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Investigation of the impact of changes in pesticide use on invertebrate populations

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

The Game & Wildlife Conservation Trust's (GWCT) Sussex study has monitored cereal flora and invertebrates for over 40 years, from 1970 to the current day. The data on pre-emergent and foliar pesticide use in cereals on the study area have formed the basis of two reports, one for JNCC in 1999 (Ewald & Aebischer, 1999; Ewald & Aebischer, 2000) and one for Defra (PSD) in 2006 (GWCT, 2006).

These focused on the effect of pre-emergent and foliar pesticides (herbicides, fungicides and insecticides) on non-target arable flora and invertebrates, specifically those taxa that provided food resources for declining farmland birds. At the time of the last report, there was a clear indication that the number of foliar insecticide treatments had increased from 1970 to 1995, but then stabilised. What was not accounted for at the time, were changes in the type and level of seed dressing, the nature of which has continued to change since the last analysis. In addition, the majority of the farms across the Sussex Study Area have also enrolled in the Higher Level Schemes (HLS) agri-environmental schemes.

This report was commissioned to provide an analysis of long term monitoring data collected by the Game & Wildlife Conservation Trusts in Sussex to determine the impact of recent changes in pesticide use on invertebrate populations.

The results will provide additional evidence of the impact of different groups of pesticides on invertebrate populations in cereal ecosytems. The findings will be used to improve the environmental outcomes of the new Countryside Stewardship agri-environment scheme and the implementation and targeting of existing agri-environment agreements.

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Investigation of the impact of changes in pesticide use on invertebrate populations

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Executive Summary

This report summarises recent changes in pesticide use (2005-2012) in the GWCT's Sussex Study, considers the use of seed treatments for the first time, and examines the effect of this pesticide use on invertebrate food resources for farmland birds. This work covers a period that has seen both the expansion of agri-environmental management directed towards reversing the trend of declining farmland flora and fauna as well as changes in pesticide availability due to legislation and agri-chemical development. The analysis on which this report is based draws on a unique dataset, the GWCT's Sussex Study, which has monitored both the farming decisions and the cereal ecosystem on 62 km^2 of the Sussex Downs since 1970. This study is the longest running cereal ecosystem monitoring exercise in the world and collates information on cropping, pesticide use, cereal weeds and invertebrates. Results from the analysis of this dataset allow long-term changes in crop management and the effects of these changes on cereal ecosystem biodiversity to be assessed. Two earlier reports have examined changes in pesticide use and the effect of this use on the food resources of farmland birds (Ewald & Aebischer, 1999 and GCT, 2007).

When the entire time span of the Sussex Study (1970 to 2012) is considered, there have been long-term increases in every measure of foliar and residual pesticide use (herbicides, fungicides and insecticides), including the intensity of use. Considering the recent time period, however, we found no significant changes from 2005 to 2012 compared to the period from 1970 to 2004 in the overall use or intensity of use of pesticides in Sussex (Ewald & Aebischer, 1999 and GCT, 2007). This stabilisation reflects changes in cropping on the study area, with recent declines in the area sown to winter wheat and an increase in spring cereals and break crops. On average, over half of all winter cereals and break crops planted since 2005 on the study area were treated with seed treatments containing neonicotinoids. We did not find that the use of neonicotinoid seed treatments in winter cereals reduced the number of subsequent foliar insecticide applications; in fact we found that, conversely, winter cereals treated with neonicotinoids were more likely to be treated with foliar insecticides. This may reflect either farmer risk-aversion or timing of the sowing of crops.

We examined the trends in the average annual abundance of six invertebrate groups and three chick-food indices over the 43 years of the Sussex Study considered here. Of these, all six invertebrate groups and three chick-food indices declined in the early part of the Sussex Study, in concert with the advent of foliar insecticide use across the area. Two invertebrate groups, Carabidae & Elateridae and Aphididae, have declined over the whole of the Sussex Study, with no evidence of a recent recovery. Four of the six invertebrate groups and all three chick-food indices have shown some signs of recovery in abundance, with the abundance of three groups in particular, Araneae & Opiliones, Chrysomelidae & Curculionidae and Non-aphid Hemiptera, increasing over the past ten years.

The main finding of this work reinforced that of previous assessments of the Sussex Study dataset: foliar insecticide use, adjusted for the use of other types of pesticides, is associated with significantly lower abundances of all groups of chick-food invertebrates. Additionally, the use of foliar insecticide is associated with a carry-over effect in the year following an application, with the abundance of seven of the nine chick-food invertebrate groups examined significantly lower. With regard to seed treatment, aphid abundance was negatively affected by neonicotinoid seed treatments, with seed treatments as a group negatively impacting the abundance of four other chick-food invertebrate groups. The overarching negative effect of foliar insecticide applications remained when controlling for seed treatments. Our results indicate that foliar insecticide applications are more of a threat to the abundance of chick-food invertebrates examined here than the use of neonicotinoid seed treatments, in a cereal ecosystem. The role and use of neonicotinoids should be considered in light of the wider suite of evidence, including their potential impact on the main groups of pollinators not monitored in this study.

1. Introduction

In Britain, a large body of scientific evidence links agricultural intensification (including field enlargement, increasing chemical inputs, the polarization of farm types and a change from spring to autumn-sown crops) to declines in wildlife, encompassing farmland birds, invertebrates and arable flora (Potts 1986, Chamberlain et al. 2000, Benton et al. 2002, Boatman et al. 2004, Donald et al. 2006, Potts et al. 2010). Invertebrates in agricultural environments provide a variety of ecosystem services, such as pollination, pest control and serve as food for farmland birds and other wildlife. The provision of all these is negatively affected by recent changes in agriculture (Geiger et al. 2010, Potts et al. 2010, Power 2010, Rusch et al. 2010, Holland et al. 2012). As global food demand increases (Schmidhuber & Tubiello 2007, Godfray et al. 2010, Chakraborty & Newton 2011), farm management, including pesticide use, is likely to intensify further in order to maintain and increase crop yields.

Not only have increases in the intensity of pesticide use raised concerns, but so has the use of neonicotinoid-based products, particularly in relation to reported declines in pollinators (Blacquiere et al. 2012, Walters 2013, Godfray et al. 2014). A recent EU restriction (to be reviewed in two years) on the use of three neonicotinoid substances (clothianidin, thiamethoxam and imidacloprid) came into effect in December 2013 for flowering crops, but not winter-sown cereals (EC 2013). The restriction was primarily instigated as a measure to limit the "high acute risk" to bee species (**http://www.efsa.europa.eu/en/press/news/130116.htm**), but the impact of neonicotinoids on other invertebrate taxa within the arable ecosystem needs to be considered too. The impact of neonicotinoids on wildlife other than bees has received less attention, although reviews of their effects on other vertebrate and invertebrate wildlife have been published (Goulson 2013, Gibbons et al. 2014). A recent study implicated neonicotinoid pollution in the decline of farmland birds in the Netherlands (Hallmann et al. 2014), with the mechanism believed to be a decline in invertebrates that provide food resources to farmland birds in water bodies contaminated with neonicotinoids.

Monitoring and understanding long-term trends in pesticide usage will enable regulatory authorities to make educated decisions regarding their use. The Game & Wildlife Conservation Trust's Sussex Study has monitored cereal flora and invertebrates for over 40 years, from 1970 to the current day. The data on foliar/residual pesticide use in cereals on the study area have already formed the basis of two reports, one to the Joint Nature Conservancy Council (JNCC) in 1999 (Ewald & Aebischer 1999 – referred throughout this report as E&A 1999) and one to the Pesticide Safety Directorate (Department for Food, Environment and Rural Affairs) in 2007 (GCT 2007). These reports focused on the effect of foliar/residual pesticides (herbicides, fungicides and insecticides) on non-target arable flora and invertebrates, specifically on taxa that provided food resources for declining farmland birds. The last report indicated that the number of foliar insecticide treatments had increased from 1970 to 1995, then stabilised up to 2004. There was no evidence of an increase in food resources for farmland birds between 1995 and 2004, but insecticide treatment showed a significant negative effect on the abundance of all chick-food invertebrates examined.

What was not realised at the time of the last analysis was that, since 1996, some cereal and oilseed rape seed had been treated with neonicotinoid dressings. This new study aims to untangle the effects of neonicotinoid seed treatment from that of foliar pesticides. It examines the suggestion that the widespread uptake of neonicotinoid seed treatments has led to a decline in the use of foliar insecticide applications (Syngenta 2013) and considers the effect of insecticidal seed treatment on invertebrates eaten by birds, using the same approach that we previously applied to foliar and residual pesticides in GCT (2007). Moreover, revisiting the effect of foliar/residual pesticides on invertebrates in the Sussex Study will determine whether there has been any change during a time when European directives have promoted the use of Integrated Pest Management (IPM), for the sustainable use of pesticides in arable agriculture (EC 2008, 2009). More generally, the Sussex Study dataset, which is the longest running monitoring study of the arable ecosystem in the world, provides detailed insight into the impact of pesticides on the arable flora and fauna. Comparison of data from the Sussex Study with national usage figures (Garthwaite et al. 2006, 2010, 2011, 2013) allows us to gauge how representative the results are likely to be for UK cereal-growing areas as a whole.

2. Materials and Methods

Summary of data

1. This project draws on a long-term monitoring study of the arable ecosystem, the Game and Wildlife Conservation Trust's Sussex Study (1970 - 2012). The Sussex Study covers approximately 62 km^2 of the chalk-based Sussex Downs and collates information on crops, cereal weeds, cereal invertebrates and pesticide use; no effort is made to alter agronomic decisions within the study area, though farmers are kept informed of the findings of research carried out on their land. Farmers have changed but mainly through family succession (i.e. father replaced by son) and management practices have remained similar.
2. Previous reports (Ewald & Aebischer 1999, GCT 2007) examined the effect of pesticide applications on weeds and invertebrates in cereals from the Sussex Study area over 1970 - 2004. This project uses the same methodology to evaluate the impact of changing pesticide usage during the time period 2005-2012.
3. We collated pesticide information from 2005 to 2012, including both foliar applications and seed treatment treatments applied to cereal fields.
4. We divided herbicides, fungicides and insecticides according to their specificity and mode of action:
    - herbicide specificity: grass-weed specific, broadleaf-weed specific, and broad-spectrum.
    - herbicide mode of action: pre-cultivation, contact, residual, and contact + residual.
    - fungicide mode of action: site-specific/non-penetrative and multi-site/penetrative.
    - insecticide mode of action: pyrethroids, non-systemic organophosphates, systemic organophosphates and carbamates (pirimicarb exclusively).
5. We collected information on seed treatments used from 2003 to 2012. Seed treatment was divided into those containing fungicide only and those that also included insecticides. Seed treatments containing insecticides were divided into those that contained neonicotinoids or pyrethroids or a combination of neonicotinoids and pyrethroids.
6. We examined the effects of pesticide use, including seed treatments, on the abundance of six invertebrate taxa and three derived indices important as avian chick-food.
7. Conservation headlands were used in a proportion of these cereal fields each year. We examined the effect of conservation headlands on pesticide use in the remainder of the field.

2.1 Study area

From 1970 to the present day, The Game & Wildlife Conservation Trust has collected data on the invertebrate, plant and avian components of the cereal ecosystem, as well as on arable crop management, from 62 km^2 of farmland on the Sussex Downs in southern England (Aebischer 1991; Ewald & Aebischer 1999; 2000; Potts 1986, 2012; Potts et al. 2010). The study area is situated between the rivers Adur and Arun, the dominant soils are chalk rendzinas with abundant flint, isolated caps of clay on higher parts and post-glacial deposits along the lower parts of a series of 'dry valleys'. The cropping consists of a mix of cereals (winter wheat, spring barley and winter barley) with break crops (oilseed rape, linseed and peas) and some grass leys (established through direct sowing or undersowing). Arable crops were classified into four types: break crops (fodder rape, kale, linseed, maize, oilseed rape, peas, beans and fodder beet), spring cereals (spring barley and spring wheat), winter barley/oats and winter wheat (including bearded wheat), with data collated on changes through time.

No effort is made to influence the management undertaken by the farmers on the study area, although they are kept informed of the results of research carried out on their land and from other GWCT research. The farmers on the Sussex Study area have incorporated agri-environment in their management regimes since the UK instigated schemes to protect and enhance the environment. Beginning in 1987, several farmers entered land into the South Downs Environmentally Sensitive Area Scheme (ESA) which was particularly directed towards supporting extensive grazing, as well as conserving hedgerows and field margins and retaining overwinter stubbles. With the roll out of Environmental Stewardship in 2005, all of the farms signed up to the Entry Level Stewardship (ELS) and subsequently all have now joined the Higher Level Stewardship (HLS). Each farmer has selected options from ELS/HLS that suit their management (Ewald et al. 2012, Potts 2012). Several farmers have chosen to focus on ELS options (and their HLS equivalents) included in the Farmland Bird Package (Winspear et al. 2010) with three farmers using conservation headland options (EF9, EF10, HF9, HF10, HF14), three beetle banks (EF7, HF7) and four wild bird seed mixtures (EF2, EF3, HF2, HF12).

2.2 Data collection

2.2.1 Pesticide data

Detailed data were collected on the application of herbicides (foliar and residual), fungicides (foliar and seed treatment), insecticides (foliar and seed treatment), molluscicides and growth regulators. Information regarding the rate and timing of an application was collected, if available. In most cases, farmers recorded the compounds that they applied to their fields as trade names, not active substances. Information on active substances was obtained from the UK Pesticide Guide (**http://www.plantprotection.co.uk/**), product labels or directly from the manufacturers' website. All available pesticide information was then entered into a GIS (MapInfo Professional 11.0) on a field-by-field basis. Data concerning applications of molluscicides and growth regulators were not extensively or consistently recorded and were excluded from analysis. Information on the use of seed treatments was available on a subset of the dataset, beginning reliably in 2003.

We considered pesticide use coded as both yes/no and as the number of applications.

The timing of pesticide applications was described by two variables, one for each application period, each coded yes/no. The first variable identified autumn/winter applications (post-harvest from the previous year until the end of February). The second variable identified spring/summer applications (beginning of March until the time of invertebrate sampling in June).

Herbicides were divided initially into three groups based on the type of plants that they were effective against, namely dicotyledons (broad-leaved weeds), monocotyledons (grasses) and both classes of plants. They were also divided into four groups reflecting the mode of action and timing of application of the products involved: herbicides applied pre-cultivation (usually very broad-spectrum), those effective only on contact with weeds, residual-acting herbicides, and ones that were effective both on contact and as a residual.

Fungicides were divided on the basis of their activity into two groups, ones that acted on a specific target in the pathogen (site-specific and penetrative) and ones that acted against multiple targets in the pathogen (multi-site and non-penetrative).

Foliar insecticides were divided into four groups, reflecting the chemical class of the active chemicals: pyrethroids, systemic organophosphates, non-systemic organophosphates and carbamates. Pirimicarb was the only compound recorded in the carbamate group, and this group is henceforth referred to as pirimicarb.

Seed treatments were divided into ones that were directed only towards fungal diseases (fungicide only) and ones that contained insecticide as well. The insecticide dressings were subdivided into neonicotinoids, pyrethroids and neonicotinoid and pyrethroid mixes. One farm had not used seed treatments at all, relying on "kept seed" that was tested for disease before drilling from 2003 to 2012. The farmer in this instance commented "Why treat for a problem that does not exist?[1]"

In addition to pesticide use in the current year, within each field, information concerning pesticide use and crop type in the previous year was extracted. This allowed for the analysis of a "carry-over" effect.

2.2.2 National Pesticide data

Data on national pesticide use on arable crops from 2006 to 2012 is published in a series of Pesticide Usage Survey reports (Garthwaite et al. 2006, 2010, 2011, 2013), providing data grouped by crop type for Great Britain (2006, 2010) and UK (2011, 2013). We followed Davis *et al.* (1993) and Garthwaite *et al.* (1995) in using the "percentage of area treated with pesticides in any one year" as the total cropped hectarage treated divided by the total cropped hectarage, multiplied by 100. We also calculated the spray area, which takes into account the number of times a field is treated with a pesticide (if a field is treated twice then its spray area is twice the area of the field). This value is then transformed to percentage spray area by dividing total spray area by total cropped area and multiplying by 100. The corresponding figures for the Sussex Study were calculated by summing, for all cropped fields, the number of pesticide applications in a field multiplied by the cropped area of that field, dividing this figure by the total cropped area, then multiplying by 100 to give a percentage.

We used both the national percentage area of crops treated with pesticides and the national percentage spray area for comparison with figures from Sussex. The average number of applications per treated field was also included in the analysis, as a measure of intensity of pesticide use.

[1] No information is available on crop failures or yields within the Sussex Study dataset. Using paired t-tests, to compare the use of pesticides on this farm to the remainder of the Sussex Study area from 2003 to 2012, the proportion of arable cropping on this farm treated with herbicides (t_9 = 0.68, P = 0.511) and fungicides (t_9 = 0.82, P = 0.435) was equal to that across the remainder of the study area while the proportion treated with insecticides was lower (t_9 = -2.33, P = 0.045). Fewer applications of herbicides were used on this farm, compared to the remainder of the study area, when they were used – i.e. the intensity of herbicide treatment was lower (t_9 = -3.70, P = 0.005) but the numbers of fungicide (t_9 = -1.25, P =0.244) and insecticide applications used were similar to the rest of the study area (t_3 = -12.23, P = 0.001).

Weighted averages were calculated from the national figures, based on the annual crop composition in the Sussex Study area, to ensure that all comparisons between the two datasets were consistent. The 'Other' category of seed treatments in the national reports contained a wide range of active substances, including both fungicide and insecticides; this forced us to either knowingly over- or under-inflate the area treated with each type of seed treatment. We elected to include the 'Other' category with both insecticide and fungicides in our calculation of weighted national figures, reasoning that including these 'Other' seed treatments would provide a 'worst case' national estimate to compare with Sussex.

2.2.3 Invertebrates

The Sussex Study dataset contains information on the abundance of cereal invertebrates in approximately 100 cereal fields per year from 1970 to 2012. Efforts were made to sample every cereal field across the study area each year. Samples were collected in the third week of June using a Dietrick vacuum suction trap (D-Vac, Dietrick 1961) to take five ten-second sub-samples, each of 0.092 m^2, along a diagonal transect into the field. The method of sampling needs to be considered when thinking about the results of this analysis. D-vac suction sampling is known to sample invertebrates in the vegetation itself, with pitfall traps more useful for ground-dwelling and larger bodied invertebrates, particularly beetles (Sunderland et al., 1995). D-vac sampling allows for efficient sampling on a limited budget with a short time period available for sampling. An emphasis on continuity of methods and changes in invertebrate abundance is the key to extensive studies across several years, such as the Sussex Study.

The invertebrate groups chosen for analysis were ones that figured prominently in the diet of farmland birds, especially at the chick stage. They included five from the first pesticide report (E & A 1999), where taxa had been grouped according to five broad taxonomic categories:

- **Araneae** & **Opiliones** (all sizes of spiders and harvestman)
- **Carabidae** & **Elateridae** (adults of ground and click beetles)
- **Symphyta** & **Lepidoptera** (adults, larvae and shed skins of sawflies, butterflies and moths)

- **Chrysomelidae** & **Curculionidae** (adults and larvae of leaf beetles and weevils)

- **Non-aphid Hemiptera** (adults and nymphs of plant bugs/hoppers, excluding aphids)

Another four were ones considered additionally in the second report (GCT 2007) and are included here:

- **Aphididae** (adults & nymphs of aphids)

- **Grey partridge chick food index (CFI)** = 0.00614* plant bugs/hoppers (adults & larvae) + 0.0832* leaf beetles & weevils (adults & larvae) + 0.000368* aphids (adults & larvae) + 0.1199* caterpillars – Symphyta & Lepidoptera (adults & larvae) & Neuroptera+ 0.1411* ground & click beetles (adults) (Potts & Aebischer 1991).

