieties have been developed is of far less importance to the design and interpretation of the experiments than the effects of the herbicide regimes (Firbank *et al.* 2003*a*).

The papers in the special issue of Philosophical Transactions of the Royal Society address the effects of GMHT crop management on selected groups of plants and invertebrates recorded in the fields and the field margins (Brooks *et al.* 2003;

Haughton *et al.* 2003; Heard *et al.* 2003*a*; Roy *et al.* 2003). They address the three spring-sown GMHT crops, glyphosate-tolerant beet (both sugar and fodder varieties), and glufosinate-ammonium-tolerant maize and spring oilseed rape. The results have been interpreted in terms of effects on weed population processes (Heard *et al.* 2003*b*) and upon interactions between plants and invertebrate herbivores and predators (Hawes *et al.* 2003). Moreover, details of the selected sites and crop management have also been published, confirming that the sites were indeed representative of the environments in which the crops might be grown commercially, and were managed appropriately (Champion *et al.* 2003). The term biodiversity is used here in one of its wider definitions to include variation in abundance and species diversity of selected groups (in this case, particularly higher plants and selected invertebrate taxa), and also in the productivity of weeds in terms of biomass and seed production (Firbank *et al.* 2003*a*). We deliberately exclude intraspecific genetic diversity and ecosystem diversity from our definition. Because of the later sowing dates, findings from the fourth crop in the FSE, winter oilseed rape tolerant to glufosinate-ammonium, will be reported separately.

The FSE was designed with the expectation that the major ecological effects of GMHT varieties would be as a result of the effects of the different herbicide regimes on the arable weeds and those species associated with them. These would result in testable differences in the selected ecological measures between GMHT and conventional cropping regimes. Such differences might indicate potential large scale effects of conservation importance, notably through the food chain to animals not recorded directly within the FSE, such as farmland birds. It was also considered possible that the herbicide regimes would result in changes in weed abundance in future seasons, and so the weeds were assessed before, during and after the GMHT varieties were grown (Firbank *et al.* 2003*a*). Given the scale of the experiments, we would not expect to observe directly the full range of gains or losses in species richness and abundance that might be found if GMHT crops were grown over large areas for long periods of time. Therefore, we sought to detect more subtle biodiversity effects that might foreshadow more profound changes over larger scales. In particular, we asked, were critical resources altered in abundance, and were there shifts in trophic structure ? Were there changes in diversity of some groups of species, and were the abundances of species of special conservation value (such as pollinators) affected by the GMHT treatment?

This report is intended to bring together the major findings of the FSE to date to help assess potential impacts on biodiversity of large scale cultivation of GMHT beet, maize and spring oilseed rape. We first summarise the major differences in plants and invertebrates between treatments and crops, concentrating on the major trends and processes, drawing upon the more detailed analyses of particular species and species groups published in the Special Issue (Brooks *et al.* 2003; Haughton *et al.* 2003; Hawes *et al.* 2003; Heard *et al.* 2003*a*,*b*: Roy *et al.* 2003), referring back to the papers describing the overall approach and the statistical basis of the FSE (Firbank *et al.* 2003; Perry *et al.* 2003; Squire *et al.* 2003). We explore the issue of variation between crops and sites in rather more detail than in these papers. We then discuss potential larger scale and longer term effects on farmland biodiversity and conservation, should the selected GMHT crops be grown on a commercial scale. We take into account differences between the crop species, the cropped areas that might be involved, and the likely sensitivities of treatment effects to differences in crop management.

METHODS

The approach, design and detailed methods of the FSE have been detailed elsewhere (Firbank *et al.* 2003*a*; Perry *et al.* 2003;

Squire *et al.* 2003), and so here we summarise the major points. The FSE aimed to test the null hypothesis for biodiversity indicators between pairs of treatment units for each of the three crop species. Each experimental design was, therefore, a randomised block with two treatments (GMHT and conventional crops) per block. The blocks were represented by individual fields, on farms that represent the typical range of soil and environmental conditions and crop management strategies employed for each crop within GB. The treatments were allocated to halves of fields at random: one half was sown with a conventional variety and the other with a GMHT variety of the same crop. Farmers managed both field halves as they would do under commercial agricultural practice. A wide range of indicators of species abundance, productivity and species diversity were assessed before, during and after the crops were grown. Field assessments of birds were not undertaken (except for pilot observations on breeding and wintering birds) because they forage across much larger areas of land than were available within the treatments: instead, potential effects were to be evaluated on the basis of impacts on food resources.

Site selection and layout

The fields were selected in order to represent the range of variation likely to be encountered should widespread, commercial farming of GMHT varieties of the three crops take place. Fields covered the ranges of geographic variation, farm management and weather conditions that might be encountered in different years.

The sample size was determined through a power analysis using a range of scenarios that encompassed combinations of treatment differences, numbers of sites, and random variability. Perry *et al.* (2003) concluded that the use of 60 sites per crop would allow the detection of 1.5-fold differences between treatments for major biodiversity indicators with greater than 80% probability (Rothery *et al.* 2002; Perry *et al.* 2003); more were sought to take into account potential site losses.

Farmers who wished to take part in the FSE volunteered to the Supply Chain Initiative on Modified Agricultural Crops (SCIMAC), an umbrella body that includes the companies that supplied the GMHT seeds (Bayer CropScience (formerly Aventis) for maize and oilseed rape, and Monsanto for beet). Farmers were under contract to SCIMAC, which was legally responsible for ensuring that the crops were grown and disposed of within the regulations. The actual selection of field sites from this pool of farmers was the responsibility of the research scientists. The intention was to select from those farms that might potentially grow the crops commercially: thus organic farms could not be included because of their regulations. The sites were selected to represent the geographic range of sites (Fig. 1, p30), while variation due to effects of weather on species abundance and crop management was accounted for by sowing different sites in each of the years 2000-2002 (not necessarily in equal numbers). The appropriate range of farm management was achieved by using information provided by the farmers on past yield of winter wheat, a self-assessed intensity score and their uptake of environmentally-friendly farming practices such as conservation headlands or integrated farming audits (Champion *et al.* 2003; Firbank *et al.* 2003*a*). Less-intensive farms were given priority in the sample selection, because of their potentially greater importance for biodiversity (Watkinson *et al.* 2000).

There were 67 spring oilseed rape and 66 beet crops, of which 26 were fodder crops and 40 sugar beet. Previous analyses showed no substantial interactions between treatment and whether the beet crops were fodder or sugar (Brooks *et al.* 2003; Haughton *et al.* 2003; Heard *et al.* 2003*a*), and so these crop types were grouped together for the analyses presented here.

There were 68 maize crops, of which 9 had followed previous maize crops within the FSE as part of the farmers' use of continuous maize cultivation. Such "following" experimental sites have not been included in the analyses published to date, because they were not truly randomised (they retained the allocation of treatments to field halves from the previous year); they will be analysed separately, to seek any cumulative effects of GMHT cropping in successive seasons. Details of site selection for the three crops are given by Champion *et al.* (2003).

The decision to use half-fields was taken following pilot studies in 1999. Smaller treatment units were not appropriate to detect treatment effects on some of the invertebrates under study. Paired fields were tried, but it proved difficult to find whole fields on the same farm sufficiently well matched to be truly comparable, especially in terms of starting weed populations (Perry *et al.* 2003). The areas of land used for the beet crops were frequently less than the size of the whole field, partly reflecting the practice of growing multiple crops in large, open fields often used for beet, and partly because of restrictions in area for GMHT cropping imposed because of the costs of crop disposal (Champion *et al.* 2003).

Crop management

The FSE was designed to compare the effects of the selected GMHT varieties under commercial cropping conditions, taking into account variation in management by farmers. Farmers were, therefore, given maximum flexibility in how they managed both the GMHT and conventional varieties within the field (see e.g. Buzzard 2000; Firbank *et al.* 2003*b*). This flexibility included choice of conventional variety and the accompanying herbicide regime, together with pesticide, fertiliser and tillage practices, and the choice of following crops. However, any differences in crop management between the treatments were appropriate only if based on good agronomic practices; thus insecticides (for example) should have been applied to both halves of the field on the same day unless there were more crop pests on one treatment than on the other. An important exception was that the GMHT beet was harvested before the conventional varieties in order to ensure that it did not enter the human food chain. Farmers were expected to apply pesticides as specified on labels, and to follow regulations and the code of practice for managing GMHT crops (SCIMAC undated). SCIMAC was allowed to provide advice only for the herbicide regimes applied to the GMHT crops: it is usual for companies to supply advice in this way with new technologies.

It was essential that the farmers knew which treatment was which in order to apply the herbicides correctly, and the degree of flexibility was required so that farmers could respond to differences in weed levels appropriately. However, this flexibility brought a risk of bias, in that farmers might have changed their crop management to favour one treatment in some way. This risk was minimised by monitoring all advice given to them, and crop management was subject to audit to ensure that it had been appropriate. In particular, herbicide regimes had to be consistent with cost-effective weed management, accepting that the interpretation of how to achieve this goal varied between farmers. Subsequent audits of the active ingredients used, the rates and the timing of applications showed that they compared well with current practice for both GMHT and conventional crops (Champion *et al.* 2003).

Field methodologies

A range of ecological assessments were made in each half-field, using methods and sample intensities defined during pilot studies in 1999 (Firbank *et al.* 2003*a*). These assessments concentrated on weeds, field margin plants and invertebrates.

Soil seedbanks were assessed before crop sowing, and again one and two years later. Data for weed seedbanks and seed rain are presented excluding crop seeds. In addition, weed seedling assessments were made in the crops (usually cereals) in up to two seasons following the GMHT cropping (n.b. not all assessments in following crops have been completed at the time of writing). Any crop volunteers on the GMHT halves of the fields were subject to special control by farmers, and so were not included in statistical tests of treatment effects.

Otherwise, all assessments were made during and shortly after the cropping of the GMHT cultivars and contrasted with identical measurements on conventional varieties. Within the crop, observations were made on plants, slugs and snails (gastropods), and a range of insect and spider groups. Plant records and Vortis suction samples of invertebrates provided density measures, while pitfall traps, gastropod searches and traps and bee and butterfly transects assessed levels of activity-density (i.e. took into account both numbers of organisms and their behaviour). All observations were taken at fixed locations within the fields. For most sampling protocols, these locations were selected from sample points that extended from the crop edge into the field centres at distances of 2, 4, 8, 16 and 32 m along 12 transects in each treatment. Plants and invertebrates were also sampled from the field margin at fixed locations within the tilled margin (the ploughed but unsown strip at the edge of the field), the field verge (the grassy or herbaceous vegetation between the edge of the ploughed area and the boundary) and the field boundary feature such as a hedge or ditch (Roy *et al.* 2003). These features were not always present, for example when another crop was grown immediately adjacent to the test crop. Crop development and cover were very similar between the treatments (Champion *et al.* 2003; Hawes *et al.* 2003), implying that there would have been few, if any, different effects of crop growth on biodiversity. Since these trials were not intended to compare the performance of the crops but rather the effects on biodiversity of management of the crops, data on yields were not necessary and were not collected routinely: farmer estimates of yield were noted, but were not considered reliable enough for analysis (Champion *et al.* 2003). Full details of sampling methods, timing and intensities are given in the series of papers (Brooks *et al.* 2003; Champion *et al.* 2003; Haughton *et al.* 2003; Hawes *et al.* 2003; Heard *et al.* 2003*a*; Roy *et al.* 2003).

Statistical analysis

Here, we present summary results in terms of magnitude and direction of change at high taxonomic levels. We also note the results of tests of finer taxonomic groupings and smaller time periods where relevant, and we refer to comparisons of weed and carabid species number and diversity. The reader is referred to the published papers for more details of these analyses (Brooks *et al.* 2003; Haughton *et al.* 2003; Heard *et al.* 2003*a*, *b*; Roy *et al.* 2003). We also report analyses of treatment effects on the trophic structure of the plants and invertebrates of the fields, by looking at effects on species grouped into trophic levels, namely higher plants, herbivores, predators, parasitoids, pollinators and detritivores. Species found on crops were analysed separately from those associated with weeds, and soil surface predators and detritivores were analysed separately from those found on vegetation. We also analysed the consumer-resource ratios between these groups, i.e. of herbivores to plants, predators to prey, parasitoids to hosts and pollinators to non-crop plants (see Hawes *et al.* (2003) for further details).

As the treatments were applied to half-field units, data from each treatment at each site were pooled into half-field totals for tests of the null hypotheses. Where a count totalled zero or one for both treatments, the whole field was excluded from that particular test. Where only partial data had been collected from a half-field (e.g. because of damage to sample locations), the decision whether or not to use them to estimate half-field totals was made as follows. For each particular distance into the field, the half-field total for that distance was deemed missing if over half of the samples were missing or considered invalid. If half or fewer samples were missing, those missing samples were estimated proportionately. If the half-field total for a particular distance into the crop was regarded as missing, then so was the overall half-field total, and that site contributed no information towards the estimated treatment effect or test of the null hypothesis. In practice, the effects of missing values on the analyses were very minor, as the percentage of data values that were missing in the entire database rarely exceeded 5% for any variable, even before exclusion of half-field totals. While the early harvesting of GMHT beet varieties could potentially have influenced the findings for weed seedbanks, analyses by Heard *et al.* (2003*a*) suggest that this was most unlikely.

The size of treatment effects were measured as R, the multiplicative ratio of the indicator value in the GMHT treatment divided by that in the conventional. For each indicator, the null hypothesis was tested (that R= 1, or, to be more precise, that the $\log_{10}$ of R, termed *d*, equals zero) using a randomization test and estimated the magnitude of the effect with a 95% confidence interval. Randomization *p*-values are given with results significant at the 5%, 1% and 0.1% level highlighted, either here or in the accompanying papers.

The number of sites used in the FSE was set in order to detect over 80 % of 1.5-fold differences with a statistical significance of $p < 0.05$. To date, 595 analyses have been reported from the FSE. Of these, 131 (22%) were reported with absolute values larger than 1.5. Of those 131 values, 107 attained significance (82%), a proportion fully in line with our target of 80% power. Moreover, the only times that a indicator presented in this document gave mean treatment effects greater than 1.5-fold that were not statistically significant were for total weed seed rain in maize, and for differences in weed seedbanks and seedling counts for the second crops following maize, for which data are still being collected (Heard *et al.* 2003a). We conclude that the replication was indeed appropriate for our purpose, and that major effects were identified as being of statistical significance.

Whenever, as here, a large number of statistical tests are done, there is a strong likelihood that some will indicate spurious statistical significance. The statistical size of the test, traditionally taken as 0.05, specifies the probability of rejecting the null hypothesis when it is true. Hence, for every thousand tests done, we might expect 50 to be significant by chance alone. While it is possible to adopt multiple comparison procedures to allow for the excess number of significant results (Perry 1986), we, in common with many modern applied statisticians, do not find such approaches helpful in the interpretation of data (Perry *et al.* 2003). This is because statistical significance refers merely to plausibility and not to biological importance, and the outcome of a test depends partly on the degree of replication. Significance tests assist the interpretation of data, by giving confidence that unjustified conclusions are not made as a result of random error. However, they only supplement more important information on the magnitude of treatment effects, measured here by R, and their consistency across time, crops and taxa. We emphasise this point, as there is a temptation in all such studies with many analyses to take single results out of context and over-interpret them.

Where appropriate, data were analysed for possible interactions between the treatment effects and factors representing year, regions within GB, distance into the crop, farm, abundances of other groups of species within each site (e.g. seedbank densities), and beet crop type, sugar or fodder. Most tests for statistical significance used the *d* statistic and a randomisation procedure that compares values according to a log-normal distribution. Exceptions included the covariate analyses and treatment interactions, where the lognormal model was used with regression or analysis of variance (for full details see Perry *et al.* 2003; Hawes *et al.* 2003; Heard *et al.* 2003*b*).

We also cross-referred the species recorded within the FSE against those listed in the current UK Biodiversity Action Plan (BAP) (Anon 1995; Joint Nature Conservancy Committee ongoing), in order to identify species of high conservation value found within the selected crops and their adjacent boundaries. In fact, no BAP-listed species were recorded during the study.

RESULTS

Variation in initial weed composition

Because around half of the conventional crops of each species were treated with pre-emergence herbicides (Table 1, p.27); Champion *et al.* 2003), the initial weed composition of the fields was assessed from the GMHT treatments before the herbicides were applied. The mean number of weed species per half-field was between 16-21 for the three crops. By contrast, Countryside Survey 2000 reported weed species richness per arable field varying between 0 and 36, with a mean of 12[1], suggesting that the FSE has captured the range of variation in plant diversity across typical farming systems.

The variation between fields of the same crop type in species number and diversity was considerable, with ten-fold differences in species richness and abundance of weeds between fields (Fig. 2, p.31), and two orders of magnitude differences in soil seedbank densities across all sites (Champion *et al.* 2003). For each crop, a small number of fields had very large weed densities (Fig. 2, p.31), reflecting the log-normal distribution of the initial weed seedbanks, that was very similar between crops (Champion *et al.* 2003).

Variation in crop management

All maize GMHT crops, and 97 % of GMHT spring oilseed rape crops, were treated with the broad-spectrum herbicide glufosinate-ammonium. All GMHT beet crops were treated with glyphosate. Nearly all the conventional beet and spring oilseed rape crops were treated with herbicide. Atrazine was the most commonly used herbicide on conventional maize crops, applied to 75 % of sites (22 % pre-emergence only, 7 % pre- and post-emergence and 46 % post-emergence only) (Table 1, p.27); Champion *et al.* 2003).

The first applications of herbicides to the GMHT crops were usually later than to the conventional, even disregarding pre-emergence herbicides. While around half of all control crops were sprayed within the first 14 days after sowing, first spraying on the GMHT crops occurred mainly between 36-42 days in beet and maize, and 50-56 days in spring oilseed rape (Champion *et al.* 2003). Herbicide use was greater on weedier GMHT crops, and on conventional beet crops when pre-emergence herbicides had not been applied. The relationship between herbicide use and weediness was weaker for maize, and was not found at all for spring oilseed rape conventional crops, although herbicides were sometimes applied to deal with large densities of particular weed species (Champion *et al.* 2003).

The use of other agrochemicals reflected national practice for these crops (Champion *et al.* 2003). Differences in insecticide applications between treatments were far too infrequent to account for differences in invertebrate populations, and the differences in crop growth and phenology between

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[1] These data are per 100 m^2 plot along the cropped edges of 543 arable fields sampled across GB. Data provided by Smart (*pers. comm.*), see Smart *et al.* (2003) and www.cs2000.org.uk for details.

cultivars were also far too small to have any major ecological effects (Hawes *et al.* 2003).

The null hypothesis of no effect on biodiversity indicators

The FSE was established to test the null hypothesis that, for each crop, there is no difference between the management of GMHT varieties and that of comparable conventional varieties in terms of the abundance and diversity of groups of plants and invertebrates. For each of the three crops studied here, the null hypothesis was rejected (Figs 3, 4, 5 pages 32-34; Table 2, p.28); Brooks *et al.* 2003; Heard *et al.* 2003*a*,*b*; Haughton *et al.* 2003; Roy *et al.* 2003). Both formal statistical tests and considerable graphical inspection confirmed that treatment effects very rarely, if ever, demonstrated systematic variation with weed abundance. Furthermore, very few significant interactions were found between treatment effects and major environmental covariates (Brooks *et al.* 2003; Haughton *et al.* 2003; Heard *et al.* 2003*a*).

Plants and invertebrates in and around beet crops

Early in the season there were more weed seedlings on the GMHT beet due to the earlier use of herbicides in conventional crops. However, after glyphosate had been applied to the GMHT varieties, the weed biomass and seed rain in the GMHT treatments were only 17 % and 31 % respectively of the values in conventional crops (Fig. 3, p.32). While there was some variation between sites in the effects on weed biomass, there was no indication of systematic variation between years (Fig. 6, p.35). Weed diversity was not affected by treatment (Heard *et al.* 2003*a*). Weed seedbanks increased more in conventional crops, and monocot weeds were more abundant in crops following conventional crops.

Butterflies and bees were all less abundant in the GMHT crops; butterflies were also less abundant in the field margins, presumably as a result of reduced numbers of suitable plants in flower in the crop and the tilled margin (Roy *et al.* 2003). Other larger groups of invertebrates showed no overall differences in numbers totalled over the year (Fig. 3, p.32). There were significantly fewer herbivores on the weeds in the GMHT treatment, especially in August (Table 2, p.27, Hawes *et al.* 2003). Also at this time, there were significant reductions in parasitoids, though not predators (Table 2, p.27). Ground-dwelling predators were not influenced by treatments, and while there was no overall effect on year totals of ground-dwelling detritivores, these organisms were significantly more abundant in the GMHT treatments in June and August (Table 2, p.27, Hawes *et al.* 2003). Also, the most commonly recorded species of seed eating carabid, *Harpalus rufipes*, was less abundant late in the season in GMHT crops (Brooks *et al.* 2003). By and large, the consumer – resource ratios between predators and prey, pollinators and flowers, and herbivores and plants were not affected by treatments (Table 3, p.29, Hawes *et al.* 2003).

Plants and invertebrates in and around maize crops

The management regimes affected the weeds in maize crops rather differently from those in beet and spring oilseed rape. More weed species were found in the GMHT treatments after the herbicides were applied, even after accounting for differences in total abundance (Heard *et al.* 2003*a*). In general, numbers and biomass of weeds were significantly higher in the GMHT crop than in the conventional maize crop (Fig. 4, p.33, Heard *et al.* 2003*b*), as was seed rain from dicots. However, there was no strong evidence for treatment effects on weed seedbanks, whether in continuous maize or in other following crops. There were few effects on major groups of invertebrates, though there were more ground-dwelling detritivores in GMHT crops, especially in August, and more herbivores and their parasitoids in June (Table 2, p.28, Hawes *et al.* (2003)). There were also more of the seed feeding carabid *H. rufipes* in GMHT crops in July (Brooks *et al.* 2003). Plants in flower were more frequent in tilled margins and boundaries of GMHT crops, and visits by honey bees were nearly three times more frequent to GMHT field boundaries in August (Roy *et al.* 2003); visits to the fields themselves were very rare. Consumer-resource ratios were similar between treatments, except that there were more invertebrate predators per herbivore in GMHT maize (Table 3, p.29).

Plants and invertebrates in and around spring oilseed rape crops

The effects on plant biodiversity of GMHT spring oilseed rape cropping were similar to those of beet cropping. Weed densities were higher in the GMHT treatments until after the glufosinate-ammonium had been applied, and thereafter, dicot densities and biomass were lower. Dicot seed rain was only 21 % of that in conventional crops, and dicot weed seedbanks following GMHT crops were smaller than following conventional crops. Monocot weed numbers were more abundant at harvest time in the GMHT treatments because of post-herbicide germination, but because the individual plants were smaller, seed rain was only 37 % of that in conventional crops (Heard *et al.* 2003*a*). Overall weed diversity and species richness was higher in conventional crops after herbicides (Heard *et al.* 2003*a*). Flowering and seed producing plants were also fewer in the tilled margins of GMHT crops (Fig. 5, p.34). By contrast, there were few significant effects on invertebrate groups. The major exception was that butterflies were significantly less frequent both within and at the margins of GMHT crops. This was true for both *Pieris* spp., where two of the three species use oilseed rape to lay their eggs and are regarded as pests on this crop, and for other butterfly species (Haughton *et al.* 2003). In addition, there were some seasonal differences: spiders caught in Vortis samples were significantly more abundant in conventional treatments in August, while by contrast, Collembola caught in pitfall traps were significantly more abundant in GMHT crops in July (Brooks *et al.* 2003; Haughton *et al.* 2003). The carabid *H. rufipes* was more abundant in conventional crops in July and August (Brooks *et al.* 2003). Significant consumer-resource relationships were not as apparent for spring oilseed rape crops as for the other crops; in particular, there was no significant relationship between herbivore numbers caught on weeds and weed biomass, nor was there a relationship between crop pests and their predators. The remaining relationships among trophic levels were not influenced by treatment (Table 3, p.29).