- Corn bunting *Milaria calandra* four-food index (4FI) = harvestmen (all sizes) + caterpillars (as above) + Orthoptera (grasshoppers & crickets – all sizes) (Brickle et al. 2000).

- Yellowhammer *Emberzia citrinella* index (YHI) = spiders (all sizes) + Tipulidae (crane flies - adults) + Coleoptera (beetles in general - adults) + plant bugs/hoppers (adults & larvae) + aphids (adults & larvae) + butterfly & moth caterpillars (Stoate et al. 1998, Moreby & Stoate 2001).

2.3 Statistical Analysis

2.3.1 Trend in pesticide use

The analysis was carried out on annual values calculated across the study area. For herbicides, fungicides and insecticides we used linear regression to investigate trends over time in the annual percentage of cropped area treated with pesticides (transformed to radian angles), annual percentage spray area (ln(x+1)-transformed), annual number of pesticide treatments per treated field (ln(x+1)-transformed). Trends were examined for the recent period 2005 to 2012 and the full period 1970 to 2012. We tested for a linear and quadratic effect of year and also fitted a generalised additive model (GAM) of year with five degrees of freedom (one for every decade of data available). In order to select the model that best fit the trends through time, but which avoided over-fitting the data, we used an additional sum-of-squares F test to compare the relative difference in the sums of squares divided by the relative difference in degrees of freedom between the nested models. The best fitting trend was that which significantly fit the data but was the simplest in terms of minimising the degrees of freedom in the regression parameters. We present only the results that best fitted the long-term trend. We used linear regression in the same way to investigate trends in the percentage of cereal area treated with herbicides and insecticides (transformed to angles) according to the timing of applications.

We compared changes in the use of different types of herbicides (effective against dicotyledons, monocotyledons and broad-spectrum or pre-cultivation, contact, residual and contact & residual herbicides) as a percentage of the cereal area where herbicides were used, using the same method. Similarly, trends in groups of fungicide and insecticide by chemical activity as the percentage of the cereal area receiving, fungicide or insecticide respectively were also examined this way. We compared area treated to the area where pesticides were used in order to compare trends in the use of different types of pesticides, when a farmer had made the decision to use a pesticide.

We also used linear regression to examine the trend in use of seed treatments for the Sussex Study area (overall and by dressing type) using annual percentage cropped area treated (transformed to angles) from 2003 to 2012. Because of the short run of years, we considered only a linear relationships with time for the seed treatments.

2.3.2 Use of foliar pesticide sprays in relation to use of neonicotinoid seed treatments

This analysis was carried out at the level of individual fields. We examined each of the five crop groups (spring cereal, winter wheat, winter barley/oats, autumn sown break crops and spring sown break crops) separately, as each have different insecticide treatment requirements and grouping them together would not produce interpretable results. For break crop groups we not only analysed these as a group but also considered different specific crops (oilseed rape, winter beans in the case of autumn break crops and oilseed rape, fodder beet, peas and linseed in the case of spring break crops) due to the differences in management between them. We considered foliar herbicide and insecticide treatments in autumn and spring separately, coded as a binary variable (0 = no foliar pesticides; 1 = foliar pesticide applied to the field). This was analysed using chi-square analysis (with Yates' correction), where at least half of the expected values in a two by two contingency table were five or greater, to avoid problems with small sample sizes.

2.3.3 Agri-environment Schemes (AES) and pesticide use

General linear models were used to compare the area treated with herbicides, fungicides and insecticides (as well as seed treatments where available), the total spray area treated with each type of application and the number of applications on fields with AES options, i.e. conservation headlands, to those without these options, controlling for crop and year of study. For each measure of pesticide use we first tested for an interaction *between* crops in the use of pesticides on fields with conservation headlands versus those without conservation headlands. If a significant interaction was found we examined each crop separately, testing whether fields with conservation headlands differed from fields without conservation headlands in their foliar/residual pesticide use and in the seed treatments used. If no significant interaction was identified then the analysis considered all crops together, again testing to see if having a conservation headland on the field edge influenced the decision to use pesticides in the middle of the field.

2.3.4 Trends in invertebrate abundance

The analysis was carried out on the annual mean number of invertebrates, and included samples across the study area. We used generalized linear models with Poisson error distribution and logarithmic link function, corrected for over-dispersion and weighted by the sample size, to investigate trends over time in the average annual abundance of each of the invertebrate groups. We tested for a linear and quadratic effect of year and also fitted a generalised additive model (GAM) of year with five degrees of freedom (one for every decade of data available). We presented the trend that best fitted the long-term trend, again selected using an extra sum-of-squares F test to select the most parsimonious model in terms of minimising the degrees of freedom in the regression parameters.

2.3.5 Invertebrate abundance in relation to pesticide use

The analysis was carried out at the level of individual fields. It sought to identify pesticide treatments that were associated with significant changes in invertebrate abundance, after accounting for crop and year effects. It also checked whether any relationships changed between the two time periods (1970 - 2004 v. 2005 - 2012) by testing the interaction between period and the pesticide variable. Pesticide treatment (coded as yes/no), the effect of multiple applications of pesticides and the timing of application of pesticides were all investigated in this manner. From 2005 to 2012, 91 locations where invertebrates were sampled were not treated with herbicides, owing to the presence of conservation headlands. This allowed us to include herbicide treatment (yes/no) as a factor for this time period in the analysis. The uses of herbicide, fungicide and insecticide were examined simultaneously so that any detected effect took into account the use of other pesticides. For a given invertebrate group, the number in each sample was ln(x+1)-transformed before analysis in order to normalise the distribution and stabilise the variance. Invertebrate abundance was related to the different groups of herbicides, fungicides and insecticides using general linear modelling. When testing for differences between groups of a particular pesticide type, e.g. insecticide, the effects of the other two pesticide types (e.g. herbicide and fungicide) were accounted for by including two binary variables (coded yes/no) according to each one's use.

The relationship between invertebrate abundance and pesticide use in the previous year was examined using general linear modelling. In this analysis the effect of, in turn, herbicides, fungicides and insecticides in the current year, together with the effects of crop and year, were taken into account along with the crop of the previous year.

The results of the analyses of invertebrate abundances were expressed as the percentage difference in adjusted mean density between treated and untreated fields relative to the mean density in untreated fields. In practice it was calculated by exponentiating the regression coefficient of the treatment factor, subtracting one and multiplying by 100.

To evaluate the effects of seed treatment on invertebrate abundance, the dataset was restricted to fields for which seed treatment information was available. The previous analyses were rerun, with the presence/absence of seed treatment, and seed treatment groups, as additional factors.

2.3.6 Interpretation of statistical significance

Because multiple tests were undertaken in the analyses, the likelihood of finding a significant difference solely by chance at the 0.05% level of significance is one in twenty. The more tests are performed, the higher is the likelihood of finding such a difference by chance. This should always be borne in mind when interpreting the results. Generally speaking, we tended to disregard significance levels between 0.05 and 0.01, but considered that where $P < 0.01$ the null hypothesis was reliably rejected. As well as examining the significance levels for individual taxa, we gave consideration to the overall pattern of effects across all taxa, whether or not statistically significant.

3. Results

Summary of Pesticide Use Patterns

1. Since the last analysis of the Sussex Study pesticide applications the proportion of the Sussex Study planted to break crops and spring cereals has increased from 2005, particularly so with the loss of set aside in 2008. Winter cereals, which expanded in area from the 1980s, have declined.
2. Pesticide use was measured as the percentage of arable crop area treated with herbicide, fungicides or insecticides, with intensity of their use measured as percentage spray area and as number of treatments per field. Across the whole of the Sussex Study (1970 - 2012), all measures of pesticide use increased. There was no significant change in any measure between 2005 and 2012, indicating that the early intensification in pesticide inputs in Sussex has stabilised.
3. Herbicide use (percent area treated) in Sussex from 1970 to 2012 matched that across the UK but was less intense (measured as percentage spray area) than nationally. Autumn applications of foliar herbicide have stabilised since 1990. In Sussex after the mid-1990s the use of foliar herbicides in the spring increased, and remained steadily high between 2005 and 2012.
4. The use of broadleaf- and grass-specific herbicides increased after the mid-1990s, before stabilising in the latter part of the study. Broad-spectrum herbicide use increased until the 1990s and has stabilised since then.
5. Pre-cultivation and contact & residual herbicides both increased in usage between 1970 and 2012. Contact herbicide use declined from 1970 to 1990, before steadily increasing and becoming almost uniformly applied by the late 2000s. Residual herbicide use increased from 1970 to the late 1990s, before levelling off.
6. Fungicide use (percent area treated) in Sussex from 1970 to 2012 matched that across the UK, whereas the intensity of fungicide use was lower than nationally.
7. The use of different types of site-specific foliar fungicides did not change over the duration of the study, while the use of multi-site foliar fungicides increased linearly between 1970 and 2012.
8. Insecticide use and intensity were equal to national figures. Autumn applications of foliar insecticide declined slightly over the last ten years, which could be a consequence of the move away from autumn sown crops to spring sown varieties. Spring foliar insecticide treatments increased between 1970 and 2012 across the study area.
9. Pyrethroid insecticides have been used at consistently high levels since the early 1980s. Non-systemic foliar organophosphates showed a significant increase between 1970 and 2012, while systemic foliar organophosphates declined from 1970 onwards; they were last used on the study area in 2004.
10. Data covering the use of seed treatments was available from 2003 to 2012. The use of fungicide based seed treatment was 28% higher across the Sussex Study than nationally. There was an increase in the use of insecticide seed treatments on Sussex, with the same trend present in the national figures; insecticide seed treatment use in Sussex matched national figures.
11. Neonicotinoid seed treatments were used on winter cereals and break crops in Sussex from 2003, with 20% of spring cereals treated with pyrethroid-based seed treatments from 2005 onwards.
12. Winter cereals treated with neonicotinoid seed treatments were more likely to be treated with either foliar herbicides or foliar insecticides in the autumn/winter. Winter break crops treated with neonicotinoid seed treatments were as likely as crops not treated with these types of seed treatments to receive either a foliar herbicide or a foliar insecticide treatment in the autumn/winter. Fields of autumn-sown oilseed rape treated with neonicotinoid seed

treatment were less likely to be treated with autumn foliar insecticide than crops without neonicotinoid seed treatment but more likely to be treated with either a foliar herbicide or a foliar insecticide in the spring. Spring-sown oilseed rape crops treated with neonicotinoid seed treatments were more likely to receive a foliar herbicide application in the spring/summer than spring oilseed rape crops without these seed treatments.

13. Several farms within the study have undertaken management through the Higher Level Scheme (HLS, NE 2013b), including the use of conservation headlands, with limited foliar pesticide applications on cereal headlands. We compared in-field foliar pesticide applications (percentage fields treated, percentage spray area and number of treatments) and seed treatment use between conservation headland fields and non-conservation headland fields. There were no differences in fields with or without conservation headlands in the proportion that received foliar herbicide or fungicide treatments. Fields of winter cereal with conservation headlands were more likely to be treated with foliar insecticides. The intensity of herbicide and fungicide applications (measured both as percentage spray area and number of treatments) were lower on fields with conservation headlands. The percentage spray area of insecticides was higher on winter cereals with conservation headlands than fields without conservation headlands but there was no difference in the number of treatments. The use of neonicotinoid seed treatments was more common on winter cereals that had conservation headlands.

3.1 Trends in cropping

The main change in the composition of crops grown in Sussex since 1970 has been the increase in winter wheat from the 1980s until 2005, with an increase in spring cereals since then and a subsequent decline in winter wheat (Figure 1). Set-aside was an important component of the area until it was abolished in 2008, and there was an early shift from rotational grass to non-rotational grass in the late 1980s coinciding with the Environmentally Sensitive Area scheme. The area of break crops sown has steadily increased following the abolition of set-aside in 2008.

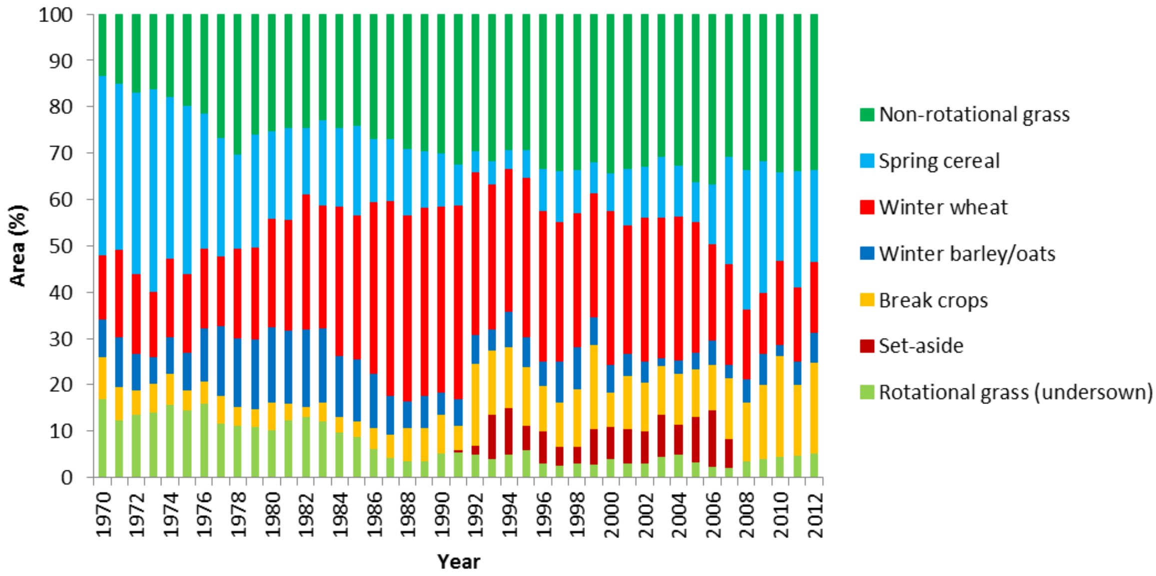

Figure 1. Changes in cropping through time on the Sussex Study area as percentage area per crop from 1970 – 2012.

3.2 Trends in pesticide use

3.2.1 Trends in foliar herbicide use

Overall, from 1970 to 2012, the percentage area treated with herbicide increased significantly ($F_{1,41}$ = 27.01, $P < 0.001$, Figure 2). There were no significant changes in percentage treated area between 2005 and 2012 for herbicide across the arable area ($F_{1,6}$ = 0.20, P = 0.672). When compared with the national figures there was no difference between percentage area treated with herbicides (t_{14} = -0.04, P = 0.967). Percentage spray area showed the same pattern as treated area, with significant increases in herbicide use between 1970 and 2012 ($F_{1,41}$ = 257.60, $P < 0.001$). There was no significant change in the percentage spray area of herbicide between 2005 and 2012 ($F_{1,6}$ = 0.99, P = 0.357). Despite the increase, herbicide percentage spray area was *lower* on average compared with the national trend (25% lower) (t_{15} = -6.33, $P < 0.001$). Overall, the number of applications of herbicide increased significantly between 1970 and 2012 ($F_{1,41}$ = 363.50, $P < 0.001$). There was no significant change in the number of applications of herbicide between 2005 and 2012 ($F_{1,6}$ =0.80, P = 0.406).

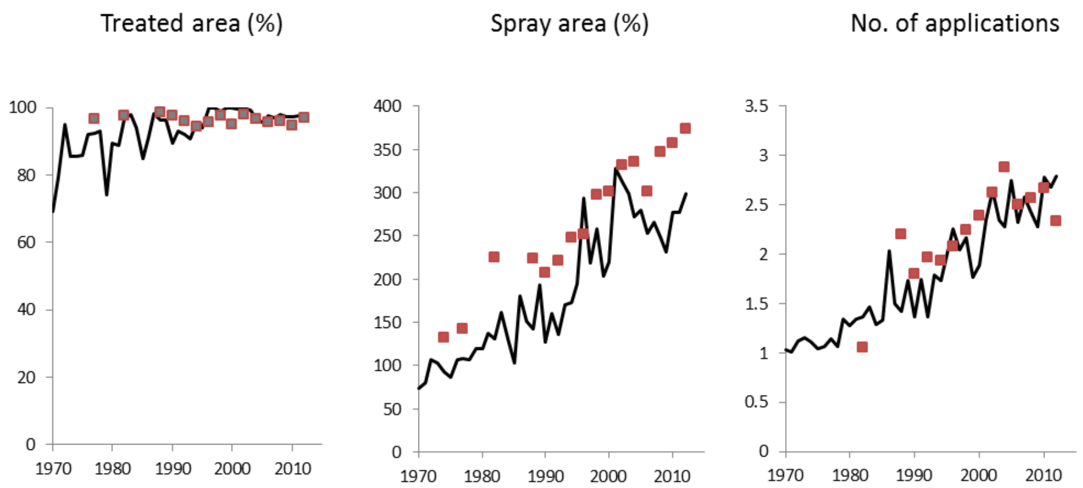

Figure 2. Long term trend in foliar herbicide usage in arable crops on the Sussex Study area (black line) and national figures (red squares). National figures are adjusted to reflect the cropping composition on the Sussex Study area. The treated area percentage of herbicide increased from 1970 to 2012 ($F_{1,41}$ = 27.01, P < 0.001).The spray area percentage of herbicide increased from 1970 to 2012 ($F_{1,41}$ = 67.53, P < 0.001). The number of treatments of herbicide also increased significantly between 1970 and 2012 ($F_{1,41}$ = 363.50, P < 0.001).

We examined trends in the timing of herbicide application on cereals (Figure 3). Herbicide applications in the autumn/winter increased through the 1970s to the 1990s, and have stabilised since then ($F_{2,40}$ = 29.40, P < 0.001) at, on average, 61% of the cereal area. The percentage of the cereal area treated with spring/summer herbicide treatment was high at the beginning of the Sussex Study, with an average of 89% of the cereal area receiving herbicide treatment between 1970 and 1985. Use declined from 1986 to 1996 to an average of 61% of the area treated, increased to 87% from 1996 to 2000 and has subsequently increased again to an average of 90% of the study area treated since 2000.

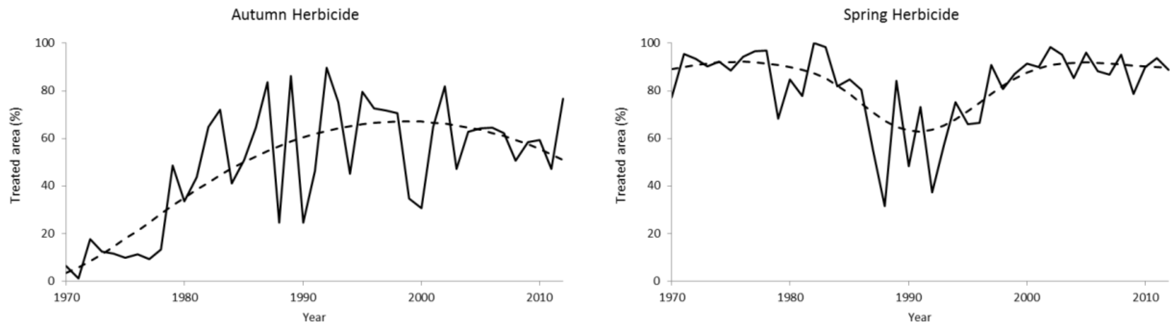

Figure 3. Trends through time in the timing of herbicide application. Autumn herbicide ($F_{2,40}$ = 29.40, *P* < 0.001) increased from 1970 to the mid-1990s, before decreasing from then on. Spring herbicide ($F_{5,37}$= 8.05, *P* < 0.001) usage declined from 1970 to 1990, before increasing and returning to the high values seen at the start of the study.