DISCUSSION

The tests of the null hypothesis

The FSE was established to test the null hypothesis that, for each crop, there is no difference between the management of GMHT varieties and that of comparable conventional varieties in terms of the abundance and diversity of weeds and invertebrates. For each of the three crops studied here, namely beet, maize and spring oilseed rape, the null hypothesis has been rejected. For beet and spring oilseed rape, the GMHT treatments were richer in weeds early in the season before the herbicides were applied to both treatment, but thereafter were poorer in dicots. By contrast, GMHT maize crops were richer in weeds throughout the season. Butterflies were less frequent in GMHT beet and spring oilseed rape; GMHT beet crops also had lower numbers of Heteroptera than conventional crops, while Collembola tended to be more abundant later in the summer in GMHT varieties of all crop species. Significant differences were also found in the vegetation of tilled margins, and in numbers of butterflies in field margins, both reflecting the results observed in the fields.

The effects of GMHT spring-sown crops on biodiversity indicators

The effects observed in the FSE can be explained in terms of the different herbicide regimes of the crops, giving rise to cascading effects through food webs. We hypothesize that, had no herbicides been applied to either crop type, there would have been no differences in biodiversity and that the same results would have been found had the herbicide tolerant crops been bred using conventional methods rather than transgenically.

Within the GMHT herbicide regimes, the weeds were allowed to germinate and develop until the broad-spectrum herbicides were applied. In beet and maize crops, this action greatly reduced, but did not eliminate, the weeds, nor was flowering and seedset totally prevented (Table 2, p.28). In spring oilseed rape, weed numbers increased during the season, presumably as a result of ongoing germination (Heard *et al.* 2003*a*). For dicot weeds, biomass and seed rain were lower in the GMHT than in conventional beet and spring oilseed rape crops, because the GMHT herbicide regimes were the more effective against them. By contrast, weed productivity was higher in GMHT maize crops than conventional regimes, because glufosinate-ammonium was less effective than the typical conventional herbicide regimes (Heard *et al.* 2003*a*). Effects on field margin vegetation were largely concentrated on the tilled margin of the fields, between the crop edge and the untilled verge, which responded in the same way as the in-field vegetation, presumably because it was also directly affected by the different herbicide regimes (Roy *et al.* 2003). Direct observations of herbicide scorching did show differences between treatments, but overall levels of such damage were low in tilled margins and verges, affecting less than 6 % of the vegetation per field (Roy *et al.* 2003).

In the conceptual model underlying the experiment, it was assumed that herbicide regimes associated with the two treatments would kill the weeds to different extents and timings, denying resources to herbivores and their predators at different levels (Firbank *et al.* 2003*a*). Such an indirect effect of herbicides on invertebrates was considered much more important than any direct effects, because of the low toxicity of the gyphosate and glufosinate-ammonium at field rates (Squire *et al.* 2003). The treatment effects would therefore be seen much more in terms of differences in absolute numbers of organisms belonging to different trophic levels, rather than effects on consumer-resource ratios. If there is less plant material, then there will be fewer organisms present to eat it. The results of the FSE are consistent with this model. In general, ratios between numbers of organisms of trophic levels were indeed unaffected by treatments, even when the absolute numbers of organisms were very different (Hawes *et al.* 2003). Thus bees and butterflies were less frequently observed in GMHT beet and spring oilseed rape crops than conventional ones, consistent with the different numbers of flowers present in the field and field margins (Figs 3, 5 p 32, 34). The seed-eating carabid beetle *Harpalus rufipes* was more frequent in conventional than in GMHT beet (Brooks *et al.* 2003), corresponding to the much higher levels of weed seed rain. Collembola that feed on decomposing plant material were consistently more frequent in GMHT crops later in the summer (Table 2, p.28), and the specialist collembolan feeding carabid *Loricera pilicornis* was more frequent in GMHT beet (Brooks *et al.* 2003). It seems that the weeds killed by the broad spectrum herbicides used on the GMHT crops broke down to produce a pulse of energy and materials into the decomposition food webs, leading to the observed increases in numbers of Collembola and their predators (Brooks *et al.* 2003). This did not happen in conventional herbicide regimes, presumably as the affected weeds were killed earlier in the year when they were small.

Many of the treatment effects on invertebrates were observed at particular times of the year, in ways that correspond to the shifting levels of food resources. Few significant effects were observed on higher taxonomic groupings of invertebrates when totalled over the whole cropping season (Table 2, p.28). This suggests a degree of buffering within the ecosystem as a whole. Perhaps this has resulted from the abilities of certain invertebrates to respond rapidly to changing resource levels, either by rapid reproduction (e.g. Collembola) or by moving between different half-field areas according to where there is the most food available (e.g. bees and butterflies, and possibly the more mobile carabid beetles).

We did not expect to detect actual species losses and gains across whole fields with our relatively small area samples over the three years of the experiment, given that most measurements were made within the year of cropping only. However, some significant effects were found on corrected weed species number following herbicides in maize and spring rape (Heard *et al.* 2003a). These effects were in opposite directions in the two crops (more species in GMHT maize and fewer in GMHT spring oilseed rape), and did not persist within the season. They were probably the result of herbicides reducing the densities of some more susceptible species disproportionately, which could have longer-term implications for within-field persistence. Effects on diversity of carabid beetles were few, suggesting that there were rather few changes in species composition within arable communities.

Very few significant interactions were found between treatment effects and major environmental covariates (Brooks *et al.* 2003; Haughton *et al.* 2003; Heard *et al.* 2003*a*). Furthermore, both formal statistical tests and considerable graphical inspection confirmed that treatment effects very rarely, if ever, demonstrated any density dependence or any relationship with weed abundance.

Taken together, these results suggest that differences in treatments, sites, years and farmers have tended to influence the absolute numbers and biomass of organisms observed rather more than the functional relationships amongst them. This particular agro-ecosystem has more conservative properties of species diversity and function than we had anticipated. The implication of these findings is that models of within-season responses of plant and invertebrates to herbicide regimes are likely to prove robust across different years and different agricultural conditions. However, these models will be sensitive to the choice of herbicide regimes both between and within GMHT and conventional cropping.

Differences in biodiversity between crops

The FSE shows that the three crops have rather different values for farmland biodiversity. These differences are summarised by the multivariate portrayal in Fig. 7, p.36. In general conventional oilseed rape and beet fields were the richest in flora and fauna, with conventional maize crops the poorest. After herbicides were applied to the GMHT crops, differences in weed densities differed as much between crops as between treatments, while invertebrate numbers differed more between crops and time of year than between treatments (Hawes *et al.* 2003). This implies that the impacts of changes from conventional to GMHT varieties may be of similar scales to those that can result from changes in the uptake and distribution of different conventional crop species. No BAP species

(Anon 1995) were found within the FSE samples. This was unsurprising, given that the scarce arable weeds (the group of species most likely to have been reported) are now highly localised (Preston *et al.* 2002).

The importance of crop management

The detection of significant treatment effects confirms the importance of crop management regimes in determining species composition and abundance in and around arable fields (see also Squire *et al.* 2003). Moreover, the lack of significant effects of environmental covariates on treatment effects, and the consistent treatment effects upon some aspects of diversity (e.g. of the action of glufosinate-ammonium on weed diversity noted above) and trophic relationships (e.g. the different parasitoid / prey relationships in beet, Table 3, p.29), all suggest that crop management has a more profound effect on the functioning of the arable ecosystem than local environmental conditions. Some fields had far more organisms than others as a result of environmental factors or past management, but the ecological responses to changes in crop management were consistent regardless of these initial differences in sites. The experiment was designed to compare the effects of GMHT and conventional cropping systems, taking into account variation of how the farmers have managed the crops (Firbank *et al.* 2003*a*). Therefore, herbicide regimes varied within both treatments from site to site (Champion *et al.* 2003).

While the treatment effects were robust to differences in environment, the same may not be true for differences in crop management. Analyses of the interactions between treatment effects and the herbicide management regimes within the treatments are ongoing.

The implications of large-scale and long-term cropping of GMHT beet, maize and spring oilseed rape for the conservation of farmland biodiversity

The implications of large-scale GMHT cropping for conservation depend not simply upon the direction and magnitude of effects detected within the FSE, they also depend upon the areas of land likely to be used for these crops, and the broader context of the changing management of farming rotations and landscapes.

Distribution and areas of the crops

Sugar beet (*c*. 170,000 ha) is concentrated in open, arable landscapes of Eastern England, spring oilseed rape (*c*. 60,000 ha) is grown across Great Britain, while the two fodder crops, fodder beet (*c*. 10,000 ha) and maize (*c*. 100,000 ha), are grown more in the mixed farming areas of western England (all areas vary between years, Champion *et al.* 2003). This totals around 6% of the arable area of GB, that itself accounts for approximately 23% of the total land cover (Haines-Young *et al.* 2000). Because these crops rotate around the farm, the areas of land that would eventually bear them is higher, by a factor of at least three.

Experience from the USA suggests a maximum uptake of GMHT cropping in the order of 70% of area, varying greatly between crops (Fernandez-Cornejo & McBride 2002). A similar penetration into British agriculture might result in a maximum area supporting these GMHT crops of the order of 700,000 ha, somewhat concentrated into the arable areas in eastern Britain, a substantial area exceeding the areas used in 2000 for set-aside land (*c*. 70,000 ha) and organic farming (*c*. 527,000 ha). Changes in the management of such large areas might well have consequences for farmland biodiversity at the national level.

Potential longer-term trends in weed populations

One of the concerns about GMHT cropping is that there might be a reduced seed production by plants important in arable food webs, leading to a long-term decline in these species, magnifying the differences between treatments on arable species over time. Evidence currently available from the FSE is equivocal on this point. Seed rain for both dicot and monocot weeds was significantly influenced by treatment, with smaller dicot weed seedbanks following GMHT beet and spring oilseed rape than under conventional varieties (Figs 3,5). By contrast, there was no significant change in weed seedbank levels following maize crops even though seed production was higher in the GMHT treatment (the significant increase in monocots after two years was based on only nine sites and so may be spurious).

All of the more abundant species of weeds in the FSE have seeds that persist in seedbanks for several seasons (Heard *et al.* 2003*b*). This means that the effects of weed management in one season are buffered: even if all weeds were removed during a year or run of years, large populations could still regenerate from the seedbank subsequently. In general, the dicot seedbanks increased in all crops and treatments, while in beet and oilseed rape, monocots decreased (Heard *et al.* 2003*a*), a situation likely to be reversed in the cereal crops that form the rest of the rotation. Dicot seedbanks and seedling numbers tended to be smaller following GMHT beet and oilseed rape than following the conventional crops (as were monocots in beet), while monocots tended to be more abundant following GMHT maize. The data being collected during the second year after the treatments is required to confirm these patterns, to clarify the dynamics of individual species (Heard *et al.* 2003*b*) and establish rates of change of seedbanks in the cereal phase of the rotations.

On the basis of available seedbank data, Heard *et al.* (2003*b*) concluded that there is the potential for an accelerated decline in abundance of weed species under GMHT beet and spring oilseed rape cropping in the order of an additional 7% per year. By contrast, there is also the potential for increases under GMHT maize. For many species, FSE seedbank changes were affected as much by the choice of crop as by the choice of herbicide regime (Heard *et al.* 2003*b*). These effects seem, again, insensitive to different years and locations, agreeing with other studies showing that weed population dynamics appear robust to differences between sites (Freckleton & Watkinson 1998; Lintell-Smith *et al.* 1999). Weed populations are often more sensitive to germination and weed control than to competitive interactions within the crop, except at very high densities (Firbank & Watkinson 1986; McCloskey *et al.* 1996; Freckleton & Watkinson 1998).

Weed population models derived from the FSE data should reflect the stochasticity in the system that ensures that even where $R < 1$ not all sites will show a reduction in GMHT abundance relative to conventional, and vice-versa (Fig. 6, p.35). A more important unknown is to what extent the farmers might change the management of the whole rotation in both GMHT and conventional systems. Weed populations would be sensitive to the banning of atrazine on conventional maize, or the adoption of delayed or band spraying of glyphosate in GMHT beet. Moreover, weed populations would also be affected should GMHT cropping in GB become associated with the more widespread use of zero and minimum tillage, as farmers came to rely less on ploughing for weed control (Firbank & Forcella 2000). Weeds that tend to increase under minimum tillage are those with short-lived seedbanks, such as sterile brome (*Anisantha sterilis*), while the species that are of greater benefit for farmland birds, such as chickweed (*Stellaria media*), tend to decline in numbers (McCloskey *et al.* 1996). In practice, many British soil types are not appropriate for minimum tillage (Cannell *et al.* 1978), and so GMHT cropping may cause less of an increase in minimum tillage than in the USA.

In recent decades, scarce weed species have disappeared, first from fields, then from larger areas (Preston *et al*. 2002). However, the more widespread weeds have tended not to be driven to regional extinction by changes in weed management (Cousens & Mortimer 1995; Heard *et al*. 2003*b*). Indeed, the seedbanks in the FSE fields were moderately large (Champion *et al*. 2003). Persistent seed, and occasional lapses in control that allow return of weed seed to the soil, together buffer against declines of the common weed flora. The selective action of management on weed assemblages (Firbank 1991) can lead to profound shifts in weed communities in as little as three years (McCloskey *et al.* 1996); such shifts have been reported following GMHT cropping in the US (Petersen, Scursoni & Forcella 2002).

The FSE showed no major relationships between treatment effects and weed density, showing that there was no tendency for farmers to manage weedier fields in a qualitatively different way. Moreover, the take-up of GMHT cropping varied little among farmers of different farm types in the USA (Fernandez-Cornejo & McBride 2002). If similar patterns were repeated in GB, then it is unlikely that weedier fields would be targeted in any way for GMHT cropping, and that rates of increase or decrease in weed populations would be similar across fields regardless of current farming intensity. Nevertheless, this implies that the effects on *absolute* numbers of weeds and weed seeds would be greatest in the weedier fields.

These conclusions would be sensitive to changes in both conventional and GMHT cropping management regimes. For example, the treatment effects may well be different should, for example, atrazine be banned in maize, or delayed or band spraying of glyphosate be widely adopted in beet.

Potential implications for detritivores

One of the strongest impacts of GMHT crops on higher trophic levels was the late-season increase in invertebrate detritivores. The effect of GMHT cropping on the total mass of dead plant material is relatively small. The material left by the crop exceeds by at least ten-fold the usual mass of the weed flora, and the total crop matter available to detritivores will probably be even greater in cereal years than in break years. However, the actual impacts may be greater because of the timing of the pulse of dead matter and its location relative to the soil surface. The dead weed matter arising in GMHT cropping in early summer and extending through the summer is unusual in arable systems, though it does arise on rotational set-aside land.

GHMT cropping could enhance abundance among the detritivore community during the summer, a period of maximum temperature and dryness, when they are normally short of food and habitat (Rusek 1998). This pulse of detritus maintains detritivore Collembola numbers until at least July/August, and could explain the responses to GMHT of a number of uni-generational, invertebrate omnivores and predators that may have beneficial agronomic effects, including carabids and spiders (see Marcussen *et al.* 1999; Bilde *et al.* 2000). However, such a benefit may be at the expense of summer herbivores in spring oilseed rape and, especially, beet.

This increase in detritivores would last only as long as there is a large enough biomass of weeds. Should the seedbank decline, so would the potential benefits for surface-feeding detritivores in the summer. There is much to learn about the relationships between detritivore diversity and their ecological function; for example, we speculate that the changes in the detritivore community might affect rates of seed decay and hence influence weed populations.

Potential implications of GMHT cropping for pollinators

Given the recent declines in bumblebee distributions (Williams 1986), and the importance of pollinators for both crops and weeds in farmland landscapes, any effects on bees and butterflies may also be of both economic and conservation concern. However, estimating possible impacts on the landscape scale is particularly difficult, as these insects can forage over distances of several kilometres. In the FSE, bee and butterflies were particularly attracted to spring oilseed rape crops, in which they were adversely affected by GMHT herbicide regimes. The effects were probably due to differences in the weed populations, rather than any direct effect of differences between the crop plants themselves (Roy *et al*. 2003). The observed responses reflect differences in foraging behaviour rather than changes in population size.

Most research on bee and butterfly conservation in arable landscapes concentrates on field margin vegetation and its management (Feber & Smith 1995; Weibull *et al.* 2000; Marshall & Moonen 2002): perhaps one of the lessons of the FSE is that pollinators use the weedy vegetation at the edge of the crop to a greater extent than realised. Arable fields are not generally considered to be important habitats for these species, but even though they may be of low quality per unit area, their large areas gives them a potential importance that should not be overlooked in areas otherwise poor in forage resources (Sears *et al.* 2001; Roy *et al.* 2003). GMHT cropping is less likely to affect pollinator populations in landscapes rich in alternative nectar and pollen resources (Roy *et al.* 2003), though in present landscapes any forecasts of changes in pollinator populations following the widespread introduction of GMHT crops will remain highly uncertain, even when the results from the FSE of winter oilseed rape are complete.

Potential implications for other invertebrates

The simplest model of longer-term invertebrate populations would assume that the functional relationships observed between different trophic levels are stable, thus allowing predictions to be driven by changes in weed populations. For example, changes in abundance of seed-eating carabids are likely to parallel the expected changes in the amount of seed rain, and changes in detritivores would track the differences in decaying weed vegetation over time. However, it is unwise to extrapolate the results of invertebrate studies from smaller to larger spatial scales (Heads & Lawton 1983; Norowi *et al.* 2000) especially for relatively mobile species such as carabid beetles (Duffield & Aebischer 1994; Perry 1997; Kennedy *et al.* 2001). Sherratt & Jepson (1993) emphasised the importance of allowing for immigration and recovery in models to assess pesticide effects and Halley *et al.* (1996) have shown the importance of accounting for large-scale movement within the agricultural landscape for spiders. These studies suggest that buffering may occur at the landscape scale and management for increased invertebrate resources in one part of the agricultural system may counterbalance any decline elsewhere.

Potential implications of GMHT cropping for farmland birds

The major effects of GMHT cropping on species of conservation concern had been expected to result from the indirect effects of the herbicide regimes on farmland birds (Krebs *et al.* 1999; Watkinson *et al.* 2000), with small mammals also affected by reductions in weed seed and invertebrate food items (Tattersall *et al.* 2001).

It is possible to analyse potential treatment effects on the food resources for individual bird species by grouping prey items at relevant time periods and, where appropriate, at relevant distances into the field. These analyses are ongoing at the time of writing, but some insights can be gained into the likely effects by considering general changes in invertebrates and dicots.

The amount of food resources for chicks during the breeding season is important for populations of birds including grey partridge (Cramp *et al.* 1986; Potts 1997), corn bunting (Brickle *et al.* 2000) and yellowhammer (Morris *et al.* 2002). In beet and spring oilseed rape, weed seedlings were more abundant at the start of the season in GMHT crops, but there was no evidence of increased numbers of invertebrates at this time. While small plot experiments on GMHT beet crops have shown considerable increases of weeds and invertebrates with delayed glyphosate spraying (Dewar *et al.* 2003; Strandberg & Bruus Pedersen 2002), farmers within the FSE applied the herbicides too early for this potential benefit for breeding birds to have been realised (Champion *et al.* 2003).

Later in the summer, numbers of dicot weed seeds were lower in GMHT beet and spring oilseed rape crops, The increased levels of weeds and invertebrates observed in GMHT maize crops throughout the season may be of less value for breeding birds, as the tall, shady architecture of the crop makes it a less valuable habitat than beet crops for birds such as skylarks, stone curlews (*Burhinus oedicnemus*) and lapwings (*Vanellus vanellus*) that require a shorter, more open habitat (e.g. Green *et al*. 2000; Donald *et al.* 2001*a*, 2002). Differences in crop growth between GMHT and conventional varieties of the same crops were too small (Champion *et al.* 2003) to have affected breeding birds, although differences in weed cover may have influenced the probability of nesting. Current analyses suggest that the FSE provides little evidence that GMHT cropping would have a major short-term, within season, effect on breeding farmland birds.

Current evidence suggests that national declines of many seed eating farmland birds have been driven by changes in survival rates, rather than by changes in breeding performance (e.g. Siriwardena *et al.* 1998, 2000). In particular, densities of granivorous birds in fields during the winter are positively related to the density of appropriate weed seeds (Moorcroft *et al.* 2002; Robinson & Sutherland 1999), and populations of breeding birds can increase if the winter food supply is increased (Hole *et al.* 2002).

The availability of weed seeds to wintering birds and small mammals depends upon post-harvest cultivation. Given the high numbers of bird food seed found in conventional spring oilseed rape crops (Fig. 3, p32), these fields seem of particular value to wintering birds and mammals, and the large reductions in dicot seed rain in GMHT spring oilseed rape crops are of potential concern for bird conservation. However, the rapid planting of winter cereals in many of these fields means that any benefit from oilseed rape stubbles for wintering birds is likely to be restricted to August and September (Gillings & Fuller 2001; Robinson & Sutherland 1999). The higher densities of bird food seed rain in GMHT maize crops (Fig 3, p32) may be of greater value to wintering birds, because the stubbles are often left well into the autumn and winter.

Beet is harvested usually between September and December, after which the soil is very heavily disturbed and only those weed seeds near the soil surface are likely to provide food for wintering birds (Robinson & Sutherland 1999). Under GMHT beet, seed rain from dicots was 32 % that under conventional crops. We speculate that the actual effects of commercial GMHT beet cropping on wintering birds will depend upon the national strategy for crop harvesting. Should conventional and GMHT beet be harvested at different times to ensure separation, the varieties to be harvested later might give the greater benefit to wintering birds regardless of differences in seed rain. This would also be true for skylarks and grey partridges that use other food items as well as weed seeds within beet crops (Cramp *et al.* 1986; Donald *et al.* 2001*b*).

It has been suggested that the ongoing long-term declines in weeds important in the diet of birds (Smart *et al.* 2000; Firbank & Smart 2002) would be accelerated by GMHT cropping, both because of the increased effectiveness of the broad spectrum herbicides and because less intensive farmers might use GMHT systems to reduce weed levels in particularly weedy fields (Watkinson *et al.* 2000). Such fields have a value to wildlife disproportionate to their area. There is no evidence from the FSE that such long-term declines might result from the introduction of GMHT maize crops. The introduction of GMHT beet crops into rotations might accelerate the declines of the more frequent dicot weed species (Heard *et al.* 2003b). For spring oilseed rape the seedbanks of dicots doubled following conventional crops, but barely increased following GMHT crops. The increase in weed seedbanks in conventional spring oilseed rape might compensate to some extent for reductions during the cereal crops within the rotation. This would not happen with GMHT varieties, suggesting that their widespread use may exacerbate long-term declines in bird food plants. This would affect the food availability for wintering birds in all of the crops of the rotation.