We split herbicide treatments into groups based on specificity and groups based on mode of action (Figure 4). The use of dicot–specific herbicides was high in 1970, but declined steadily through to the early-1990s. Usage then increased until the early-2000's, with the treated area percentage similar to those seen at the start of the study. More recently the use of dicot-specific herbicides has started to decline. Monocot–specific herbicides were rarely used until the 1990s, averaging 3% of the area treated with herbicides before 1990, but their use became more widespread since 2000, with an average of 60% of the area treated with herbicides since then receiving at least one application of these compounds. The use of broad-spectrum herbicides increased until the beginning of the 1990s; they have been used on an average of 74% of the area treated with herbicides since 1991.

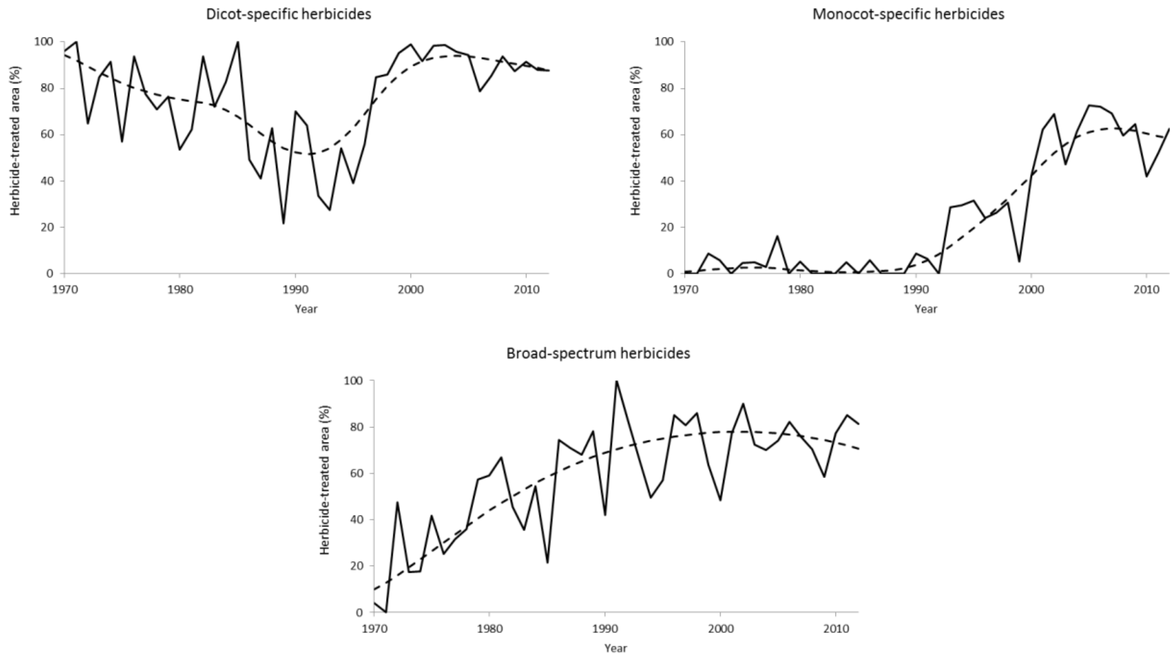

Figure 4. Trends through time in the type of herbicide used, grouped by specificity. Dicot-specific herbicide use declined from 1970 to 1990 but then steadily increased from 1990 to 2012 returning to levels similar to those in 1970 ($F_{5,37}$ = 8.53, P < 0.001). Overall, from 1970 to 2012, there has been an increase in the use of monocot-specific ($F_{5,37}$ = 42.35, P < 0.001), with a sharp increase during the 1990s and early 2000s, before stabilising during the latter part of the 2000s. Broad-spectrum herbicide usage increased from 1970 through the 1990s, before stabilising and then declining slightly in the late 2000s ($F_{2,40}$ = 31.10, P < 0.001).

Considering herbicides grouped by mode of action (Figure 5), the use of pre-cultivation herbicides has increased, with some year-to-year fluctuations; over the last five years (2008-2012) 38% of the area treated with herbicides received this type of herbicide. Although contact-acting herbicides were commonly used at the beginning of the Sussex Study (average 90% of the cereal area treated with herbicides from 1970 to 1974) their use declined until 1992, when only 28% of the area treated received this type of herbicide, with use expanding since then to an average of 94% over the past ten years. Residual-acting herbicide use increased throughout the first two decades of the Sussex Study, with use levelling off in the latter part of the study, averaging 68% of the area treated over the last two decades. Herbicides that have both a contact & residual action have increased in use throughout the study, with large year-to-year variation. Use of contact & residual-acting herbicides was particularly high from 2001 to 2004 with an average 57% of the area treated with this type of herbicide.

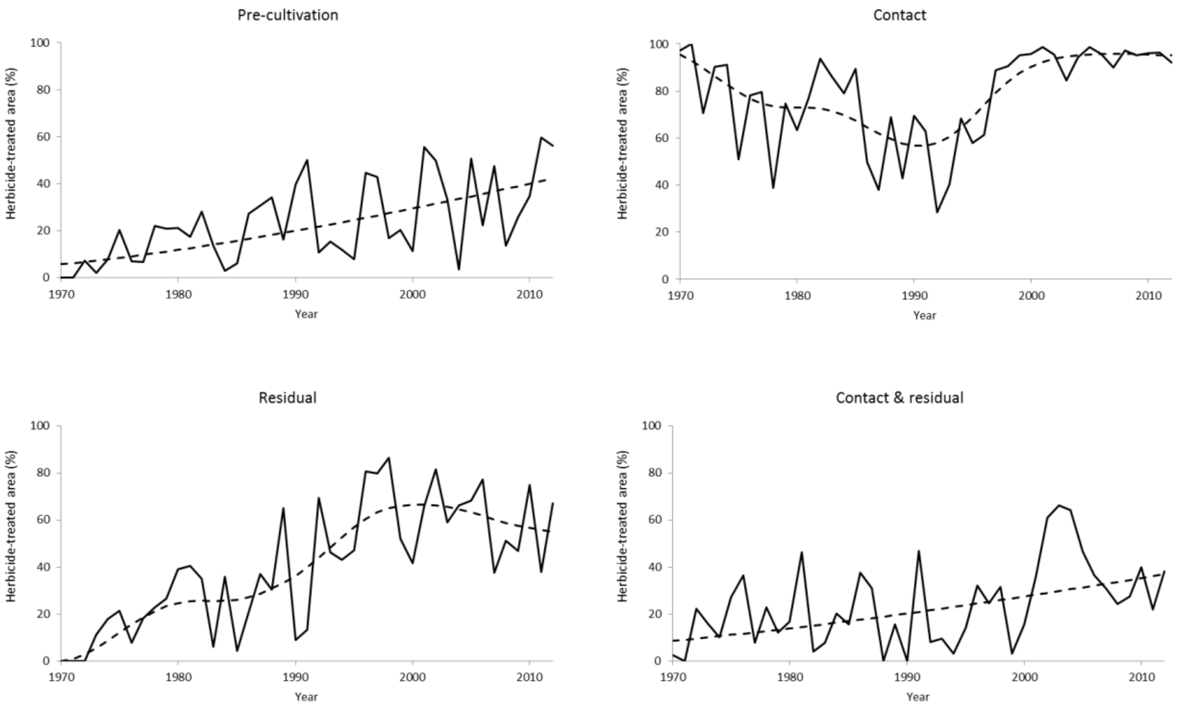

Figure 5. Trends through time in the type of the herbicide used, grouped by mode of action. Each mode of action showed a significant increase in usage between 1970 and 2012: pre-cultivation ($F_{1,41}$ = 25.04, P < 0.001) and contact & residual ($F_{1,41}$ = 10.39, P = 0.002) herbicides both showed a linear increase across the whole time period. Contact herbicide use declined from 1970 to 1990, before steadily increasing and becoming almost uniformly applied by the late 2000s ($F_{5,37}$ = 12.29, P < 0.001). Residual herbicide use increased from 1970 to the late 1990s, before declining slightly throughout the 2000s ($F_{5,37}$ = 17.96, P < 0.001).

3.2.2 Trends in foliar fungicide use

Overall, from 1970 to 2012, the percentage area treated with fungicide increased significantly ($F_{1,41}$ = 79.79, P < 0.001, Figure 6). There were no significant changes in percentage treated area between 2005 and 2012 for fungicide ($F_{1,6}$ = 1.33, P = 0.291) and when compared with the national figures there was no difference between percentage area treated with fungicides on the Sussex Study area (t_{14} = 0.75, P = 0.478). Percentage spray area showed the same pattern as seen for treated area, with significant increase between 1970 and 2012 for fungicide ($F_{1,41}$ = 60.60, P < 0.001). Fungicide percentage spray area was significantly lower on the Sussex Study area than the crop weighted national figures (27% less on Sussex, t_{15} = -3.80, P = 0.002). There were no significant change in the percentage spray area of fungicide between 2005 and 2012 ($F_{1,6}$ = 0.57, P = 0.478). Over the long-term the number of applications of fungicide increased significantly between 1970 and 2012 (fungicide $F_{1,41}$ = 125.60, P < 0.001), but there were no significant change in the number of applications of fungicide between 2005 and 2012 ($F_{1,6}$ = 0.42, P = 0.541). The number of fungicide treatments on the Sussex Study area was 9% lower than the weighted national values (t_{13} = -2.53, P = 0.025).

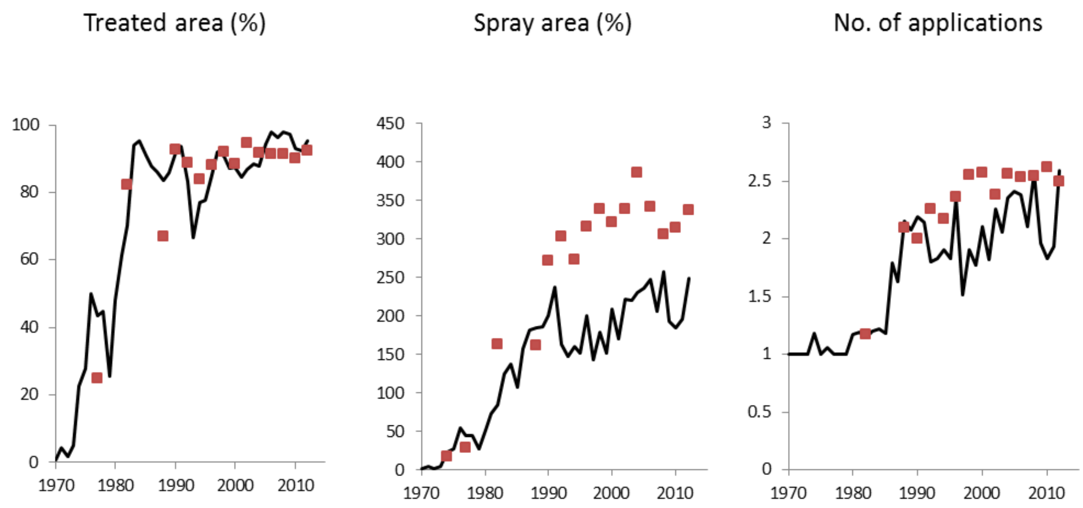

Figure 6. Long term trend in foliar fungicide usage in arable crops on the Sussex Study area (black line) and national figures (red squares). National figures are adjusted to reflect the cropping composition on the Sussex Study area. The treated area percentage of fungicide increased from 1970 to 2012 ($F_{1,41}$ = 79.79, P < 0.001).The spray area percentage of fungicide increased from 1970 to 2012 ($F_{1,41}$ = 257.60, P < 0.001). The number of treatments of fungicide also increased significantly between 1970 and 2012 ($F_{1,41}$ = 126.60, P < 0.001).

Foliar fungicide use on the Sussex Study area took place in the spring/summer, so no analysis could be undertaken on timing of applications. We looked at the use of different types of fungicide on the area where fungicides were applied. Site-specific foliar fungicide use was nearly universal across the area where fungicides were used, particularly from the mid-1990s. Multi-site specific foliar fungicide use showed wide year-to-year variation but increased overall (Figure 7).

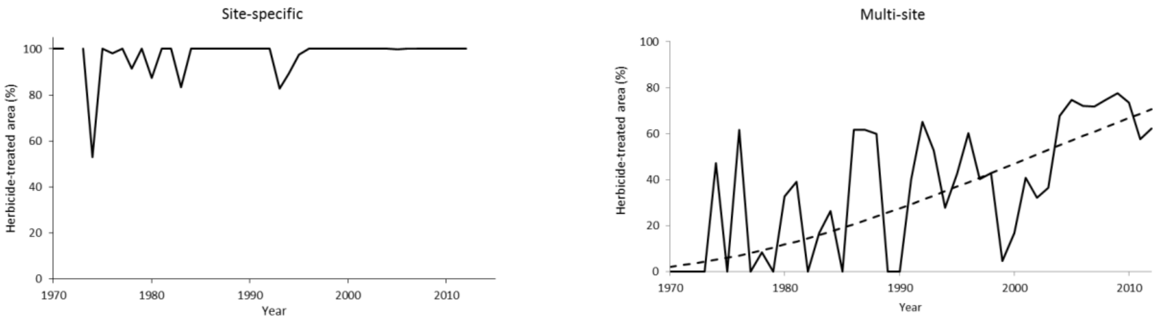

Figure 7. Trends through time in the type of fungicide used. There was no trend in use of site-specific fungicides from 1970 to 2012 ($F_{1,40}$ = 3.80, P = 0.058), while multi-site fungicides showed a significant linear increase ($F_{1,40}$ = 29.45, P < 0.001).

3.2.3 Trends in foliar insecticide use

Overall, from 1970 to 2012, the percentage area treated with insecticide increased significantly ($F_{1,41}$ = 55.99, P < 0.001, Figure 8). There were no significant changes in percentage treated area between 2005 and 2012 for insecticide ($F_{1,6}$ = 0.36, P = 0.572). When compared with the national figures there was no difference between percentage area treated with insecticide on the Sussex Study area (t_{14} = 0.04, P = 0.967. Percentage spray area showed the same pattern as seen for treated area with significant increase between 1970 and 2012 for insecticide ($F_{1,41}$ = 67.53, P < 0.001) and there was again no significant difference between insecticide percentage spray on the Sussex Study area when compared with the national trend (t_{15} = 0.70, P= 0.494). There were no significant change in the percentage spray area of insecticide between 2005 and 2012 ($F_{1,6}$ = 0.14, P = 0.717). Over the long-term the number of applications of insecticide increased significantly between 1970 and 2012 ($F_{1,41}$ = 23.88, P < 0.001) and there were no significant change in the number of applications of insecticide between 2005 and 2012 ($F_{1,6}$ = 2.39, P = 0.173). There was no significant difference in number of insecticide treatments between the Sussex Study area and the national figures (t_{13} = -1.60, P = 0.133).

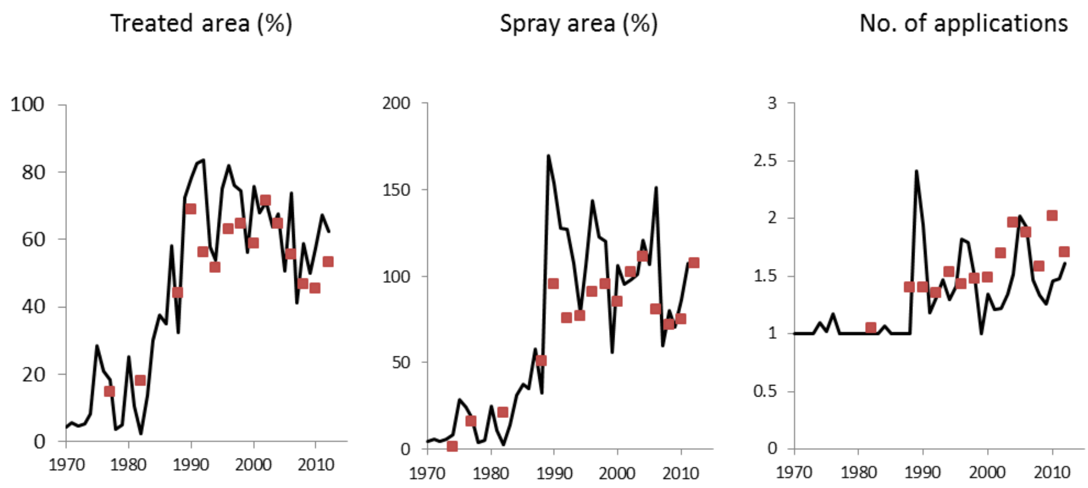

Figure 8. Long term trend in foliar insecticide usage in arable crops on the Sussex Study area (black line) and national figures (red squares). National figures are adjusted to reflect the cropping composition on the Sussex Study area. The treated area percentage of insecticide increased from 1970 to 2012 ($F_{1,41}$ = 55.99, $P < 0.001$).The spray area percentage of insecticide increased from 1970 to 2012 ($F_{1,41}$ = 60.60, $P < 0.001$). The number of treatments of insecticide also increased significantly between 1970 and 2012 ($F_{1,41}$ = 23.88, $P < 0.001$).

We examined trends in the timing of foliar insecticide application on cereals (Figure 9). Across the Sussex Study area, insecticide use has been undertaken predominately in the autumn/winter. Although there were sporadic instances of autumn/winter use in the 1970s, insecticide use in the autumn/winter began in earnest in the mid-1980s. Through the late 1980s and the 1990s, although there were large year-to-year variations, an average of 56% of the cereal area was treated with insecticides in autumn/winter, followed by a slight decline to an average of 47% of cereal area treated in the last ten years. On discussion with the farmers, applications at this time of the year were made to limit the spread of Barley Yellow Dwarf Virus (BYDV) by controlling the aphid hosts of the virus. Spring/summer insecticide use was sporadic in cereals on the Sussex Study area until the later part of the 1980s, when it peaked at an average of 44% of cereal fields treated from 1988 to 1990. Thereafter insecticide applications in spring/summer in cereal crops have shown large year-to-year variations; they have averaged 18% of the cereal area, and never exceeded 41%.

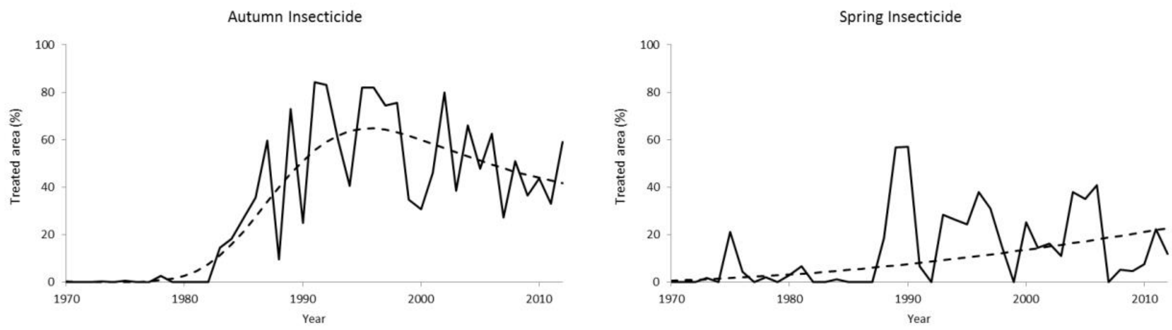

Figure 9. Trends through time in timing of insecticide application. Autumn insecticide use ($F_{5,37}$ = 35.50, $P < 0.001$) increased from 1970 to the mid-1990s, before decreasing from then on. Spring insecticide increased from 1970 to 2012 ($F_{1,41}$= 11.51, $P = 0.002$).

Foliar insecticide use on the Sussex Study was dominated by pyrethroids since they were first used in 1984, with 91% of the area treated with foliar insecticides each year receiving at least one application of this type of insecticide since then (Figure 10). Pirimicarb use has been sporadic throughout the 43 years where information is available and was last reported used in 2010. Non-systemic organophosphate was first used in 1984 then showed large year-to-year variation, with the last large-scale use occurring in 2010; on average since then 10% of the area treated with foliar insecticides has received non-systemic organophosphates. Systemic organophosphates were last used in 2004 on the Sussex Study area.

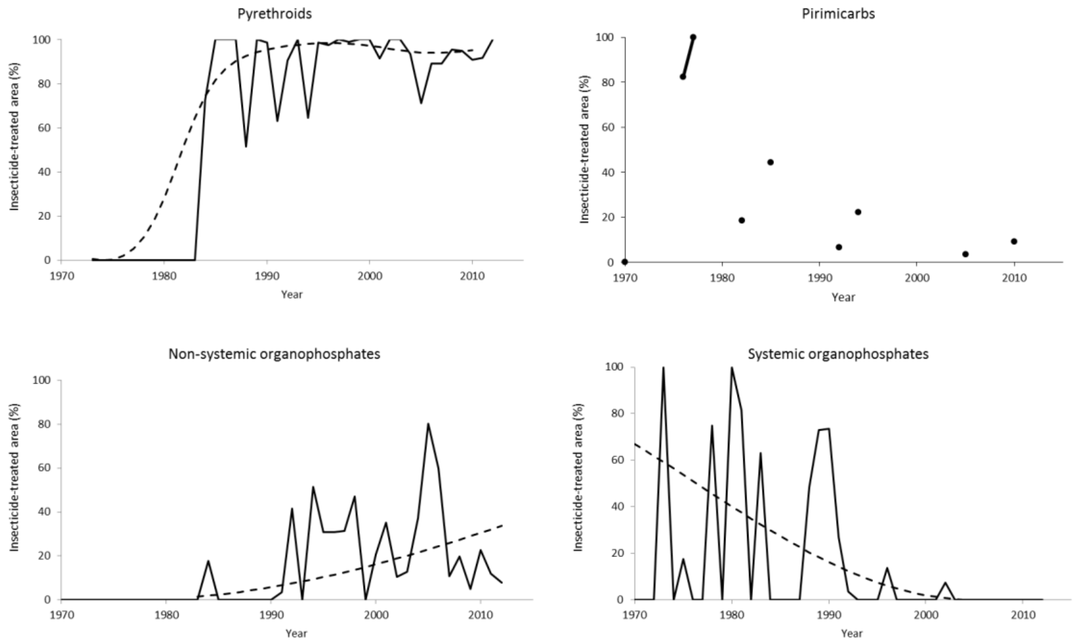

Figure 10. Trends through time in the type of foliar insecticide used. Pyrethroid insecticides showed a significant increase from no use between 1970 and the mid-1980s, and were used at consistently high levels since then ($F_{5,30}$ = 22.95, $P < 0.001$). Non-systemic organophosphates showed a significant increase between 1970 and 2012 ($F_{1,35}$ = 18.89, $P < 0.001$). Systemic organophosphates showed a significant decrease over the same time period ($F_{1,35}$ = 21.74, $P < 0.001$).

3.2.4 Trends in use of seed treatment

The area where seed treated with fungicide only had been used was 28% higher on average on the study area than the weighted national figures (t_4 = 7.81, P = 0.001), but with no significant change on the study area between 2003 and 2012 ($F_{1,8}$ = 1.30, P = 0.287, Figure 11). There was a significant increase in insecticide seed treatments from 2003 to 2012 ($F_{1,8}$ = 10.79, P = 0.011) and no significant difference between the Sussex figures and the national trend (t_4 = 0.97, P = 0.385, Figure 11).

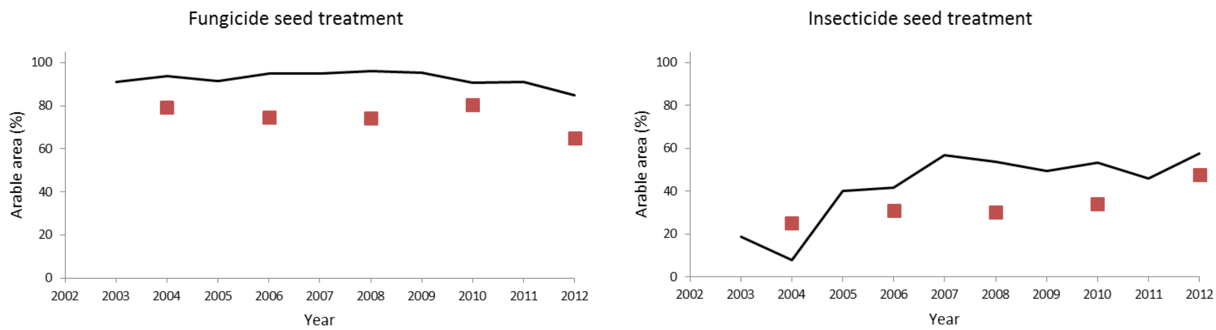

Figure 11. Long-term trend in use of dressed seed in arable crops on the Sussex Study area (black line) and national figures (red squares). National figures are adjusted to reflect the cropping

composition on the Sussex Study area. Use of fungicide-only seed remained steady between 2003 and 2012 with no significant change in area ($F_{1,8}$ = 1.30, P = 0.287). Use of insecticide seed treatment increased significantly in area from 2003 to 2012 ($F_{1,8}$ = 10.79, P = 0.011).

3.3 Foliar pesticide use following insecticidal seed treatment

The use of neonicotinoids differed between the four crop types, with very few spring cereal crops treated with these types of seed treatments (Figure 12). Each crop type was considered separately in the analysis of pesticide use following neonicotinoid seed treatments (we split the break crops into those sown in autumn and those sown in spring to make it easier to take into account the timing of foliar insecticides and then into each main break crop).

Autumn foliar herbicide use following planting was more common in those winter wheat and winter barley/oats crops that were treated with neonicotinoid seed treatments, but there was no significant difference in the use of herbicides at this time in autumn break crops (Table 1). There was no difference in the use of spring/summer applied herbicides in spring cereals, winter wheat or winter barly/oats depending on the use of neonicotinoid seed treatments. In 96.2% of autumn sown break crops treated with neonicotinoid seed treatments (all winter oilseed rape), spring/summer herbicides were used, compared to only 61.5% of those break crops not treated with neonicoitinoid seed treatments. Spring sown oilseed rape crops also showed a similar pattern, with all those crops that were treated with neonicotinoid seed treatments receiving a spring/summer herbicide after sowing while only 55.6% of those not treated with neonicotinoid seed treatment received a spring/summer herbicide application.

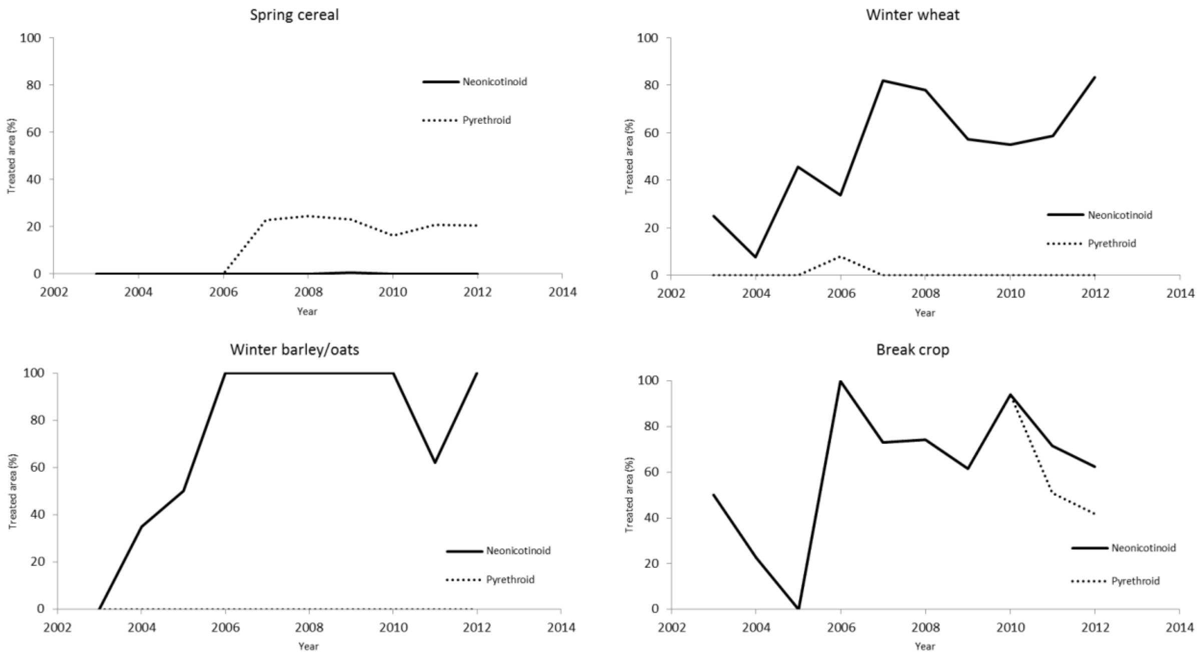

Figure 12. Trends in the percentage area of each crop type treated with insecticide seed treatments, separated by crop type. Spring cereals were treated with pyrethroid seed treatments when insecticidal dressings were used, winter wheat and winter barley/oats were treated with neonicotinoids and break crops were treated with both neonicotinoid and pyrethroid seed treatments.

The use of neonicotinoid seed treatments was associated with an increased use of fungicides in spring oilseed rape crops, 85.7% of those fields treated with neonicotinoid seed treatments were treated with fungicides, while no fields of spring-sown oilseed rape without neonicotinoid seed treatments received a fungicide treatment (Table 2). There were no other differences in fungicide use in all other crops considered, based on the use of neonicotinoid seed treatment.

For winter wheat the percentage of fields treated with foliar insecticide in the autumn (Table 3) was significantly higher where neonicotinoid seed treatments were used with 82.6% of fields where neonicotinoid seed treatments were used treated with foliar insecticides in the autumn while only 62.8% of fields without neonicotinoids received an autumn application of foliar insecticides. For winter barley/oats, the percentage of fields treated with foliar insecticide (93.1%) was higher on fields with neonicotinoid seed treatments than on fields without neonicotinoid seed treatment (20.0%). In the case of autumn-sown break crops overall there was no difference in autumn insecticide use depending on neonicotinoid seed treatments. However when autumn-sown oilseed rape was considered separately, all of the fields without neonicotinoid seed treatment were treated with foliar insecticides in the autumn, while only 52% of the fields with neonicotinoid seed treatment were treated with insecticides at that time.

There was no significant difference in the percentage of fields treated with spring foliar insecticide applications in spring cereals, winter wheat and winter barley/oats fields where neonicotinoid seed treatments had been used when compared to fields without this seed treatment. Autumn-sown oilseed rape treated with neonicotinoid seed treatment was more likely to be treated with a foliar insecticide in the spring than fields without neonicotinoid seed treatment. For spring-sown break crops, the percentage of fields treated with a foliar insecticide spray was lower (60.4%) for crops with neonicotinoid seed treatments than for ones without neonicotinoid seed treatments (91.4%). This difference disappeared however when considering the different types of spring break crops planted.

3.6 Pesticide use in relation to agri-environmental scheme options

The effect of having agri-environment options present in a field on pesticide use within that field was examined, comparing fields with and without conservation headlands in terms of pesticide treatment, the percentage treated spray area, number of treatments and seed treatments used. There were a total of 244 fields with conservation headlands where we know the detail of pesticide applications.

3.6.1 Herbicide use in relation to conservation headlands

The use of herbicides on fields with conservation headlands did not differ between the three crops ($F_{5,1077} = 1.87$, $P = 0.096$), with fields with and without conservation headlands equally likely to be treated with herbicide applications ($F_{1,1081} = 0.11$, $P = 0.743$, Figure 13). The herbicide spray area on fields with and without conservation headlands did differ between crop ($F_{5,1077} = 20.52$, $P < 0.001$) so we compared herbicide spray area on fields with and without conservation headlands for each crop separately. Two of the three crop types showed a significant difference in herbicide spray area between fields with headlands and those without. For spring barley, the average percentage spray area was 187% for fields without conservation headlands and significantly lower at 136% for fields with conservation headlands ($F_{1,485}$ = 9.43, P = 0.002). The same pattern was seen for winter wheat fields with average percentage spray area of 264% on fields without conservation headlands and significantly lower at 228% on fields with conservation headlands ($F_{1,470}$ =4.85, P = 0.028). There was no significant difference between herbicide percentage spray area in winter barley/oats fields with or without conservation headlands ($F_{1,104}$ = 1.58, P = 0.212, 198% and 163% respectively, Figure 13). There was a significant interaction between crops in the number of herbicide treatments used on fields with or without conservation headlands ($F_{5,1077}$ = 31.94, P < 0.001), so we examined the number of herbicide treatments on fields with or without conservation headlands for each crop separately. The number of herbicide applications used was higher in fields without conservation headlands than in ones with conservation headlands for both spring barley (2.2 treatments versus 1.5 treatments respectively, $F_{1,485}$ =26.27, P < 0.001) and winter wheat (2.9 treatments versus 2.5 respectively, $F_{1,470}$ =7.21, P = 0.008). There was no significant difference in the number of herbicide treatments used on fields with or without conservation headlands for winter barley fields (2.1 treatments versus 2.2 treatments respectively, $F_{1,104}$ = 0.08, P = 0.777, Figure 13).

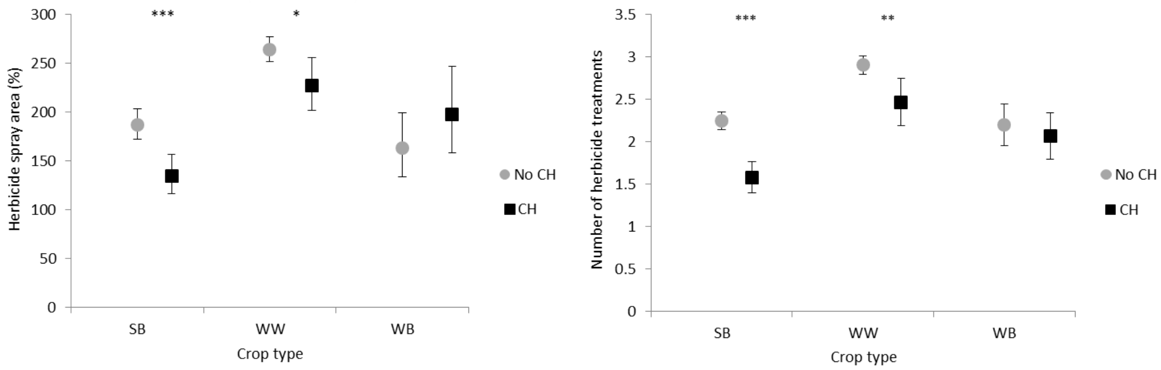

Figure 13. Mean (and 95% CI) percentage herbicide treated area and number of herbicide applications for fields with conservation headlands (black square) and those without (grey circle), grouped by crop type (SB – spring cereals, WW – winter wheat, WB – winter barley/oats). Asterisks indicate a significant difference between fields with headlands and those without (* P < 0.05, ** P < 0.01, *** P < 0.001).

3.6.2 Fungicide use in relation to conservation headlands

Fungicide use on fields with or without conservation headlands did not differ between the three crops ($F_{5,1077}$ = 0.77, P = 0.571), with fields with or without conservation headlands in them equally likely to be treated with fungicides ($F_{1,1081}$ = 0.01, P = 0.956, Figure 14). There were significant interactions in fungicide percentage spray area on fields with or without conservation headlands depending on crop in the field ($F_{5,1077}$ = 49.97, P < 0.001). However, the percentage spray area for fungicide was significantly higher on non-conservation headland fields than on fields with conservation headlands for all three crop types. For spring barley, in fields without conservation headlands the percentage spray area was 170% compared with 117% for fields with headlands ($F_{1,485}$ = 22.52, P < 0.001). Fungicide percentage spray area for winter wheat fields was 265% for fields without headlands compared to 210% on fields with headlands ($F_{1,470}$ = 12.14, P < 0.001), and for winter barley/oats percentage spray area was 228% on fields without headlands compared to 200% on fields with them ($F_{1,104}$ = 8.80, P = 0.004). There were significant interactions between crop and the number of fungicide treatments applied to fields with or without conservation headlands ($F_{5,1077}$ = 96.78, P < 0.001). The number of applications of fungicide was significantly higher on fields without conservation headlands than on ones with conservation headlands for each of the three crop types (Figure 14). For spring barley, on average, the number of applications was 1.9 fungicide treatments applied to fields without conservation headlands compared to 1.3 treatments on fields with conservation headlands ($F_{1,485}$ = 54.12, P <0.001). On fields of winter wheat without headlands, there were an average of 2.9 fungicide treatments applied compared to 2.3 treatments on fields with headlands ($F_{1,470}$ = 21.78, P <0.001). For winter barley/oats there were 2.4 fungicide applications on non-conservation headland fields and 2.0 on fields with conservation headlands ($F_{1,104}$ = 12.31, P <0.001, Figure 14).

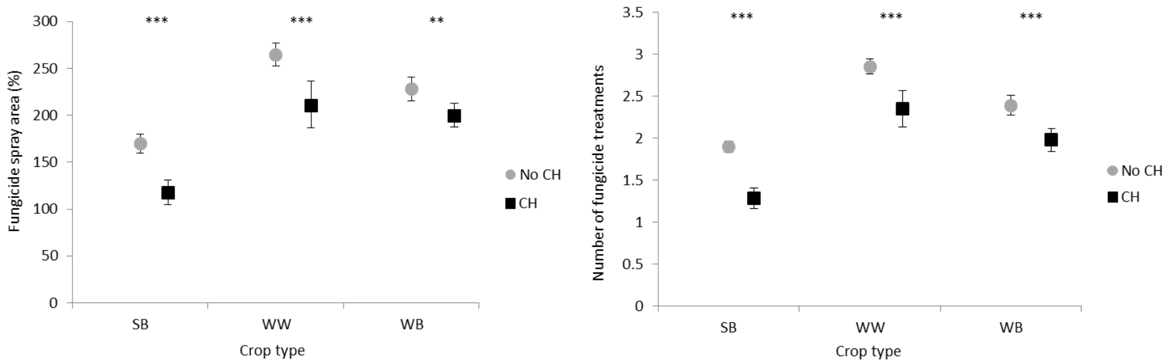

Figure 14. Mean (and 95% CI) percentage fungicide treated area and number of fungicide applications for fields with conservation headlands (black square) and those without (grey circle), grouped by crop type (SB – spring cereals, WW – winter wheat, WB – winter barley/oats). Asterisks indicate a significant difference between fields with headlands and those without (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

3.6.3 Insecticide use in relation to conservation headlands

The use of insecticides on fields with conservation headlands did differ between the three crops ($F_{5,1077} = 131.81$, $P < 0.001$). For spring cereals, a higher proportion of those fields without conservation headlands (18%) were treated with foliar insecticides compared to fields with conservation headlands (1% treated, $F_{1,485} = 33.77$, $P < 0.001$). In the case of both winter wheat ($F_{1,470} = 17.26$, $P < 0.001$) and winter barley/oats ($F_{1,104} = 8.77$, $P = 0.003$), a higher proportion of fields with conservation headlands were treated with foliar insecticides (96% in both cases) compared to fields without conservation headlands (77% and 80%, respectively). There was a significant interaction in insecticide percentage spray area between the three crop types and fields with and without conservation headlands ($F_{5,1077} = 158.20$, $P < 0.001$). In spring cereals the insecticide percentage spray area was higher on fields without conservation headland (1.3%, $F_{1,485} = 24.96$, $P < 0.001$) compared to fields with conservation headlands (0.04 %). Insecticide percentage spray areas were higher on fields with conservation headlands than those without for both winter barley and winter wheat (Figure 15). For winter wheat the percentage spray area on fields without conservation headlands was 45% compared with 96% on fields with headlands ($F_{1,470} = 8.79$, $P = 0.003$) and for winter barley/oats fields 43% on fields without conservation headlands and 81% on fields with them ($F_{1,104}$ = 5.51, P = 0.021). There was a significant interaction in the number of insecticide treatments used between fields with or without conservation headlands in the different crops ($F_{5,1077}$ = 158.20, P < 0.001). Spring cereals with conservation headlands received fewer insecticide treatments (0.01 applications) than spring cereals without conservation headlands (0.14 applications, $F_{1,485}$ = 24.24, P < 0.001). There was no difference in the number of insecticide applications between fields with conservation headlands and those without on either winter wheat (1.3 applications in both groups, $F_{1,470}$ = 1.58, P = 0.210) or winter barley (1.0 applications in both groups, $F_{1,104}$ = 1.53, P = 0.220).