The importance of the farmed landscape in determining the effects of GMHT cropping

The FSE gives little evidence for effects of GMHT cropping on biota of non-cropped field margins. Moreover, other research has shown no evidence for more distant effects of GMHT cropping on biodiversity in the wider landscape; while gene flow can occur between spring oilseed rape and wild relatives, the resulting plants are unlikely to become more common or invasive as a result, and there is no evidence of toxicity of GMHT pollen on populations of butterflies or bees (Squire *et al.* 2003). However, the nature of the farmed landscape as a whole has a major influence on the potential effects of large-scale and long-term use of GMHT crops.

Crops now typically support fewer weeds than in the past (Squire *et al.* 2003), and farmed landscapes in GB have become more homogenous, with different parts of the country specialising in different forms of production. Field margins, streamsides and lanes have become less rich in forage plants for bees and butterflies (e.g. Haines-Young *et al.* 2000). In this context, impacts of GMHT cropping practice for biodiversity conservation are proportionately more important than they would be within landscapes that provide more resources for wildlife. Thus, for example, the effects of GMHT beet cropping on bees and butterflies would be minor if there were plenty of alternative nectar sources and host plants in the areas around the fields, but are likely to be severe in present agricultural landscapes. Likewise, the potential effects of GMHT beet and spring oilseed rape cropping on wintering granivorous bird populations, small mammals and their predators, would be much the greatest in landscapes without the provision of alternative forage resources from set-aside or game cover crops. By contrast, the increases in weeds and invertebrates in GMHT forage maize crops might be of value to granivorous birds and mammals disproportionate to their area, as maize is often the only arable crop in areas otherwise used for livestock (Robinson *et al.* 2001).

Biodiversity may be restored to degraded arable landscapes. Breeding success and provision of food for wintering birds can both be increased by managing areas of land appropriately, for example by sowing game cover crops. In conservation headlands, the outer areas of arable fields are treated with only a restricted set of pesticides in order to encourage the development of flora and fauna (Sotherton 1991). While few major interactions were observed in the FSE between treatment effects and distance into the crop, there were highly significant effects of distance into the crop on a wide variety of ecological indicators, usually with greater species abundances nearest to the crop edge (Fig. 8, p.37). If broad-spectrum herbicides were not used on the outer few meters of GMHT beet and spring oilseed rape, we predict that there would be potential benefits for the species that forage within the crop and the tilled verge, notably butterflies (Roy *et al.* 2003) and the Grey Partridge (Potts 1997). However, note that differences between abundances in the outer 2 m and towards the crop centre were typically of the order of one- to three-fold (Fig. 8, p.37), so the rest of the field area contained the vast proportion of individual organisms. Small plot experiments on GMHT beet crops have shown considerable increases of weeds and invertebrates with delayed glyphosate spraying (Dewar *et al.* 2003; Strandberg & Bruus Pedersen 2002; May 2003). These might increase food resources available to chicks in the breeding season, with potential benefits for species like grey partridge (Cramp *et al.* 1986; Potts 1997), corn bunting (Brickle *et al.* 2000) and yellowhammer (Morris *et al.* 2002). This potential benefit for breeding birds was not realised by farmers within the FSE who, following current recommendations, applied the herbicides earlier (Champion *et al.* 2003).

In practice, broader changes in agriculture such as large increases in energy crops, or increased habitat creation in and around arable fields are likely to affect farmland biodiversity to extents at least as great as the introduction of GMHT cropping.

CONCLUSIONS

The FSE was designed to investigate the potential effects on GMHT beet, maize and spring oilseed rape cropping on farmland wildlife in GB, by establishing a large number of field trials across the range of variation of farming conditions likely to be encountered should they be commercialised. These trials involved splitting the fields in half, sowing one half with GMHT and the other with conventional varieties of the same crops, managing each half appropriately, and recording a wide range of weeds and invertebrates from before the crops were sown until two years afterwards.

Some significant differences were found between treatments for each crop, although these effects were not the same from crop to crop. There was no evidence that treatment effects had arisen because the crops had been produced using genetic modification, as opposed to conventional breeding. Rather, the differences could be explained entirely by the effects of the contrasting herbicide regimes used on the GMHT and conventional treatments.

Conventional spring oilseed rape and beet crops supported more weeds than GMHT crops after herbicides had been applied to both treatments, but the reverse was true for maize crops, because the herbicides currently used in conventional maize are more effective than those used on the GMHT varieties. There were corresponding differences in seed rain, resulting in smaller seedbanks of dicot weeds following GMHT beet and, especially, spring oilseed rape crops. It is not yet certain whether these effects persist into the second year after the crops were harvested.

Effects on invertebrates tended to be associated with particular species groups and particular times of year, according to the availability of food resources. Thus bees and butterflies were less frequent in GMHT spring oilseed rape than in conventional varieties, because there were fewer nectar-providing weeds in the very edge of the crops, while a type of seed-eating beetle was more abundant in conventional than in GMHT beet and spring oilseed rape because of the greater numbers of weed seed available. The later use of herbicides on all GMHT crops meant that there was more decomposing plant material, giving rise to increased numbers of soil-dwelling Collembola and their predators in late summer. In general, though, invertebrate numbers were less affected by GMHT cropping than weed numbers. There were few effects on plants and invertebrates in field verges and boundaries.

Even though the individual field sites showed a wide range of species richness and abundance, geographic location and crop management, the actual effects of the GMHT cropping on biodiversity were remarkably consistent for each crop. This finding gives us confidence that the findings would represent what would actually happen under large-scale growing, unless the management regimes altered somewhat, for example if changes in regulations meant that atrazine was no longer allowed on maize crops, or if farmers were given incentives to delay herbicide applications to GMHT beet.

The major potential effect of large-scale GMHT cropping on species of conservation concern is likely to be as a result of changes to food resources for pollinating insects (bees and butterflies) and for breeding and, especially, wintering birds. GMHT maize crops supported more dicot weeds, and the increased seed rain from these plants might well benefit birds in the autumn and winter. By contrast, GMHT beet crops contained fewer dicots and invertebrates in late summer. Spring oilseed rape GMHT crops gave rise to only 21 % of dicot seeds as conventional crops. Both GMHT beet and spring oilseed rape crops supported fewer pollinators, because of the reductions in nectar-providing weeds.

The FSE results suggest that the reductions in dicot weed seed rain in GMHT beet and spring oilseed rain resulted in corresponding reductions to the weed seedbank. In particular, in spring oilseed rape crops, dicot seedbank densities doubled following conventional crops, but increased only very slightly in GMHT crops. The FSE currently has insufficient data to show whether or not these differences persist over years to affect weed populations in the longer term; the programme of follow-up sampling of weed seedbanks from FSE sites is not yet complete. Nevertheless, if the trends are maintained under widespread GMHT cropping, then the present herbicide regimes associated with GMHT beet and spring oilseed rape might exacerbate long-term declines of those weeds that are important food resources for granivorous birds. By contrast, these same weeds might increase in abundance following a shift from conventional to GMHT maize cropping. Rates of increase or decrease in weed populations would probably be similar across fields regardless of current farming intensity, although the effects on absolute numbers of weeds and weed seeds would be greatest in weedier fields.

Overall, therefore, evidence from the FSE suggests that large-scale cropping of GMHT maize will be of benefit to farmland wildlife, with increased levels of weeds that may well be of value to granivorous birds. By contrast, GMHT cropping of beet and, especially, spring oilseed rape will provide fewer nectar resources for pollinators and fewer weed seed resources for granivorous birds.

Since weed and invertebrate abundance differed at least as much between crops and time of year as between treatments, we conclude that the impacts on biodiversity of changes in the uptake and distribution of different crop species may be of similar sizes to those that might result from changes from conventional to GMHT varieties. Also, weed and invertebrate populations may prove to be sensitive to changes in both conventional and GMHT crop management regimes. The implications of large-scale GMHT cropping for conservation depend not simply upon the direction and magnitude of effects detected within the FSE, but also on the areas and distribution of land adopted for these crops, the uptake of minimum tillage systems and the broader context of the changing management of farming rotations and landscapes. These agricultural issues represent the major uncertainties in forecasting the medium-term and large-scale impacts of GMHT cropping.

Crop and field margin management is particularly important for conserving and enhancing biodiversity in the arable landscapes of GB, because of the intimate inter-connection between fields and their surrounding semi-natural habitat. There have undoubtedly been enormous declines in forage resources for pollinators, birds, mammals and other wildlife over the last sixty years, and we might reasonably expect farmland wildlife to continue to decline across whole landscapes under scenarios of further agricultural intensification. By contrast, research is now showing how biodiversity can be enhanced in arable landscapes by the manipulation of both GMHT and conventional farming systems and their adjacent field margins. If wildlife is to be conserved and restored in the British countryside, this balance between agricultural production and opportunities for biodiversity needs to be shifted back to a significant degree. GMHT cropping is but one factor in determining whether, and how far, this shift in balance might be achieved.

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Table 1.
Herbicide applications to conventional (Conv) and genetically modified herbicide-tolerant (GMHT) varieties of beet, maize and spring oilseed rape. The number of active ingredients represents the total number of compounds used (excluding desiccants on spring oilseed rape), regardless of the number of times they were applied. From Champion *et al*. (2003), where data on other pesticides can be found.

	beet		maize		spring oilseed rape	
number of sites	66		68		67	
	Conv	GMHT	Conv	GMHT	Conv	GMHT
herbicides						
treated (% sites)	100	97	100	100	94	97
pre-emergence herbicide (% sites)	46	0	46	0	46	0
mean no. active ingredients	4.4	1.0	1.9	1.0	1.4	1.7
mean no. applications	3.5	1.6	1.3	1.2	1.9	1.7

Table 2.
Comparisons of relative counts and biomass of a range of vegetation and invertebrate taxa across crop types, contrasting GMHT and conventional (Conv) treatments. Data are geometric means for in-field observations only, with probability values symbolised (* $p < 0.05$,** $p < 0.01$, *** $p < 0.001$). Significant results are shown in bold when values were larger in the GMHT crops, italics when smaller. Plant data are presented m^{-2}; note that seed rain numbers exclude seeds from the oilseed rape crop. Dashes indicate data not collected for that crop. Other data are half-field totals, with units depending upon the source protocol. See text and Brooks *et al.* (2003); Haughton *et al.* (2003); Hawes *et al.* (2003); Heard *et al.* (2003*a*) for further details.

	beet			maize			spring oilseed rape		
	Conv	GMHT		Conv	GMHT		Conv	GMHT	
initial weed seedbanks	1196	1179		2266	2518		2065	2050	
May, weed seedling counts	**42**	**59**	**	**39**	**88**	***	**29**	**50**	**
June, herbivores (Vortis)	25	24		**5**	**8**	*	*11*	*8*	*
June, herbivores on crop plants	16	14		-	-		33	34	
June, predators (Vortis)	11	13		3	3		3	3	
June, predators on crop plants	8	7		-	-		4	5	
June, predators (pitfalls)	1031	1008		679	690		497	512	
June, parasitoids (Vortis)	13	15		**2**	**3**	*	10	8	
June, parasitoids on crop plants	*4*	*2*	*	-	-		3	3	
June, detritivores (pitfalls)	68	92		181	210		**97**	**140**	**
June, pollinators	1	3		2	1		8	6	
after herbicide weed seedling counts	32	35		**14**	**42**	***	*47*	*33*	**
July, herbivores on crop plants	119	97		165	190		159	174	
July, predators on crop plants	18	16		9	7		5	5	
July, parasitiods on crop plants	5	5		6	4		5	3	
July, pollinators	3	2		2	4		29	26	
Aug, herbivores (Vortis)	*49*	*31*	***	6	9		10	8	
Aug, predators (Vortis)	*34*	*31*	***	9	10		11	10	
Aug, predators (pitfalls)	956	924		666	693		914	916	
Aug, parasitoids (Vortis)	*58*	*37*	***	13	16		46	39	
Aug, detritivores (pitfalls)	**56**	**86**	**	**86**	**139**	**	175	198	
Aug, pollinators	*5*	*3*	**	3	3		15	12	
total gastropods	5	5		8	9		11	12	
total collembola (pitfalls)	353	404		613	725		529	582	
total carabids (pitfalls)	1707	1577		799	812		1024	1049	
total spiders (pitfalls)	270	298		266	238		209	217	
total heteroptera	*9*	*5*	*	6	6		9	7	
total bees	*4*	*2*	*	1	2		44	37	
total butterflies	*6*	*4*	**	3	4		*16*	*12*	*
final weed counts	*33*	*25*	*	**16**	**49**	***	75	61	
total weed biomass	*23*	*4*	***	**10**	**18**	*	*41*	*14*	***
total weed seed rain	*621*	*188*	***	404	758		*3023*	*626*	***
weed seedbank in following crop	*2061*	*1652*	*	2806	3010		*3242*	*2412*	*
weed seedlings in following crop	35	30		49	40		*31*	*23*	*
weed seedbank in 2nd following crop	1937	1602		1911	2039		2623	2113	
weed seedlings in 2nd following crop	33	32		7	17		40	35	