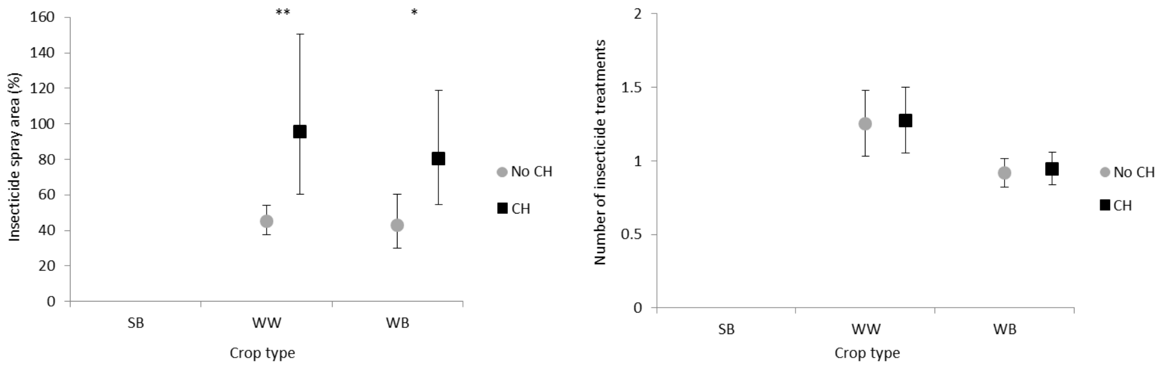

Figure 15. Mean (and 95% CI) percentage insecticide treated area and number of insecticide applications for fields with conservation headlands (black square) and those without (grey circle), grouped by crop type (SB – spring cereals, WW – winter wheat, WB – winter barley/oats). Asterisks indicate a significant difference between fields with headlands and those without (* P < 0.05, ** P < 0.01, *** P < 0.001).

3.6.4 The use of seed treatments in relation to conservation headlands

We compared the use of different types of seed treatment on fields with or without conservation headlands for the three different crop types, spring cereals, winter wheat and winter barley/oats. The three types of seed treatment were fungicide only, neonicotinoid based seed treatments and pyrethroid based seed treatments. There was a significant interaction in the use of fungicide only seed treatments between the different crops depending on whether they had conservation headland in the field or not ($F_{5,847}$ = 56.32, P < 0.001, Figure 16). Nearly all (97%) of the spring cereals with conservation headlands were treated with fungicide only seed treatment, with 69%

(significantly less) of the spring cereals without conservation headlands treated with this type of seed treatment ($F_{1,388}$ = 46.27, P < 0.001). Similar proportions of winter wheat fields with or without conservation headlands were treated with fungicide only seed treatment (37% and 46% respectively, $F_{1,369}$ = 1.83, P = 0.177). Eighteen percent of winter barley/oats fields without conservation headlands were treated with fungicide only seed treatments, significantly higher than was the case for winter barley/oats fields with conservation headlands where fungicide only seed treatments were not used ($F_{1,72}$ = 8.43, P = 0.004). In the case of neonicotinoid seed treatments, there was again a significant interaction in the use of these seed treatments between different crops and whether or not there were conservation headlands in a field ($F_{5,847}$ = 104.42, P < 0.001, Figure 16). Three (3%) of the spring cereal crops with conservation headlands received neonicotinoid seed treatments, while none of the spring cereals without conservation headlands were treated with neonicotinoid seed treatments; this was significantly lower ($F_{1,388}$ = 7.35, P = 0.007). In the case of winter wheat crops, a higher proportion of fields with conservation headlands were treated with neonicotinoid seed treatments (63%, $F_{1,369}$ = 8.49, P = 0.004) than were fields of winter wheat without conservation headlands (45%). The same was true of winter barley/oats fields, with all winter barley/oats crops with conservation headlands receiving neonicotinoid seed treatment (100%, $F_{1,72}$ = 8.43, P = 0.004), compared to 82% of winter barley/oats crops without conservation headlands (82%). A significant interaction was found between the use of pyrethroid seed treatments in fields of different crops with or without conservation headlands ($F_{5,847}$ = 19.98, P < 0.001). No spring cereals with conservation headlands were treated with pyrethroid seed treatments, with significantly more fields of spring cereal (19%) without conservation headlands treated with pyrethroid seed treatments ($F_{1,388}$ = 41.96, P < 0.001, Figure 16). Only three winter wheat fields without conservation headlands dressings (1%) and no winter wheat fields with conservation headlands were treated with pyrethroid seed; this was not significantly different ($F_{1,369}$ = 0.01, P = 0.999). No fields of winter barley/oats were treated with pyrethroid seed treatment.

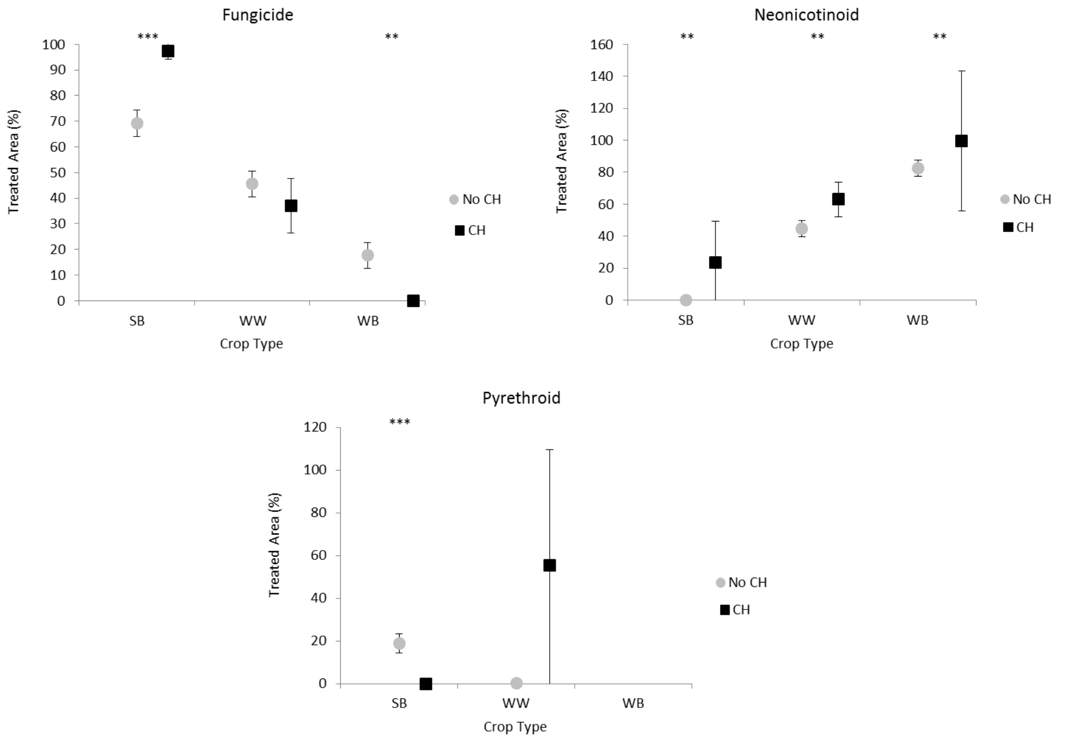

Figure 16. Mean (and 95% CI) percentage treated area for fungicide, neonicotinoid and pyrethroid seed treatments for fields with conservation headlands (black square) and those without (grey circle), grouped by crop type (SB – spring cereals, WW – winter wheat, WB – winter barley/oats). Asterisks indicate a significant difference between fields with headlands and those without (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

Summary of Invertebrate abundance and indices

1. Ground & click beetles (Carabidae & Elateridae) after showing an increase in the 1980s and aphids (Aphididae) declined since 2004. Caterpillars (Symphyta & Lepidoptera) declined through the mid-1990s and then increased until the mid-2000s, followed by a decline. Spiders & harvestmen (Araneae & Opiliones), leaf beetles & weevils (Chrysomelidae & Curculionidae), grey partridge chick-food index (CFI), corn bunting four-food index (4FI) and yellowhammer index (YHI) declined through the mid-1980s and then increased, leaf beetles & weevils substantially so. Plant bugs/hoppers (Non-aphid Hemiptera) declined in the early part of the study, before increasing in the 1980s and again more recently.
2. Pre-cultivation herbicides were associated with significantly lower abundances of spiders & harvestmen, ground & click beetles, plant bugs/hoppers, aphids, grey partridge chick-food index and yellowhammer index.
3. The abundance of spiders & harvestmen, caterpillars, leaf beetles & weevils, plant bugs/hoppers and corn bunting index were significantly lower where multi-site/non-penetrative foliar fungicides were used. Other than this no clear patterns emerged for invertebrate abundances and indices in relation to use, intensity of use, timing of use and mode of action of herbicides and fungicides.
4. All nine invertebrate taxa and indices declined with foliar insecticide use (all significantly from 1970 to 2012), number of foliar insecticide applications (all significant from 1970 to 2012) and use of foliar insecticides in the spring (eight significantly from 1970 to 2012). Autumn foliar insecticide use was also associated with lower abundance of invertebrate taxa or indices, with eight out of nine significantly declining from 1970 to 2012.
5. The use of foliar pyrethroids and non-systemic organophosphates was associated with declines in all nine taxa (significant in seven). Foliar pirimicarb, which was used only sporadically throughout, was associated with higher abundance of aphids and yellowhammer index. Foliar systemic organophosphate use has stopped recently (2005-2012) but was associated with lower abundance of all taxa, significantly so for spiders & harvestmen and plant bugs/hoppers over all.
6. The abundances of spiders & harvestmen, ground & click beetles, caterpillars, plant bugs/hoppers, aphids, grey partridge chick-food index and yellowhammer index were lower where foliar insecticide was used in the previous year (after adjusting for treatments in the current year and crops in both years) across all the years.
7. The abundance of four invertebrate groups (ground & click beetles, caterpillars, leaf beetles & weevils and grey partridge chick-food index) was lower where any seed treatment was used (fungicide, neonicotinoid or pyrethroid) compared to where no seed treatments were used. The abundance of aphids was significantly lower in fields treated with neonicotinoid seed treatments compared to the other types of seed treatment, controlling for foliar herbicide, fungicide and insecticide treatment as well as year and crop. The abundance of spiders & harvestmen was significantly lower in fields treated with fungicide or pyrethroid seed treatments compared to fields treated with neonicotinoids.

3.7 Trends in invertebrate abundance

The annual densities of Araneae & Opiliones ($F_{2,40} = 8.40$, $P < 0.001$), Chrysomelidae & Curculionidae ($F_{2,40} = 12.05$, $P < 0.001$, Figure 17) and the three chick food indices Grey partridge CFI ($F_{2,40} = 4.40$, $P = 0.019$), Corn bunting 4FI ($F_{2,40} = 5.44$, $P = 0.008$) and Yellowhammer CFI ($F_{2,40} = 9.54$, $P < 0.001$, Figure 18) all showed declines, followed by increases. The annual abundance of Carabidae &

Elateridae ($F_{5,37}$ = 6.89, P < 0.001) and Aphididae ($F_{1,41}$ = 5.53, P = 0.024, Figure 17) declined between 1970 and 2012, while Symphyta & Lepidoptera first declined, then increased and latterly have declined again ($F_{5,37}$ = 4.75, P = 0.002, Figure 17). Trends in the annual densities of Non-aphid Hemiptera were complex, with early declines in the 1970s, an increase and stabilization from the 1980s through the 1990s, with more recent increases ($F_{5,37}$ = 2.55, P = 0.044, Figure 17).

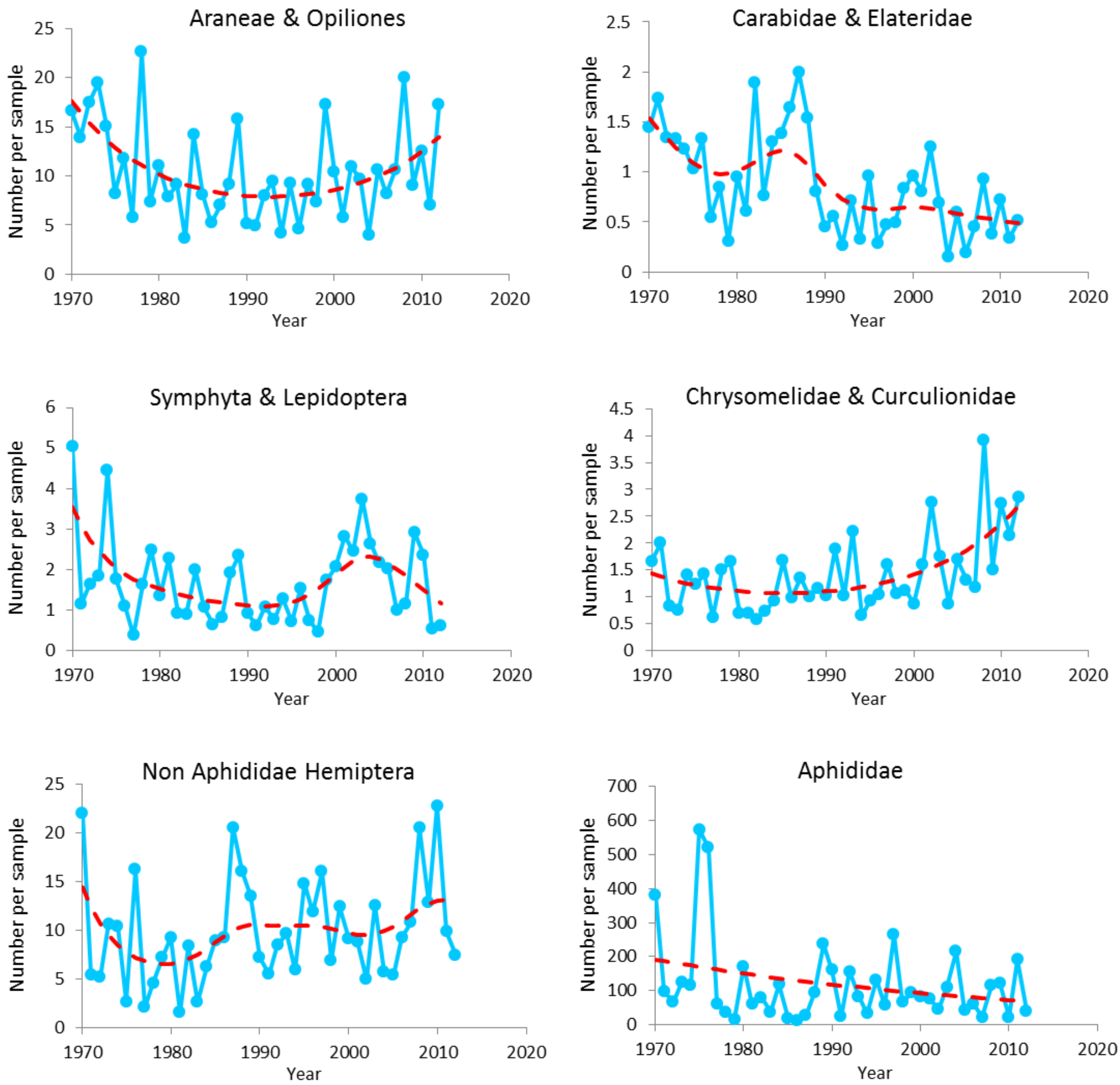

Figure 17. Trends in annual arthropod densities through time. Average annual abundance of each of the invertebrate groups (blue line) calculated using a generalized linear model with Poisson distribution and logarithmic link function, corrected for over-dispersion and weighted by the sample size. A significant long-term trend is shown by the red dashed line. There was a quadratic trend through time in the annual densities of Araneae & Opiliones ($F_{2,40} = 8.40$, $P < 0.001$), and Chrysomelidae & Curculionidae ($F_{2,40} = 12.05$, $P < 0.001$). Annual densities of Carabidae & Elateridae ($F_{5,37} = 6.89$, $P < 0.001$) and Aphididae ($F_{1,41} = 5.53$, $P = 0.024$) declined linearly while the trend in Symphyta & Lepidoptera abundance was more complex, with increases in the first decade of this century and a subsequent decline ($F_{5,37} = 4.75$, $P = 0.002$). Non-aphid Hemiptera declined in the early part of the study, before increasing steadily ($F_{5,37} = 2.55$, $P = 0.044$).

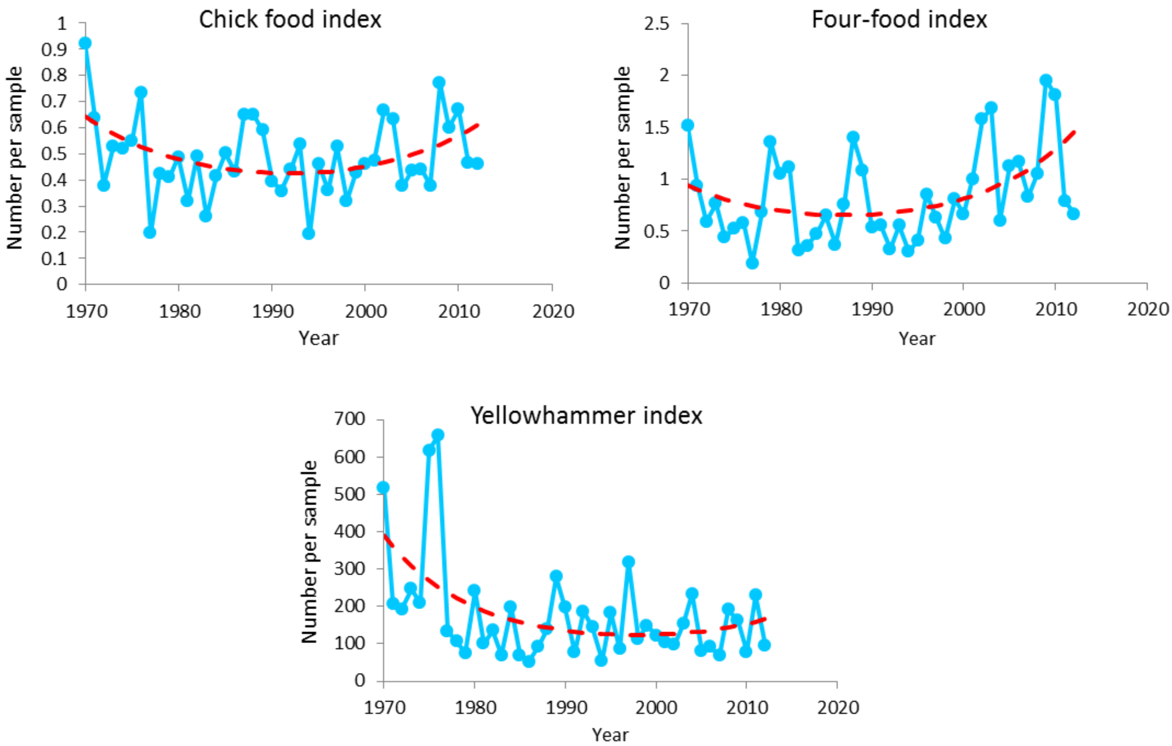

Figure 18. Average annual abundance of each of the chick food indices (blue line) calculated using a generalized linear model with Poisson distribution and logarithmic link function, corrected for over-dispersion and weighted by sample size. A significant long term trend is shown by the red dashed line. There was a quadratic trend through time in the annual densities of Grey partridge CFI ($F_{2,40}$ = 4.40, P = 0.019), Corn bunting 4FI ($F_{2,40}$ = 5.44, P = 0.008) and Yellowhammer Index ($F_{2,40}$ = 9.54, P < 0.001).

3.8 Invertebrate abundance and herbicides

3.8.1 Invertebrate abundance and herbicide treatment

From 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, Chrysomelidae & Curculionidae abundance was significantly lower (12% lower) where herbicides were used and Aphididae abundance was significantly higher (22% higher, Figure 19). The abundance of the other invertebrate groups were not significantly affected by herbicide use over the full span of the study years (Table 4).

However, comparing the effect of herbicide use between the time periods, 1970 - 2004 and 2005 - 2012, there were significant differences for five of the nine groups. From 2005 to 2012, the abundances of four invertebrate groups (Carabidae & Elateridae, Aphididae, CFI and YHI) were higher in fields where herbicides were used compared to where they were not (significantly so for

Carabidae & Elateridae, Aphididae and YHI with abundance 24%, 88% and 22% higher respectively), with no significant effect of herbicide use from 1970 to 2004. From 2005 to 2012 the abundance of Araneae & Opiliones was lower in fields where herbicides were used but from 1970 to 2004 it was higher; in both cases the differences were not significant.

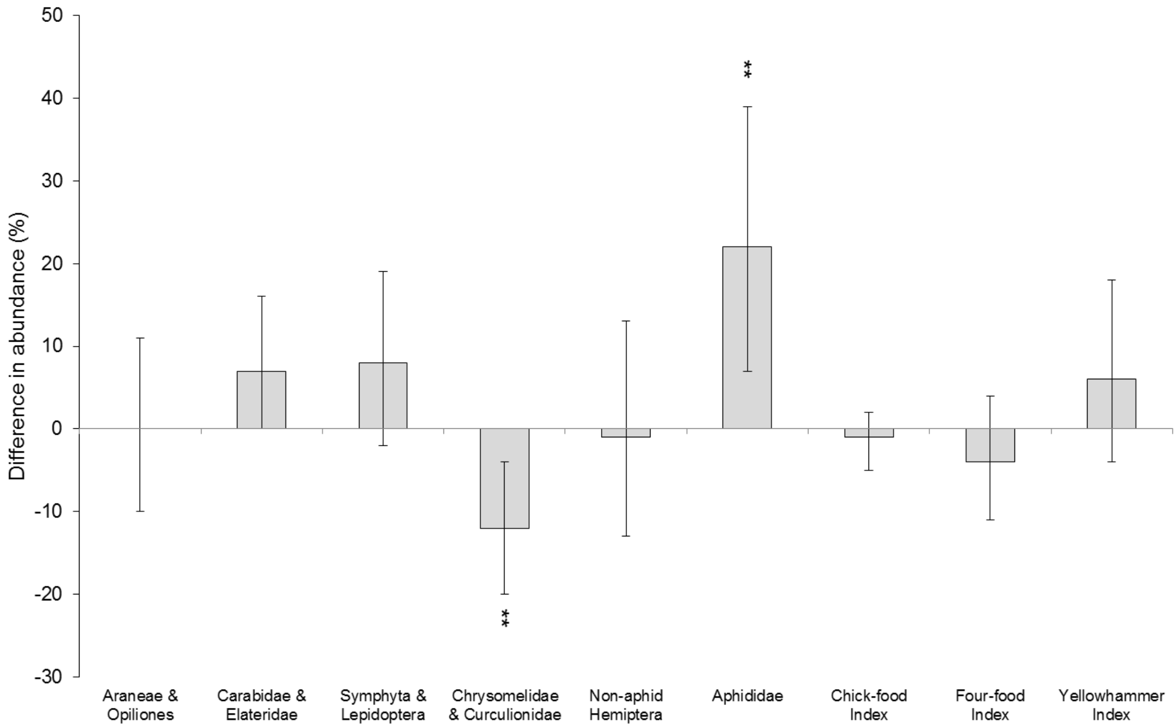

Figure 19. The effect of foliar/residual herbicide applications (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases where herbicide was used and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2588, error bars are 95% confidence intervals.

3.8.2 Invertebrate abundance and intensity of herbicide treatment

From 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundance of Non-aphid Hemiptera declined with increasing numbers of herbicide treatments, while the abundance of two invertebrate groups (Araneae & Opiliones and Carabidae & Elateridae) increased with increasing numbers of herbicide treatments (Table 5).

The relationship between abundance and increasing herbicide use differed between the two time periods for five invertebrate groups. For Araneae & Opiliones and Non-aphid Hemiptera, increases in abundance with increasing numbers of herbicide applications from 1970 to 2004 (significant in the case of Araneae & Opiliones) switched to decreases in abundance with more herbicide applications from 2005 to 2012 (highly significant in the case of Non-aphid Hemiptera). The opposite was the case for the abundance of Chrysomelidae & Curculionidae, Aphididae and CFI, where declines in abundance with increasing numbers of herbicide applications from 1970 to 2004 (significantly so for Aphididae) became increases in abundance with increasing herbicide use (again significantly so for Aphididae).

3.8.3 Invertebrate abundance and timing of herbicide treatment

Overall, 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundance of Carabidae & Elateridae increased by 8% with autumn/winter herbicide use (Figure 20). The abundance of Chrysomelidae & Curculionidae, Non-aphid Hemiptera, CFI and 4FI declined where herbicides were used in the spring/summer from 1970 to 2012, with abundance 10%, 12%, 3% and 6% lower respectively, while the abundance of Aphididae increased by 22%. Overall, the abundances of five of the nine invertebrate groups (Symphyta & Lepidoptera, Chrysomelidae & Curculionidae, Non-aphid Hemiptera, CFI and 4FI) were lower where herbicide were used in the spring/summer compared to use in autumn/winter, with the abundance of one group, Aphididae, higher where herbicides were used in the spring/summer compared to autumn/winter use (Table 6). There were several significant differences between the two time periods in the effect of timing of herbicide use on the abundance of the invertebrate groups (Table 6). From 1970 to 2004, the use of herbicides in autumn/winter went from being related to higher abundances of four invertebrate groups (Carabidae & Elateridae, Non-aphid Hemiptera, Aphididae, and CFI, significantly so for Carabidae & Elateridae - 14% higher and CFI – 4% higher) as well as no change in abundance for YHI, to lower abundance from 2005 to 2012 (significantly so for Non-aphid Hemiptera – lower by 17% , Aphididae – lower by 32%, CFI – lower by 7% and YHI – lower by 24%). The abundance of Chrysomelidae & Curculionidae was lower where autumn/winter herbicides were used from 1970 to 2004 but this was not significant; from 2005 to 2012 this negative effect of autumn/winter herbicides was significant, with abundance of this group 18% lower.

The abundance of Araneae & Opiliones and Non-aphid Hemiptera went from being higher where herbicides were used in the spring/summer from 1970 to 2004 to significantly lower from 2005 to 2012, by 18% and 28% respectively. The opposite was the case for Carabidae & Elateridae, Chrysomelidae & Curculionidae, Aphididae, CFI and YHI, with the abundance of Carabidae & Elateridae (17%) and Aphididae (92%) significantly higher where spring/summer herbicides were used from 2005 to 2012 (Table 6).

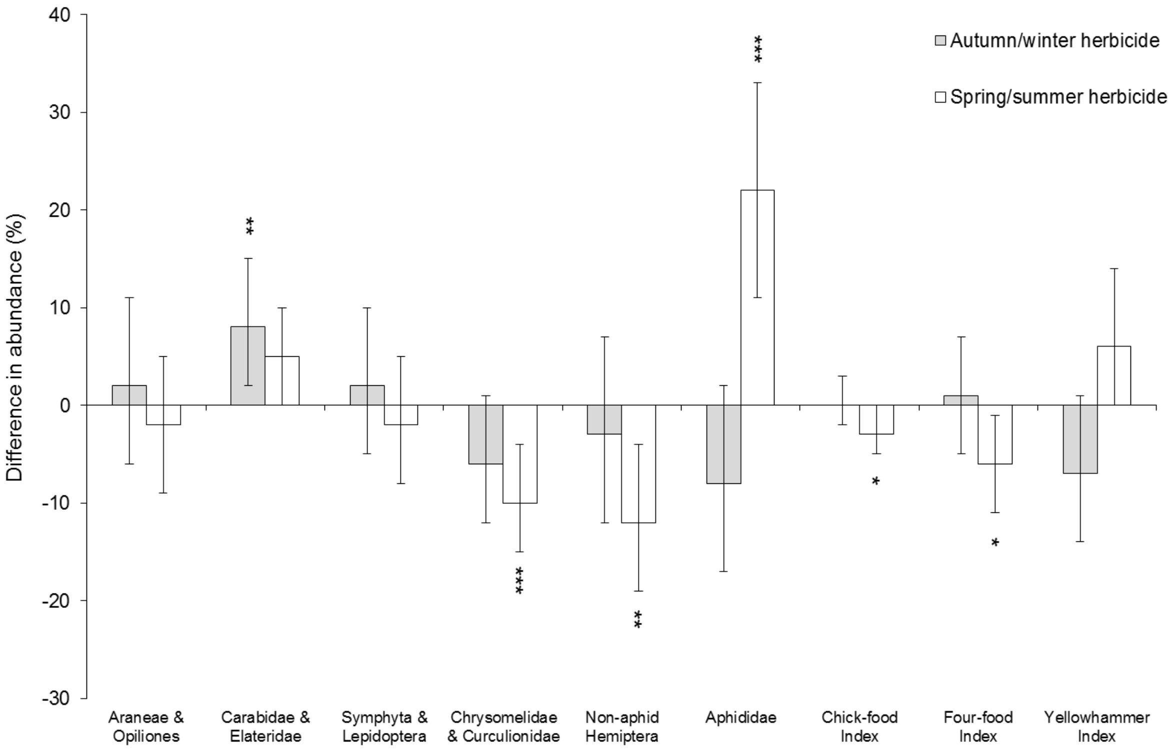

Figure 20. The effect of the timing (autumn/winter or spring/summer) of herbicide applications (controlling for crop, year and the use of other pesticide types, grouped by timing of application) on invertebrate densities on a field-by-field basis. Bars below the line indicate decreases in abundance and vice versa. * *P* < 0.05, ** *P* < 0.01, *** *P* < 0.001, sample size is 2588, error bars are 95% confidence intervals.

3.8.4 Invertebrate abundance and herbicide grouped by specificity

Overall, from 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, dicot-specific herbicide use was associated with higher abundances of Carabidae & Elateridae (9% higher), Aphididae (35% higher) and YHI (18% higher). The abundance of Araneae & Opiliones and Non-aphid Hemiptera declined where monocot-specific herbicides were used (11%

and 17% lower respectively). Broad-spectrum herbicide use negatively affected Aphididae (10% lower) and YHI (8% lower, Figure 21).

Considering the effects of dicot-specific and monocot-specific herbicides between time periods, three invertebrate groups (Araneae & Opiliones, Non-aphid Hemiptera and Aphididae) showed significant differences (Table 7). From 1970 to 2004 the abundances of Araneae & Opiliones and Non-aphid Hemiptera were higher where dicot-specific herbicides were used, significantly so for Araneae & Opiliones (20% higher), with non-significant higher abundances where monocot-specific herbicides were used. This contrasted with the case from 2005 to 2012, when abundances of these two groups were lower when either dicot- or monocot-specific herbicides were used, significantly so in the case of Araneae & Opiliones and monocot-specific herbicide (21% lower) and for the use of either dicot- or monocot-specific herbicides in the case of Non-aphid Hemiptera (respectively, 15 and 24% lower). From 1970 to 2004, the abundance of Aphididae was significantly higher (17%) where dicot-specific herbicides were used and non-significantly lower where monocot-specific herbicides were used. From 2005 to 2012, the increase in Aphididae abundance where dicot-specific herbicides were used became highly significant (60% higher) and non-significantly higher where monocot-specific herbicides were used. Comparing the effect of broad-spectrum herbicides between the two time periods, there were significant differences between the two time periods for Symphyta & Lepidoptera and 4FI, where non-significant negative relationships from 1970 to 2004 were replaced by non-significant positive ones from 2005 to 2012.

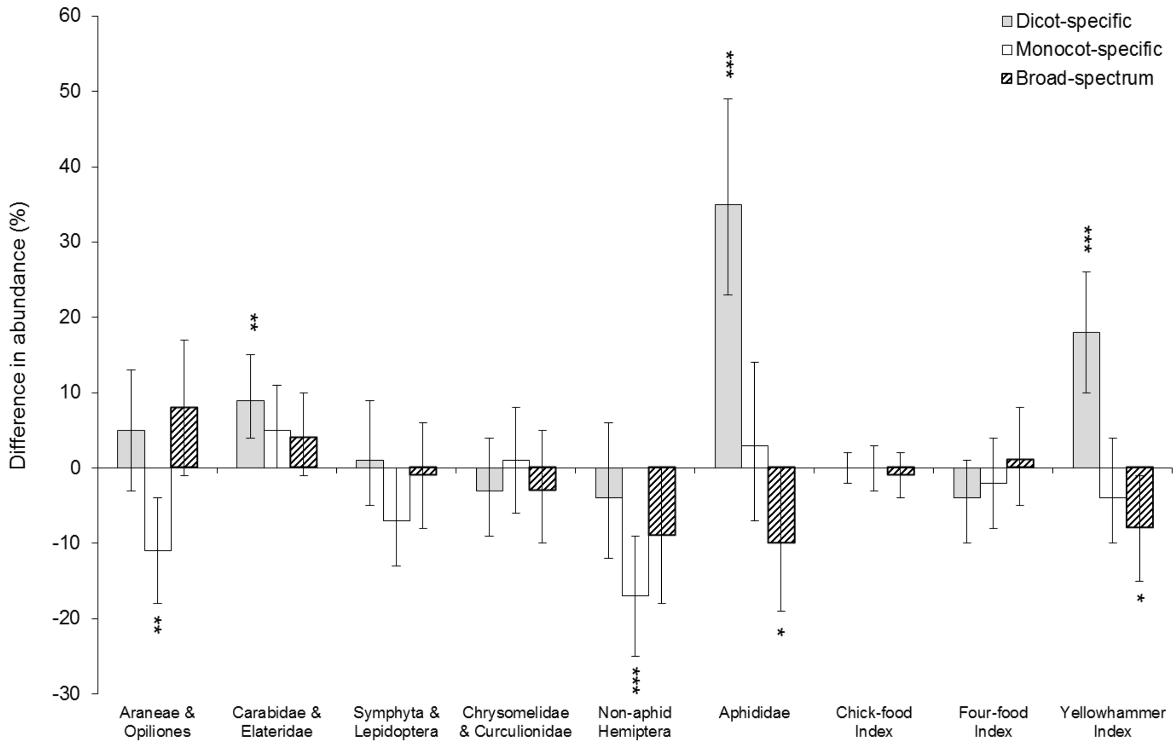

Figure 21. The effect of herbicide used grouped by specificity (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in abundance and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 1895, error bars are 95% confidence intervals.

3.8.5 Invertebrate abundance and herbicide grouped by mode of action

Overall, from 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the use of pre-cultivation herbicides resulted in significantly lower abundances of six of the nine invertebrate groups, significantly so for Araneae & Opiliones (10% lower), Carabidae & Elateridae (7% lower), Chrysomelidae & Curculionidae (9% lower), Non-aphid Hemiptera (28% lower), CFI (6% lower) and YHI (12% lower). Contact-acting herbicide use was associated with higher abundances of Carabidae & Elateridae (8% higher), Aphididae (48% higher) and YHI (21% higher). Samples from fields treated with residual herbicides had higher abundances of Carabidae & Elateridae (11% higher) but lower abundances of Aphididae (18% lower) and YHI (14% lower). Three of the nine invertebrate groups examined had lower abundances where contact + residual-acting herbicides were used with abundances of Chrysomelidae & Curculionidae (10%), Aphididae (11%) and YHI (9%), significantly lower (Figure 22).

Comparing the time periods, several differences were found in the relationships between invertebrate abundance and the use of herbicides, categorised by their mode of action (Table 8). For herbicides applied pre-cultivation, the abundances of both Araneae & Opiliones and Non-aphid Hemiptera were more severely negatively affected from 2005 to 2012 (17% and 38% lower, respectively) than was the case from 1970 to 2004 (no change in abundance for Araneae & Opiliones and 14% lower for Non-aphid Hemiptera). Similar results were seen for contact-acting herbicides on the abundance of these two invertebrate groups. While higher abundances were seen where contact-acting herbicides were used from 1970 to 2005 (significantly so for Araneae & Opiliones – 15% higher), from 2005 to 2012 significantly lower abundances of both Araneae & Opiliones (12% lower) and Non-aphid Hemiptera (21% lower) were found where these herbicides were applied. In the case of Non-aphid Hemiptera, a significant negative relationship between the use of contact + residual-acting and the abundance of this group from 1970 to 2004 (20% lower) changed to a non-significant positive one from 2005 to 2012. The opposite pattern was found for the abundance of Carabidae & Elateridae and the use of contact + residual-acting herbicides, with a non-significant positive relationship from 1970 to 2004 becoming a significant negative one from 2005 to 2014 (10% lower). The abundance of three invertebrate groups (Carabidae & Elateridae, Aphididae and YHI) was higher where contact-acting herbicides were used from 1970 to 2004, just significant for Aphididae (18% higher) and YHI (12% higher); these increased to highly significant positive effects from 2005 to 2012 (respectively 99% and 33% higher). From 1970 to 2004, the abundances of three invertebrate groups (Symphyta & Lepidoptera, CFI and 4FI) were lower where residual-acting herbicides were used, though this was non-significant; this changed from 2005 to 2012, with the abundances of these three groups higher where residual-acting herbicides were used, significantly so in the case of CFI (6% higher) and 4FI (22% higher).

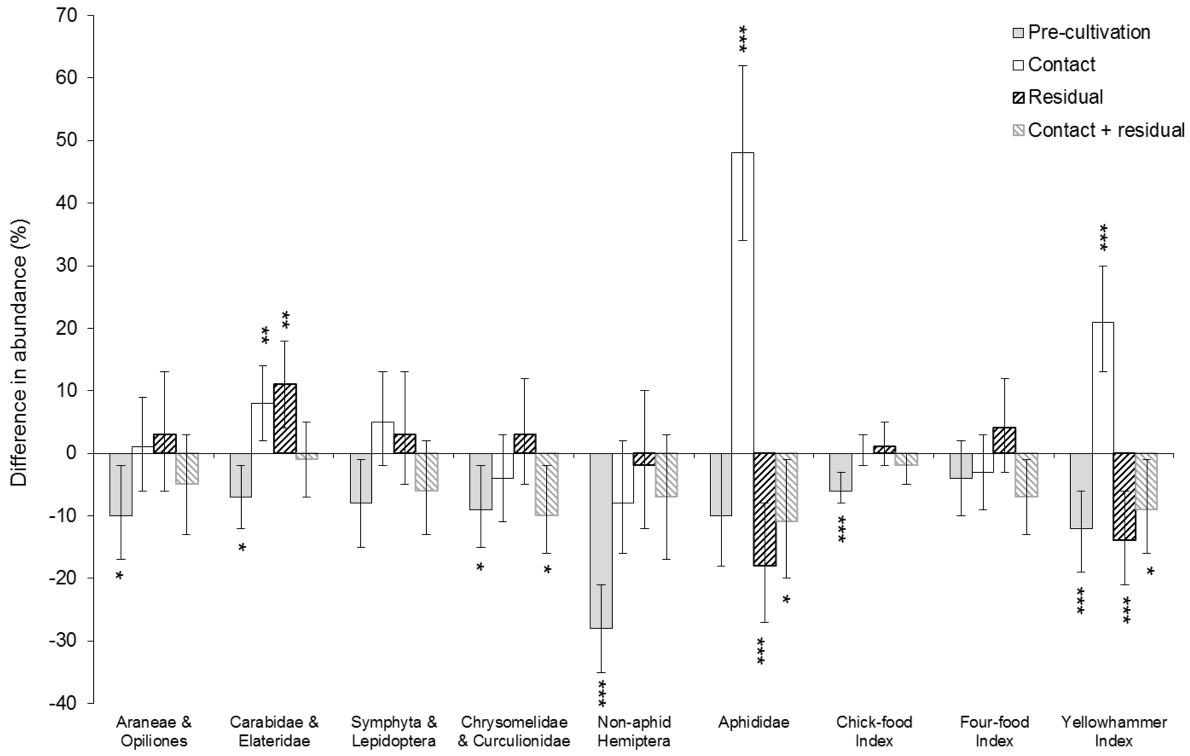

Figure 22. The effect herbicides grouped by mode of action (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in abundance and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 1855, error bars are 95% confidence intervals.