Table 3.
Effects of conventional and GMHT crop management on relationships between counts of organisms within trophic levels, and between counts of herbivores and weed biomass, in the weed / invertebrate systems of beet, maize and spring oilseed rape. The probability p is given of the regression describing these relationships using data from across both treatments, followed by the probability of a difference in regression coefficients between the treatments. The direction of change in regression coefficient is indicated (↑, regression coefficient in GMHT > regression coefficient in conventional crops; ↓, regression coefficient in GMHT < regression coefficient in conventional crops, where the difference is significant at $p < 0.05$). See Hawes *et al.* (2003) for further details. Significance levels are given and are symbolised with asterisks as in Table 2.

	beet			maize			spring oilseed rape		
	p of primary effect	*p* of effect on reg. coeff.	change in reg. coeff.	*p* of primary effect	*p* of effect on reg. coeff.	change in reg. coeff.	*p* of primary effect	*p* of effect on reg. coeff.	change in reg. coeff.
herbivore / biomass	<0.001***	0.059		<0.001***	0.784		0.321	-	
predator / herbivore	<0.001***	0.135		<0.001***	0.050*	↑	<0.001***	0.319	
parasitoid / herbivore	<0.001***	0.009**	↓	<0.001***	0.901		<0.001***	0.151	
predators / pests on crops	<0.001***	0.975		<0.001***	0.97		0.162	-	
parasitoids / pests on crops	0.004**	0.852		<0.001***	0.637		0.017*	0.85	
pollinators / non-crop plants	0.02*	0.14		0.85	0.35		0.62	0.84	

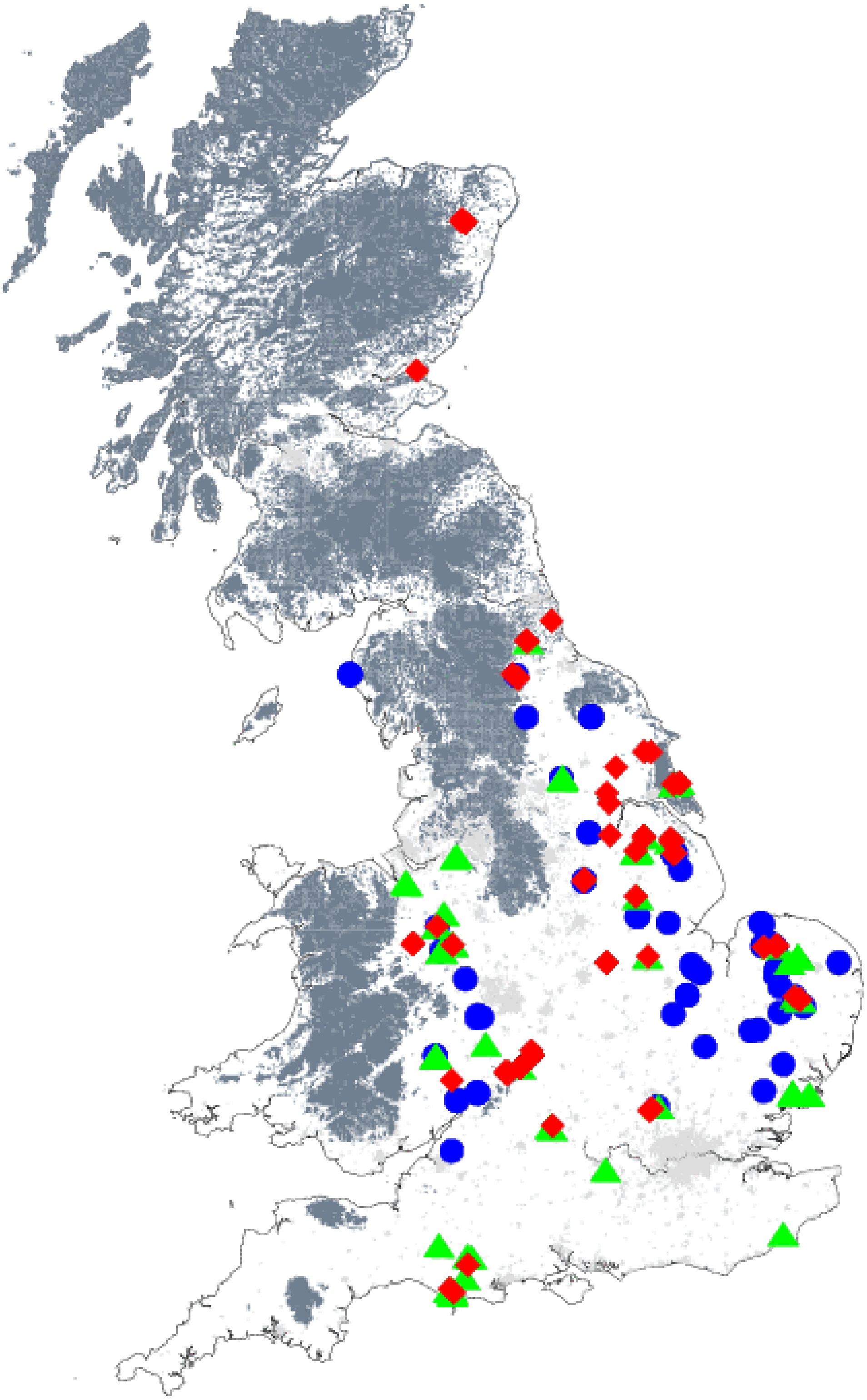
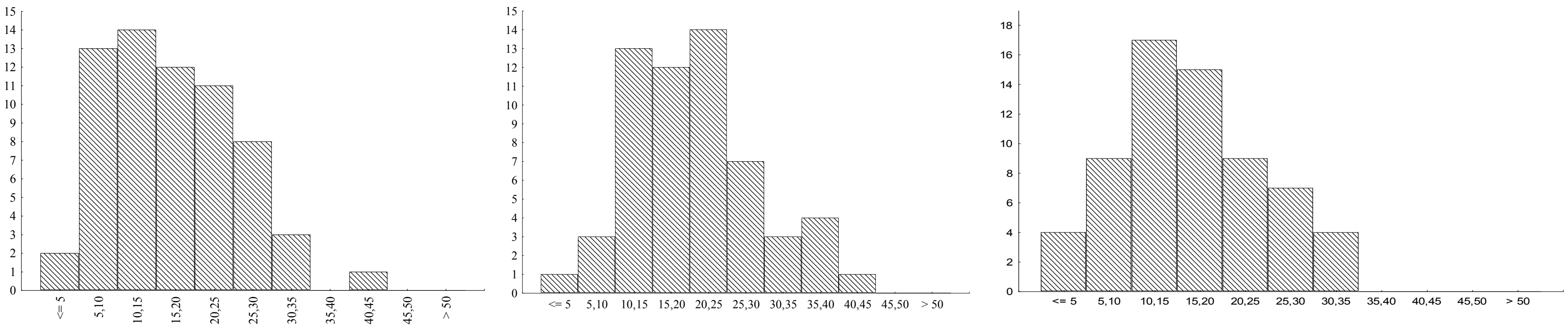
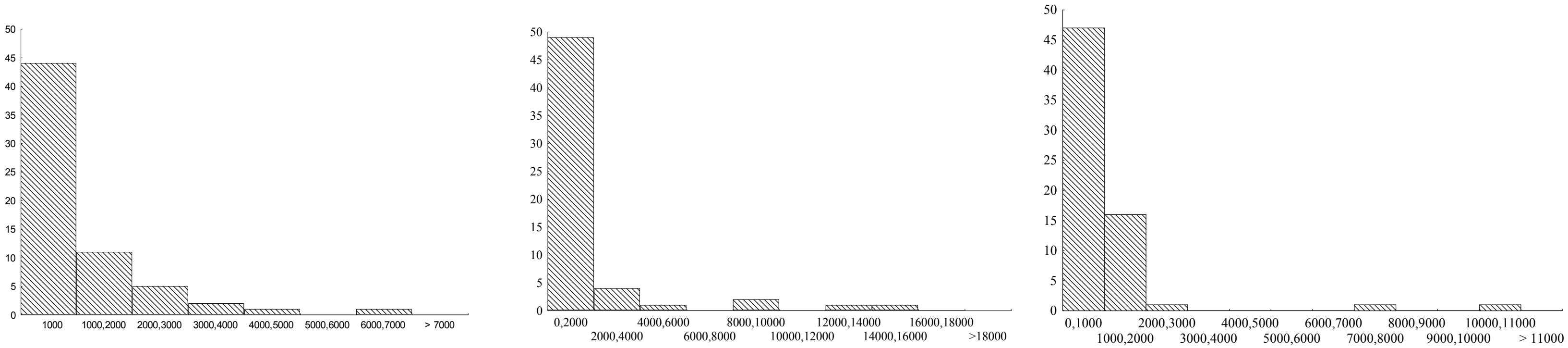


Fig. 1,
Distribution of field sites for the Farm Scale Evaluations of beet (blue circles), maize (green triangles) and spring oilseed rape (red diamonds) within Great Britain. Urban areas are shaded in light grey, while land in the uplands and marginal uplands (data from Countryside Survey 2000, Haines-Young *et al.* 2000), are shaded in dark grey, indicating parts of the country not suitable for growing these crops.

a) Number of species



b) Number of seedlings



Beet **Maize** **Spring oilseed rape**

Fig. 2,
Frequency distributions of species number and of number of seedlings of weeds across all sites within the GMHT treatments before herbicides were applied.