3.8.6 Invertebrate abundance and previous year's herbicide treatment

Overall, from 1970 to 2012, controlling for year, crop, and foliar/residual pesticide applications in the current year and for crop and other foliar/residual pesticide applications in the previous year, the only significant effect of herbicide use in the previous year was the higher abundance of Aphididae (19% higher, Figure 23).

Comparing the time periods, there was a significant difference between them in the response of Aphididae to herbicide use in the previous year. From 1970 to 2004, the abundance of Aphididae was 13% higher where herbicides were used, while from 2005 to 2012 their abundance was 29% higher, though in both cases this was not significant (Table 9).

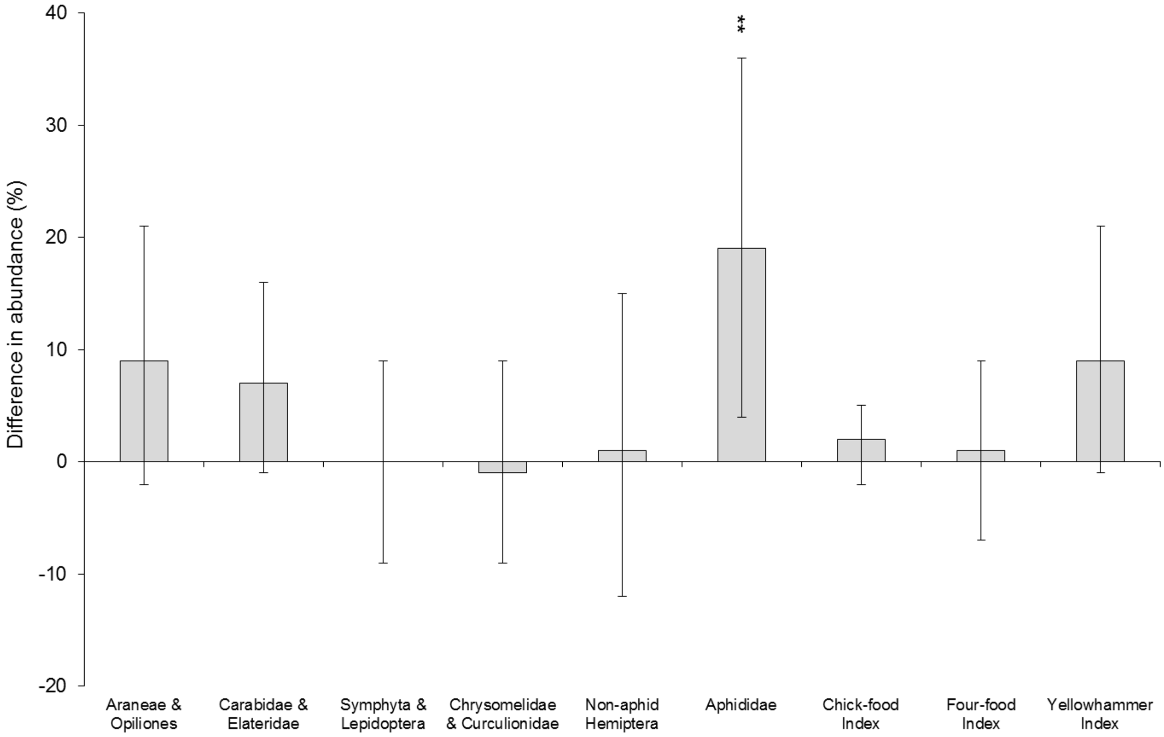

Figure 23. The effect of foliar/residual herbicide use in the previous year (controlling for year, crop in the current and previous year, and the use of other pesticide types in the current and previous year) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in abundance and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2044, error bars are 95% confidence intervals.

3.9 Invertebrate abundance and fungicides

3.9.1 Invertebrate abundance and fungicide treatment

Overall, from 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundance of Araneae & Opiliones and Non-aphid Hemiptera were significantly lower where fungicides were applied (both 13% lower), and Carabidae & Elateridae, were 7% more abundant where fungicides were used (Figure 24). There were no differences between the time periods in the effect of fungicide use (Table 10).

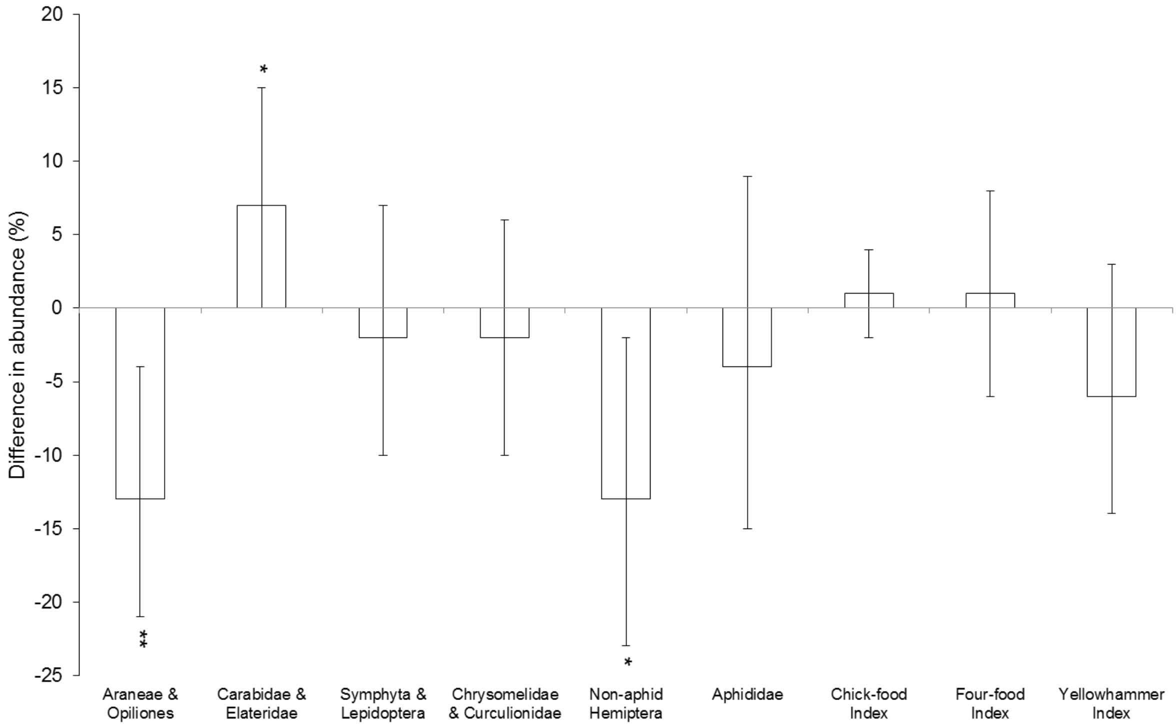

Figure 24. The effect of foliar/residual fungicide applications (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases where fungicide applications were used and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2588, error bars are 95% confidence intervals.

3.9.2 Invertebrate abundance and intensity of fungicide treatment

Overall, from 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundance of Araneae & Opiliones, Symphyta & Lepidoptera, Chrysomelidae & Curculionidae, Non-aphid Hemiptera and 4FI all declined with increasing intensity of fungicide use (Table 11). The relationship between the abundance of Carabidae & Elateridae and CFI and increasing numbers of fungicide treatments differed between the time periods; in both cases a positive relationship with increasing numbers of fungicide treatments (significant for Carabidae & Elateridae) from 1970 to 2004, became a negative one from 2005 to 2012 (significantly so for CFI).

3.9.3 Invertebrate abundance and fungicide grouped by mode of action

From 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundance of seven invertebrates groups were lower where multi-site/non-penetrative fungicides were used. These were Araneae & Opiliones (21% lower), Symphyta & Lepidoptera (7% lower), Chrysomelidae & Curculionidae (9% lower), Non-aphid Hemiptera (19% lower) and 4FI (9% lower, Figure 25).

The relationship between multi-site/non penetrative fungicides and invertebrate abundance differed between the time periods for six invertebrate groups. From 1970 to 2004, the use of multi-site/ non-penetrative fungicides lowered Araneae & Opiliones abundance significantly by 31% but from 2005 to 2012, although abundance declined, this was not significant (Table 12). The use of multi-site/non-penetrative was associated with significantly lower abundances for Carabidae & Elateridae (9% lower), Symphyta & Lepidoptera (11% lower), Aphididae (15% lower), CFI (5% lower) and YHI (20% lower) from 1970 to 2004, with the opposite effect from 2005 to 2012. Then the abundance of all five groups were higher where these types of fungicides were used, significantly for Carabidae & Elateridae (18% higher), Aphididae (50% higher) and YHI (21% higher).

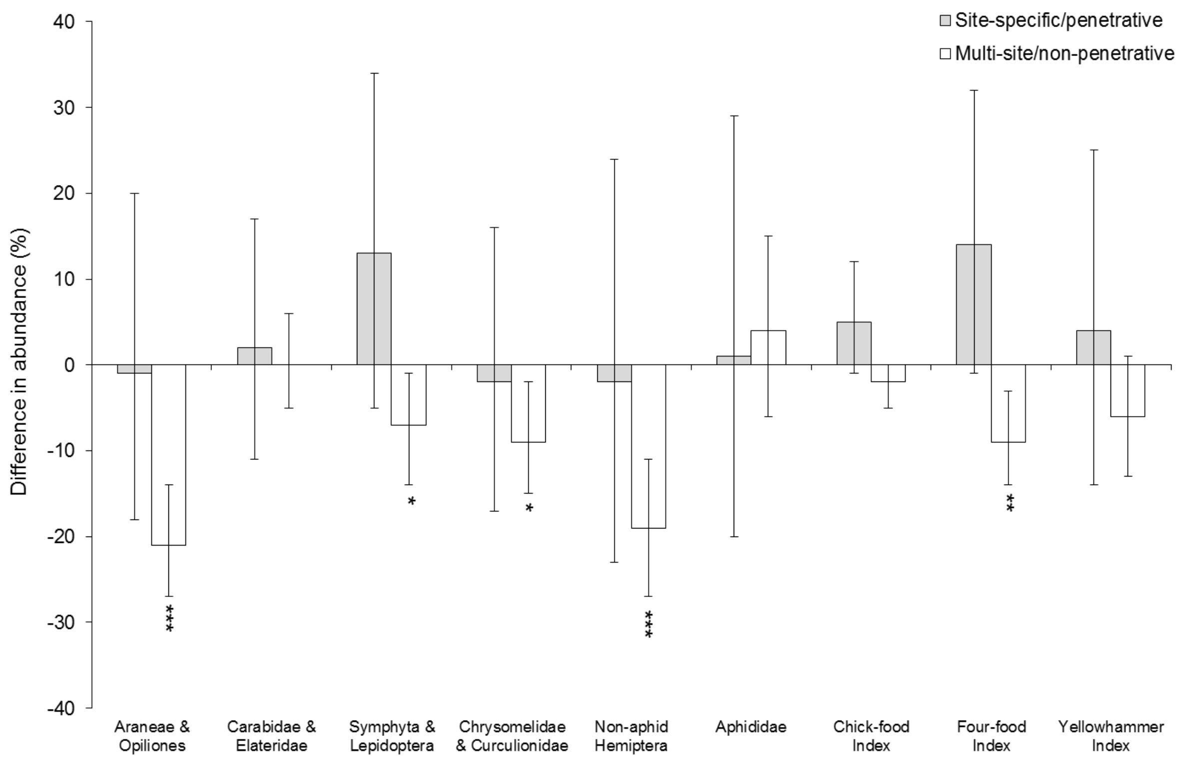

Figure 25. The effect of the type of foliar/residual fungicide used grouped by mode of action (controlling for crop, year and the application of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in density and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2490, error bars are 95% confidence intervals.

3.9.4 Invertebrate abundance and previous year's fungicide treatment

From 1970 to 2004, controlling for year, crop, and foliar/residual pesticide applications in the current year and for crop and other foliar/residual pesticide applications in the previous year, there were no significant effects of fungicide use in the year previous (Figure 26) and no significant differences in the carry-over effect of fungicide use between the time periods (Table 13).

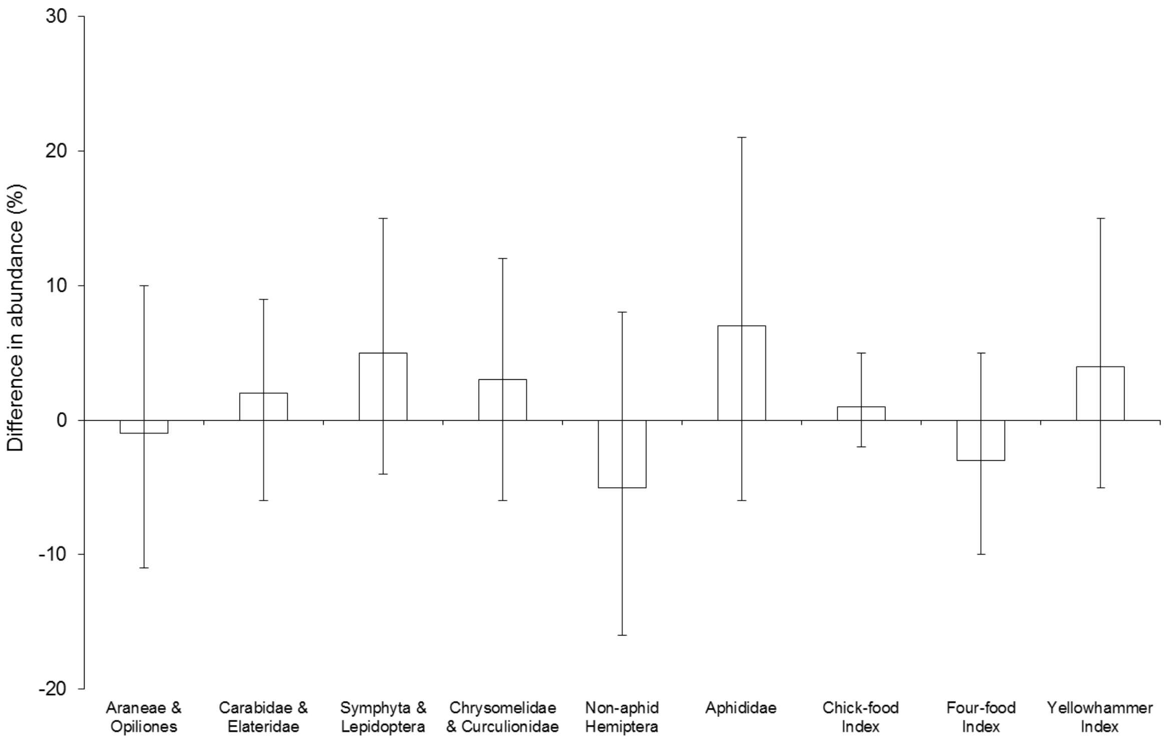

Figure 26. The effect of foliar/residual fungicide use in the previous year (controlling for year, crop in the current and previous year, and the use of other pesticide types in the current and previous year) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in density and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2044, error bars are 95% confidence intervals.

3.10 Invertebrate abundance and insecticides

3.10.1 Invertebrate abundance and insecticide treatment

From 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundance of all nine invertebrate groups, Araneae & Opiliones (11% lower), Carabidae & Elateridae abundance (6% lower), Symphyta & Lepidoptera (21% lower), Chrysomelidae & Curculionidae (14% lower), Non-aphid Hemiptera (31% lower), Aphididae (35% lower), CFI (8% lower), 4FI (16% lower) and YHI (29% lower) were significantly lower where insecticides were used (Figure 27).

Comparing time periods (1970 - 2004 with 2005 - 2012), the abundance of three invertebrate groups were less affected by insecticide use from 2005 to 2012 than from 1970 to 2004 (Table 14). These groups were Symphyta & Lepidoptera (abundance went from being 27% lower where insecticides were used from 1970 to 2004 to 14% lower from 2005 to 2012), Aphididae (abundance went from

42% lower to 23% lower) and YHI (from 36% lower to 15% lower). In all cases the abundance of these three invertebrate groups were still significantly negatively affected by insecticide use from 2005 to 2012.

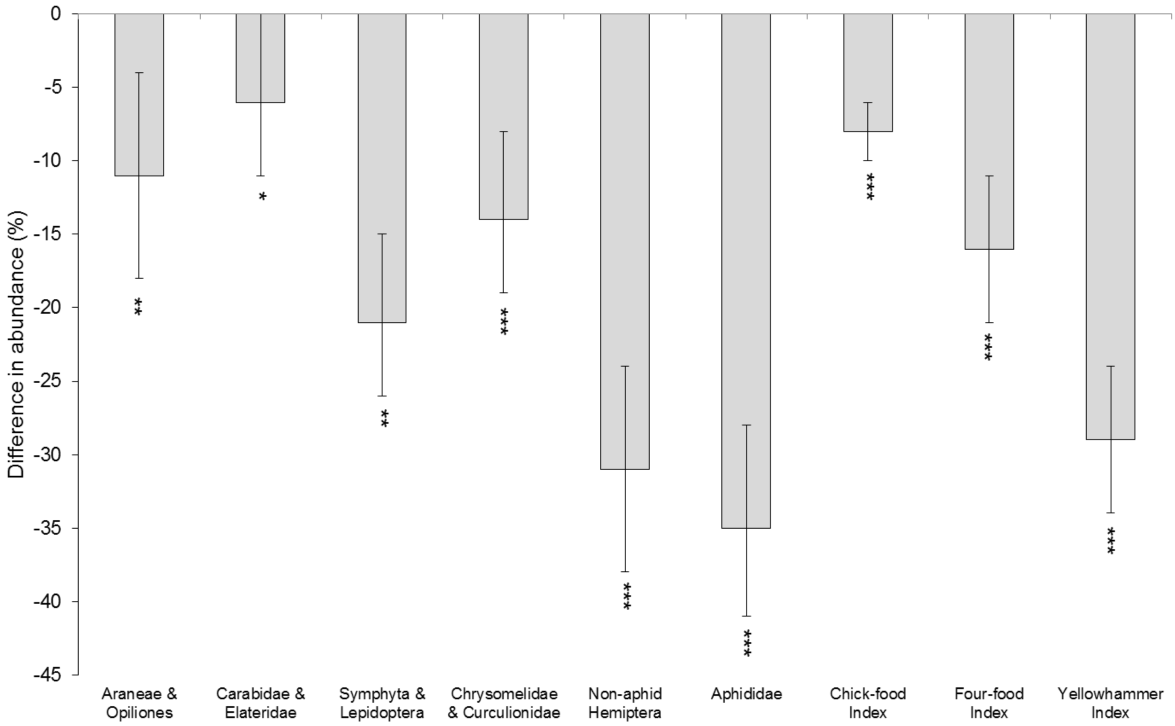

Figure 27. The effect of foliar/residual insecticide applications (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases where insecticides were used and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2588, error bars are 95% confidence intervals.