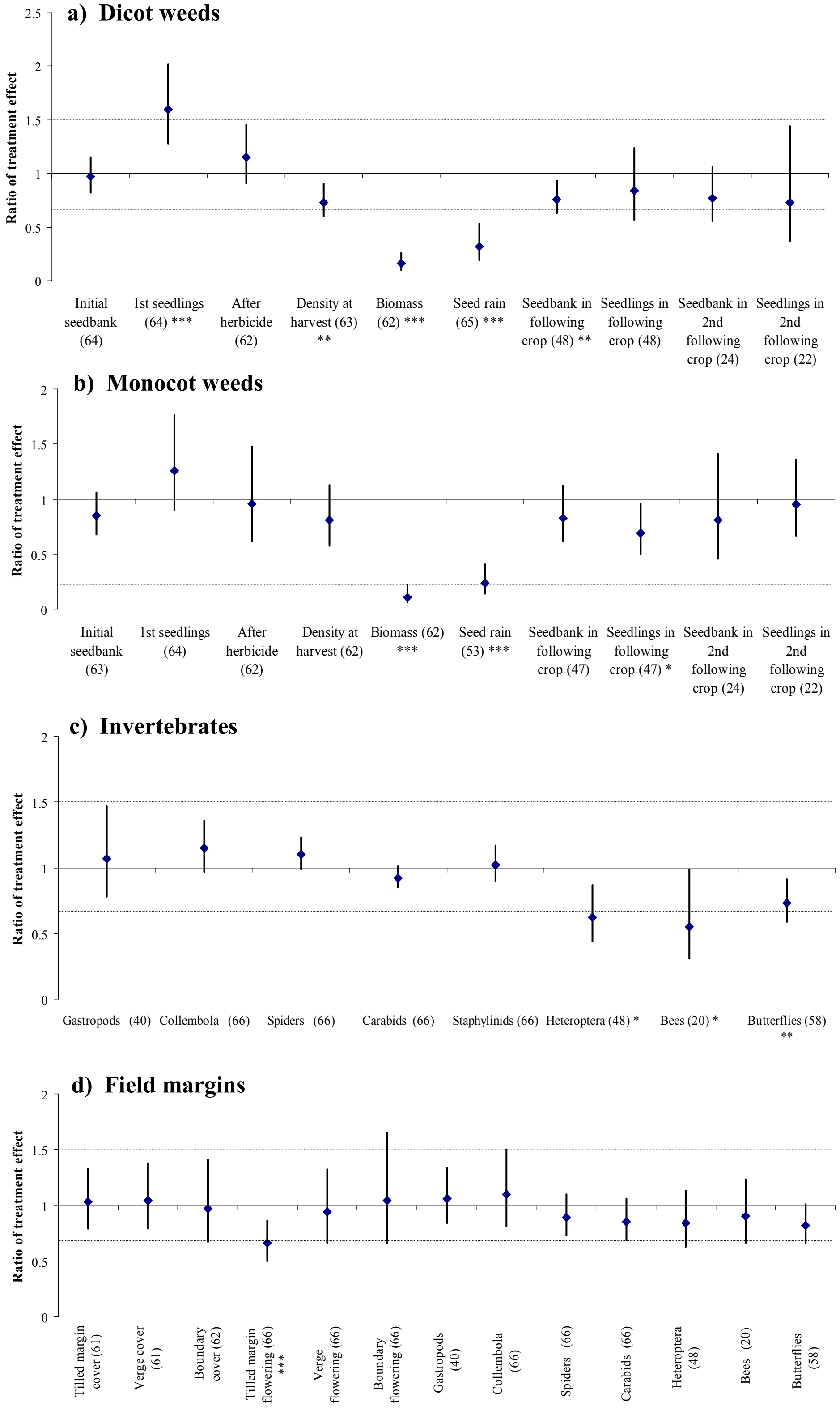


Fig. 3,
Treatment effects of GMHT beet cropping on (a) dicot weeds, (b) monocot weeds, (c) invertebrates and (d) field margin biota. Data are presented as the geometric mean treatment effect, given by the value in the GMHT treatment divided by that in the conventional treatment. 95 % confidence limits are given by bars, with horizontal lines indicating the treatment ratios of 1.5 and 0.67 that the FSE was designed to detect with at least 80 % power. Note that data on dicot and monocot weeds are presented in a sequence through time, from left to right. See text for details and sources. Sample sizes are given by numbers in brackets, and statistical significance by asterisks (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

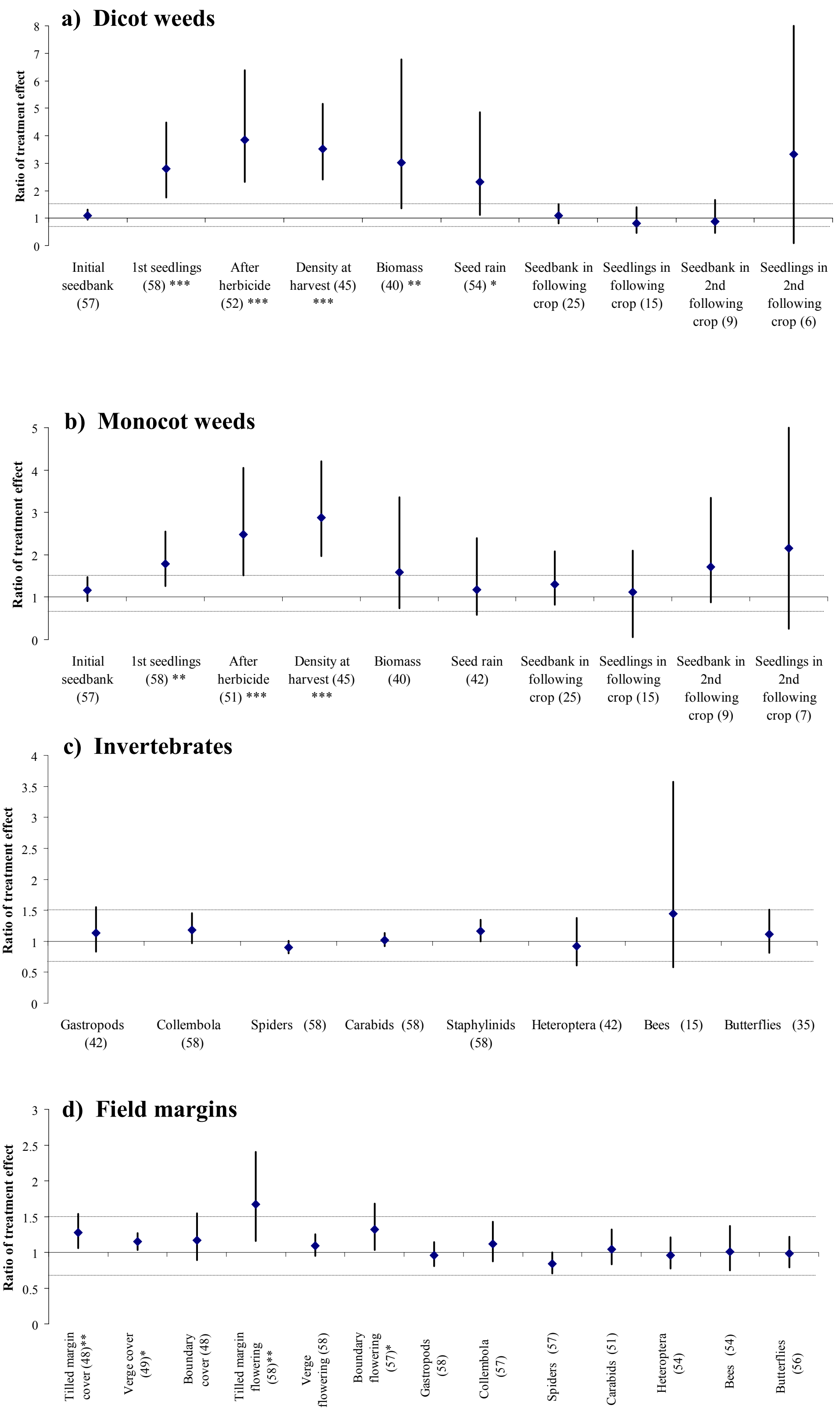


Fig. 4,

Treatment effects of GMHT maize cropping on (*a*) dicot weeds, (*b*) monocot weeds, (*c*) invertebrates and (*d*) field margin biota. See legend to Fig. 3, p.32 for more details of data presentation. The upper confidence limit for seedlings in the second following crop has been truncated from the actual value of 18 to facilitate reading the rest of the graph.

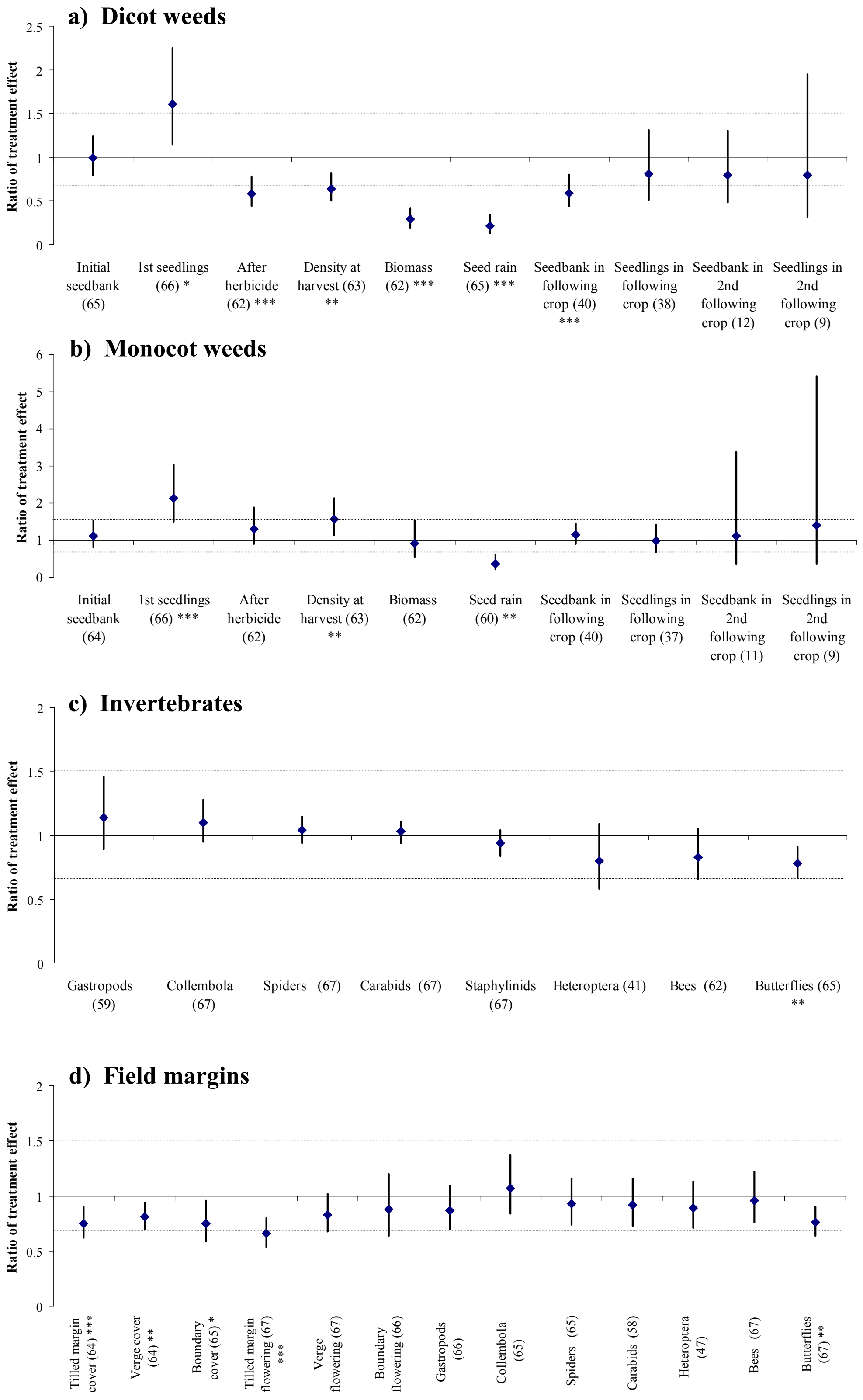


Fig. 5,.

Treatment effects of GMHT spring oilseed rape cropping on (*a*) dicot weeds, (*b*) monocot weeds, (*c*) invertebrates and (*d*) field margin biota. See legend to Fig. 3, p.32 for more details of data presentation.

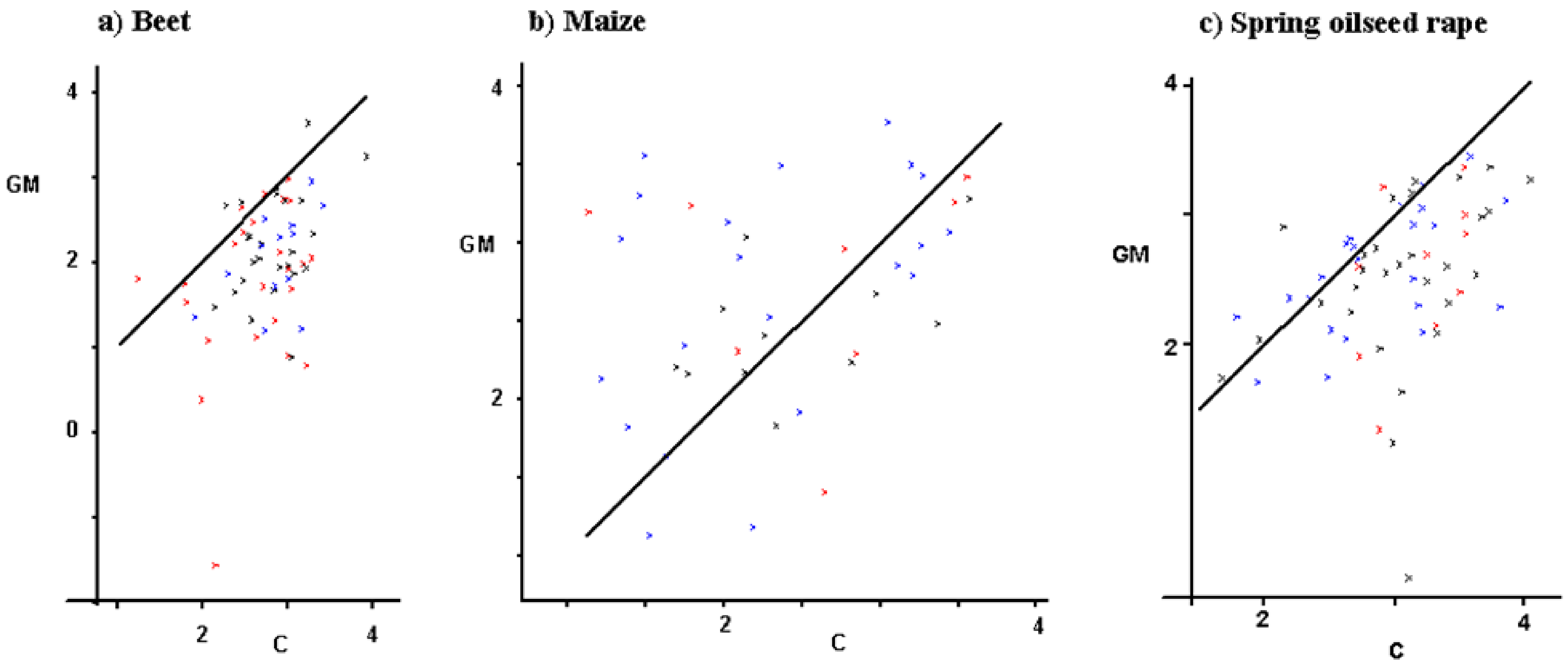


Fig. 6,
Logarithmically transformed weight of total weed biomass in GMHT (GM) half-fields plotted against the same variable in conventional (C) half-fields, in beet (above, left), oil seed rape (above, right), and maize (below) crops. Colour of symbols relates to year. Equality line shown for reference. A treatment effect is demonstrated for each crop by consistent displacement of symbols away from equality line, here in a different direction for maize than the other two crops. Lack of density dependence of effect in each crop is shown by the parallel nature of this displacement from equality line. Variability of treatment effect for each site shown by degree of vertical scatter. Note the constancy of the treatment effect over years

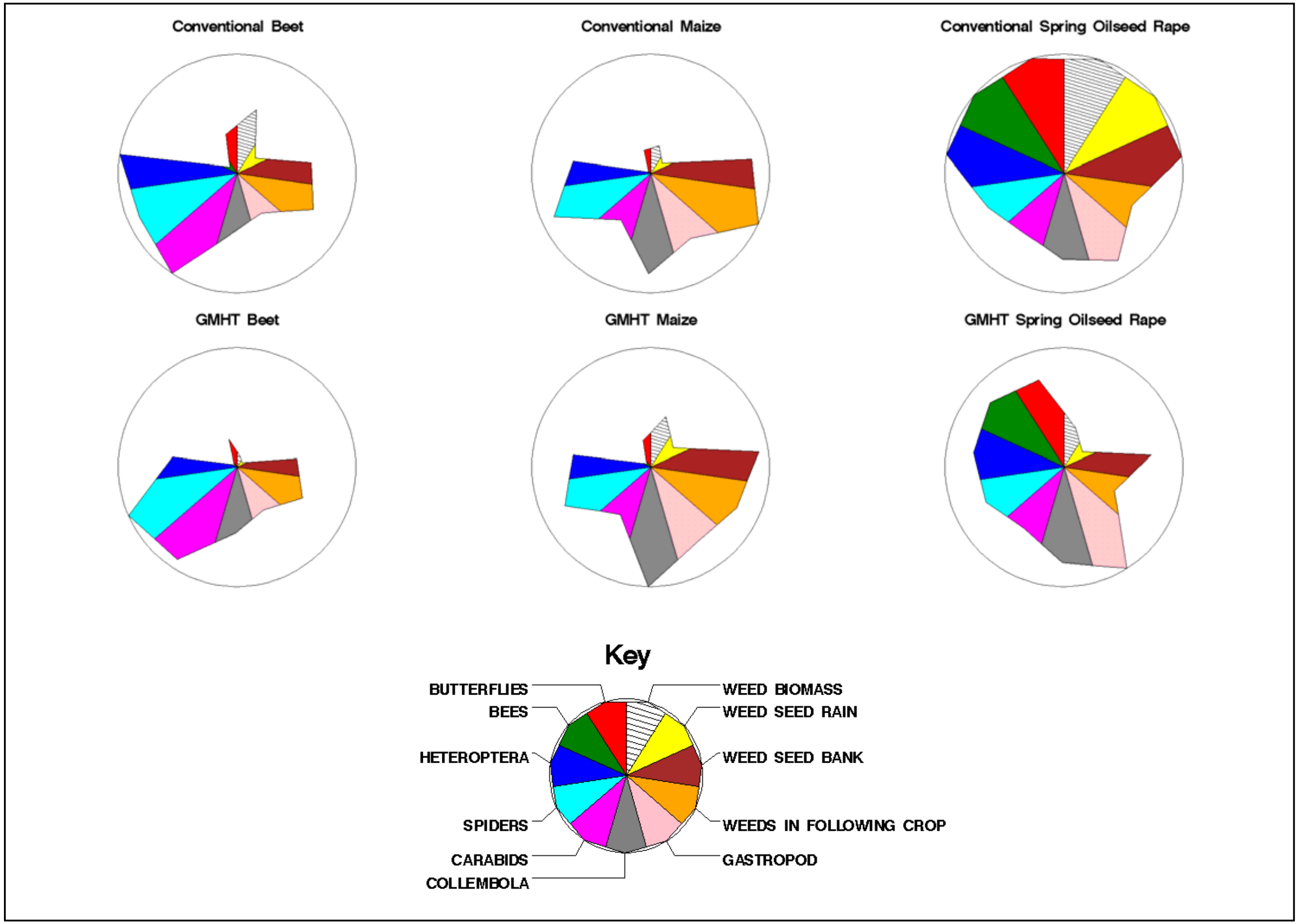


Fig. 7,
Star plots comparing mean values of major biodiversity indicators across conventional and GMHT treatments of beet, maize and spring oilseed rape crops, as given in Table 2, p.28. For each indicator, the length of the star corresponds to the value relative to the maximum value found in any of the six combinations of crop and treatment; for example, the most gastropods were found in GMHT spring oilseed rape. The key diagram shows which section of the star plots star relates to which indicator.

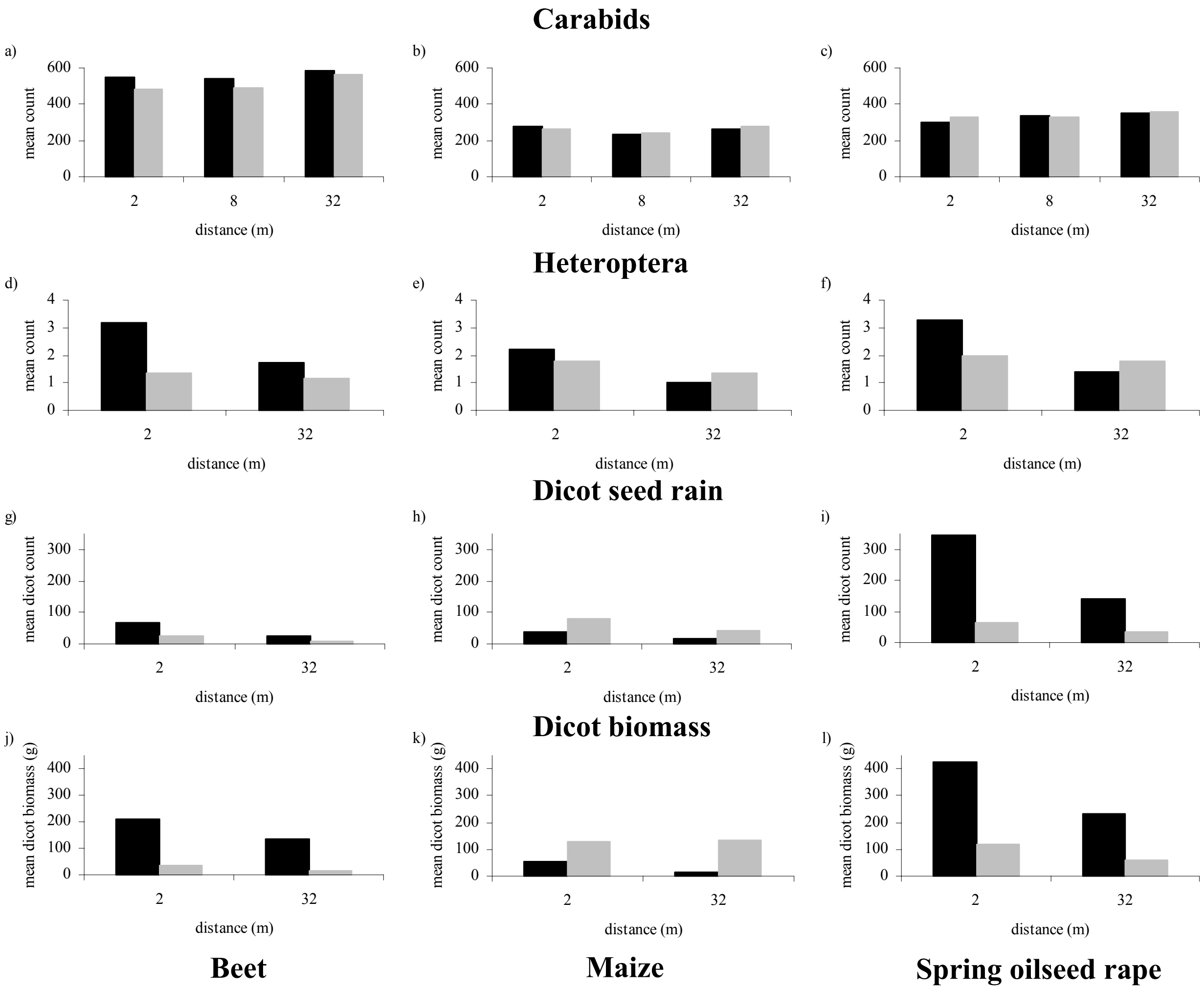


Fig. 8,

Relationships between mean count and distance into crop for each crop for: (*a*) – (*c*) mean annual total carabid counts (largest standard error of difference s.e.d. of log-transformed data = 0.032); (*d*) – (*f*) mean annual total Heteroptera counts (largest s.e.d. = 0.08); (*g*) – (*i*) mean seed rain of dicot weeds (largest s.e.d. = 0.16); and (*j*) – (*l*) mean biomass for dicot weeds (largest s.e.d. = 0.26). (*a*), (*d*), (*g*), (*j*) beet crops; (*b*), (*e*), (*h*), (*k*) maize crops; and (*c*), (*f*), (*i*), (*l*) spring oilseed rape crops. Numbers in conventional crops (black) are contrasted with numbers in GMHT crops (grey).

ISBN 0-85521-036-2

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