3.10.2 Invertebrate abundance and intensity of insecticide treatment

Considering the effects on invertebrate abundance across the 1970 to 2012 and controlling for year, crop and the other foliar/residual pesticide applications, the abundance of all nine invertebrate groups was significantly negatively related to increasing insecticide use (Table 15). The effect of intensity of insecticide use differed between the time periods for Araneae & Opiliones and YHI, with declines from 2005 – 2012 less (but still significant) than those from 1970 to 2004.

3.10.3 Invertebrate abundance and timing of pesticide treatment

From 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, the abundances of eight of the nine groups of invertebrates were significantly lower where insecticide

was used in the autumn/winter (Figure 28). The abundances of Carabidae & Elateridae (11%), Symphyta & Lepidoptera (20%), Chrysomelidae & Curculionidae (9%), Non-aphid Hemiptera (15%), Aphididae (27%), CFI (8%), 4FI (16%) and YHI (21%) were all lower. In fields treated with spring/summer insecticide from 1970 to 2012 the abundances of eight invertebrate groups, Araneae & Opiliones (29%), Symphyta & Lepidoptera (23%), Chrysomelidae & Curculionidae (20%), Non-aphid Hemiptera (59%), Aphididae (37%), CFI (10%), 4FI (16%) and YHI (40%) were all significantly lower than in fields not treated with insecticides at this time of year. For Carabidae & Elateridae abundance, autumn/winter insecticide use was more damaging than use in the spring/summer; for Araneae & Opiliones, Chrysomelidae & Curculionidae, Non-aphid Hemiptera, Aphididae and YHI spring/summer insecticide use was more damaging than autumn/winter use (Table 16).
Comparing the time periods, autumn/winter insecticide use went from having a significant negative effect on the abundance of five invertebrate groups from 1970 to 2005, including Symphyta & Lepidoptera (27% lower), Non-aphid Hemiptera (26% lower), Aphididae (39% lower), CFI (10% lower) and YHI (32% lower) to only a significant positive effect for Aphididae abundance (22% higher, Table 16). The abundance of Non-aphid Hemiptera and CFI were affected more severely by spring/summer insecticide use from 2005 to 2012 (respectively, abundance was 66% and 15% lower) compared to the case from 1970 to 2004 (53% and 9% lower, respectively).

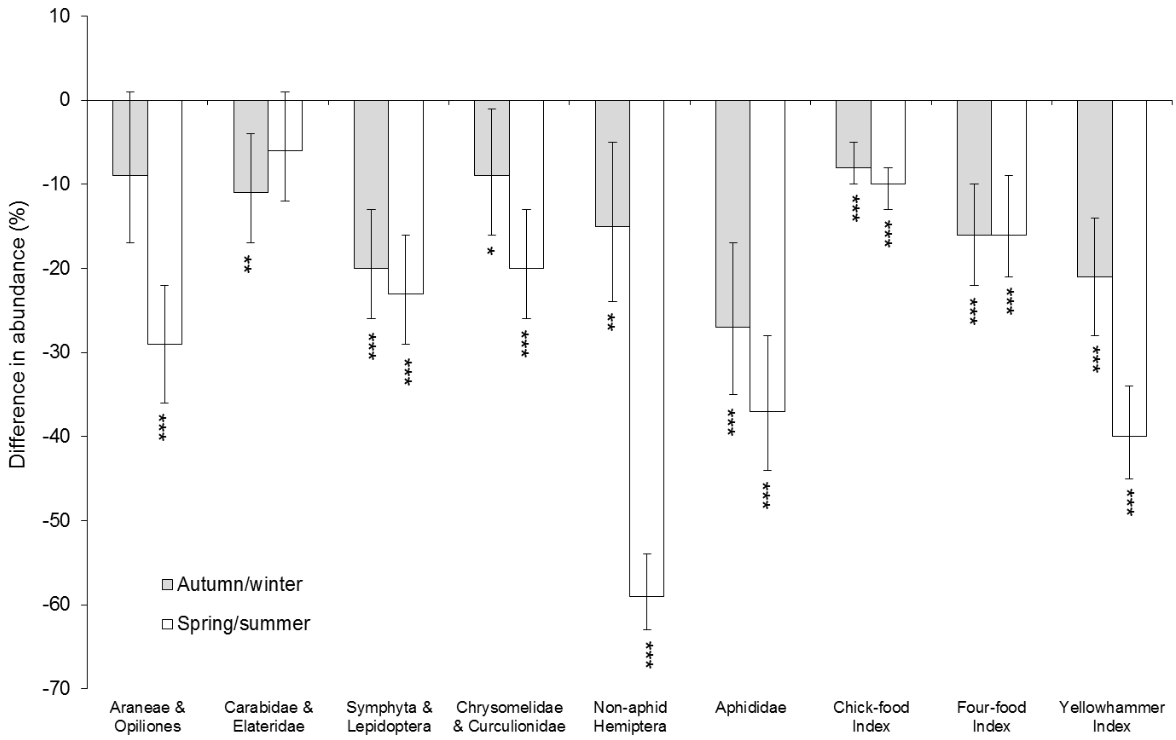

Figure 28. The effect of the timing (autumn/winter or spring/summer) of insecticide applications (controlling for crop, year and the use of other pesticide types, grouped by timing of application) on invertebrate densities on a field-by-field basis. Bars below the line indicate decreases in density and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2588, error bars are 95% confidence intervals.

3.10.4 Invertebrate abundance and insecticide grouped by mode of action

Overall, from 1970 to 2012, controlling for year, crop and the other foliar/residual pesticide applications, pyrethroids, systemic and non-systemic organophosphate use was associated with significantly lower abundances of several of the invertebrate groups examined (Figure 29). The use of pyrethroid insecticides lead to significant declines in the abundance of eight of the nine invertebrate groups, Carabidae & Elateridae (6% lower), Symphyta & Lepidoptera (20% lower), Chrysomelidae & Curculionidae (13% lower), Non-aphid Hemiptera (19% lower), Aphididae (32% lower), CFI (8% lower), 4FI (15% lower) and YHI (24% lower) in fields where pyrethroids were used. The use of systemic organophosphates significantly affected the abundance of Araneae & Opiliones (28% lower) and Non-aphid Hemiptera (47% lower). All nine invertebrate groups were significantly lower in fields where non-systemic organophosphates were used: Araneae & Opiliones (40%), Carabidae & Elateridae (9%), Symphyta & Lepidoptera (23%), Chrysomelidae & Curculionidae (17%), Non-aphid Hemiptera (64%), Aphididae (47%), CFI (12%), 4FI (15%) and YHI (50%). The use of pirimicarb only affected the abundance of Aphididae and YHI, with both higher where it was used, (respectively 44% and 40% higher). Non-aphid Hemiptera, Aphididae and YHI abundance significantly differed between the four types of insecticides; the abundance of these groups was significantly lower in fields with pyrethroid, systemic and non-system organophosphate use, compared to pirimicarb use (Table 17).

Comparing results between the time periods, two invertebrate groups (Aphididae and YHI) differed in their response to both pyrethroid and non-systemic organophosphate use, with both insecticides having less of a negative effect on abundance from 2005 to 2012, compared to the earlier time period. From 1970 to 2004 where pyrethroids and non-systemic organophosphate were used, Aphididae abundance was lower (respectively, 37% and 53% lower), as was YHI (respectively 30% and 54% lower). The use of these two insecticides was still associated with significantly lower abundances of Aphididae from 2005 to 2012, but these declines were significantly less than those from the earlier time period (21% lower where pyrethroids were used and 35% lower where non-systemic organophosphates were used, Table 17). For YHI, the use of pyrethroids from 2005 to 2012 was no longer associated with significant declines, while non-systemic organophosphate use did significantly affect YHI (40% lower) but again this was less of a decline than what was found from 1970 to 2004.

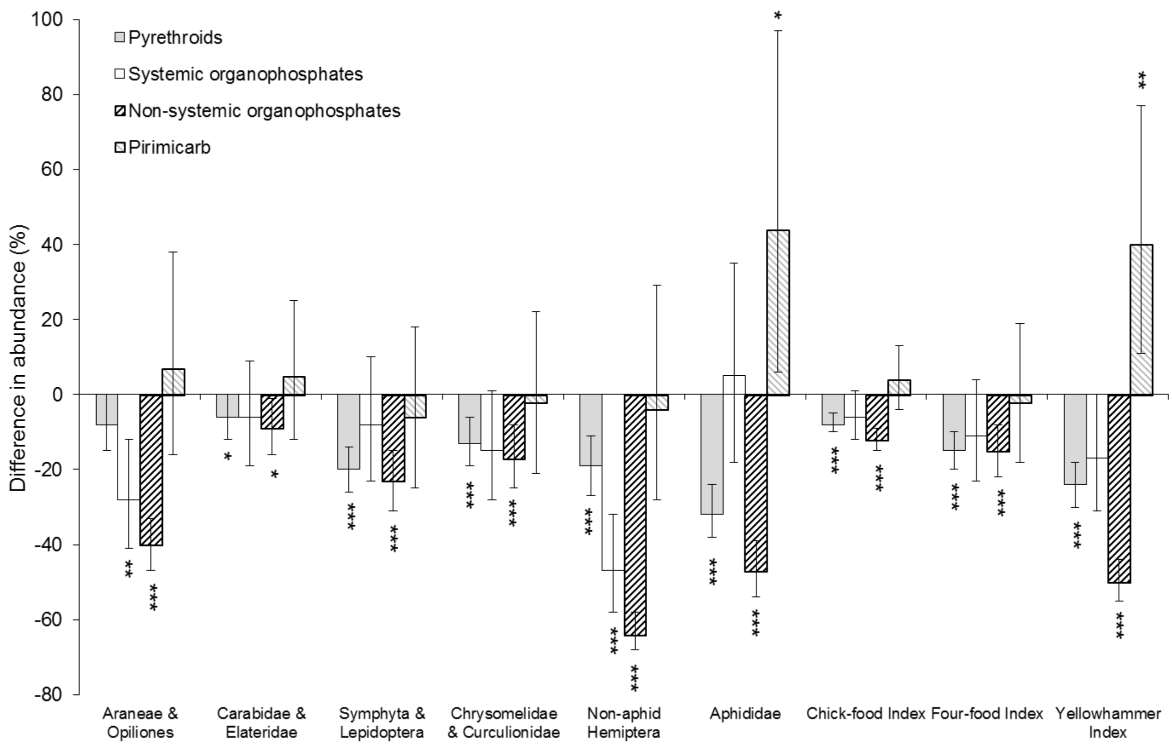

Figure 29. The effect of foliar/residual insecticide used grouped by mode of action (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in density and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 2556, error bars are 95% confidence intervals.

3.10.5 Invertebrate abundance and previous year's insecticide treatment

From 1970 to 2012, the abundance of seven of the nine invertebrate groups was significantly lower where insecticides were used in the previous year, controlling for year, crop, and foliar/residual pesticide applications in the current year and for crop and other foliar/residual pesticide applications in the previous year (Figure 30). The seven invertebrate groups were Araneae & Opiliones (19% lower), Carabidae & Elateridae (11% lower), Symphyta & Lepidoptera (10% lower), Non-aphid Hemiptera (24% lower), Aphididae (21% lower), CFI (5% lower) and YHI (18% lower). There were no significant differences between the time periods in the response of invertebrates to insecticide use in the previous year (Table 18).

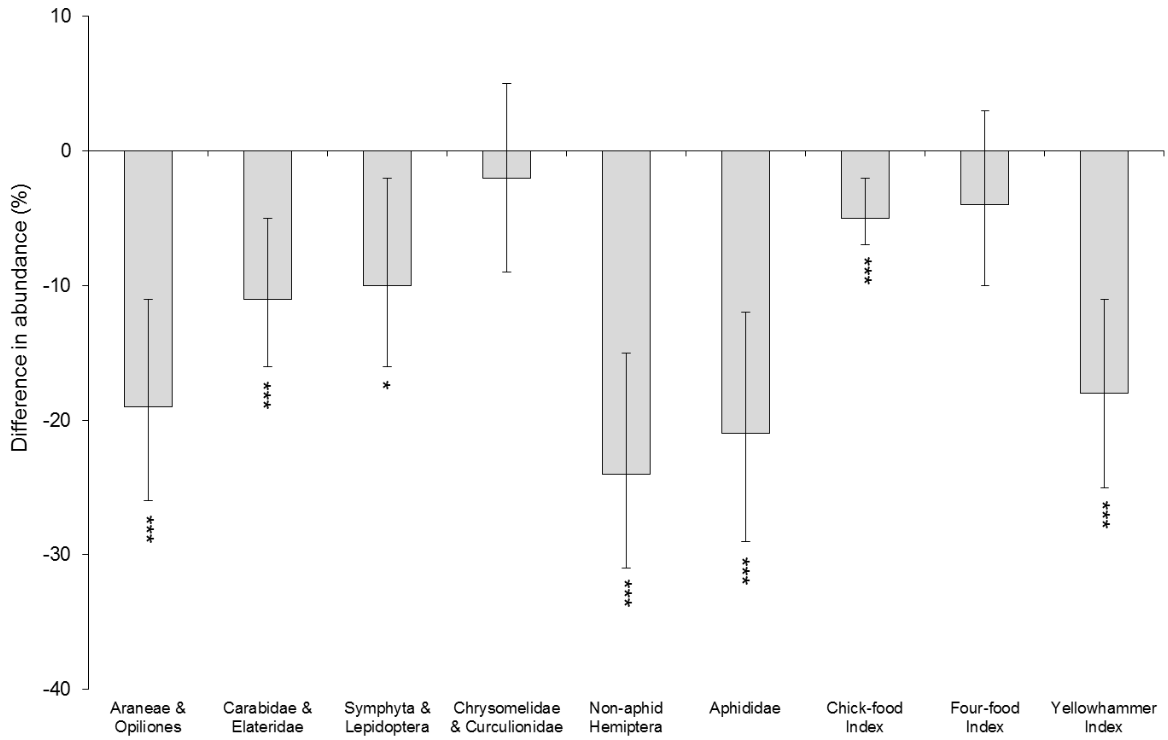

Figure 30. The effect of foliar/residual insecticide use in the previous year (controlling for year, crop in the current and previous year, and the use of other pesticide types in the current and previous year) on invertebrate densities on a field-by-field basis for 1970 – 2012. Bars below the line indicate decreases in density and vice versa. * *P* < 0.05, ** *P* < 0.01, *** *P* < 0.001, sample size is 2044, error bars are 95% confidence intervals.

3.11 Invertebrate abundance and seed treatments

3.11.1 Invertebrate abundance and the use of seed treatments

We restricted the analysis to include only fields where information was available on both foliar/residual applications and seed treatments and controlled for year, crop and the use of foliar/residual pesticide use. From 2003 to 2012, controlling for year, crop and foliar/residual pesticide applications, the abundance of four invertebrate groups was significantly less where seed treatments were used than where they were not (Figure 31). The use of fungicide, neonicotinoid and pyrethroid seed treatments all negatively affected the abundance of Carabidae & Elateridae (28%, 31% and 21% lower where these seed treatments were used, respectively), Symphyta & Lepidoptera (22%, 20% and 24% lower, respectively), Chrysomelidae & Curculionidae (22%, 26% and 29% lower, respectively) and CFI (13%, 15% and 13% lower, respectively). Araneae & Opiliones abundance was lower where fungicide or pyrethroid seed treatment was used, compared to fields where no seed treatment was used (25% and 28% lower, respectively). The abundance of Non-aphid Hemiptera was lower (37%) on fields treated with pyrethroid seed treatment compared to fields with no seed treatments. The only indication of a negative effect of neonicotinoid seed treatments but not fungicide or pyrethroid seed treatments, controlling for foliar applications of pesticides, was for Aphididae abundance, which was significantly lower in fields treated with neonicotinoid seed treatments compared to those treated with fungicide or pyrethroid seed treatments (indicated by the significant 'Test of Difference' in Table 19; $F_{2,621} = 4.59$, $P = 0.011$) but did not differ significantly from the abundance in fields without seed treatment. Conversely fields treated with either fungicide or pyrethroid seed treatment had significantly lower abundance of Araneae & Opiliones compared to fields treated with neonicotinoid seed treatment (indicated by the significant 'Test of Difference' in Table 19; $F_{2,621} = 3.74$, $P = 0.024$).

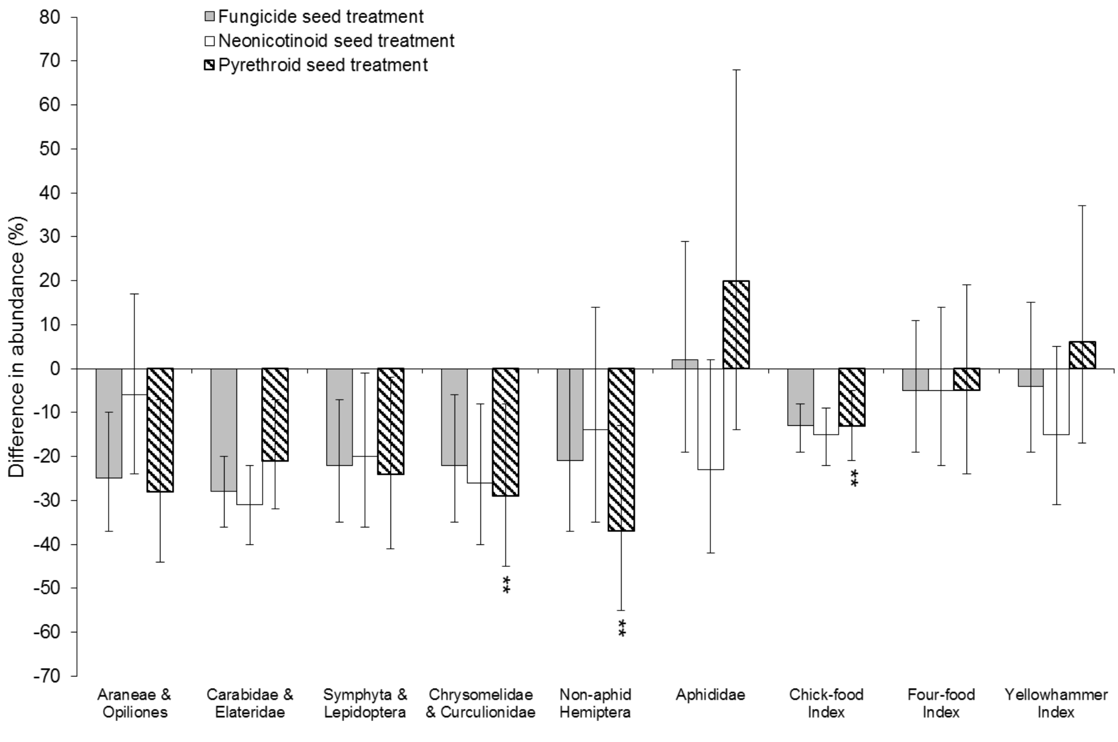

Figure 31. The effect of seed treatment use (controlling for year, crop and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 2003 – 2012, compared to where no seed treatment was used. Bars below the line indicate decreases in density and vice versa. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, sample size is 700, error bars are 95% confidence intervals.

4. Discussion

4.1 Pesticide use: Sussex versus national

Following on from the last analysis of pesticide use on the Sussex Study area which covered the period up to and including 2004 (GCT 2007), measures of the use of foliar/residual pesticides have remained steady across the Sussex Study area and this reflects national figures (Garthwaite et al. 2006, 2010, 2011, 2013). The overall long-term picture from 1970 to 2012 on the Sussex Study area shows increasing pesticide usage, in terms of number of applications and both measures of area treated, which is again reflected in the national pattern. We found that the percentage spray area of herbicide applications in Sussex was 25% lower than national figures and that of fungicide applications in Sussex was 27% lower than national figures. This suggests that results for the effect of herbicide and fungicide use on invertebrates on the Sussex Study may underestimate those for the country as a whole, results for the effect of insecticide use on invertebrate abundance on Sussex will be broadly applicable to other arable systems across Britain, as the insecticide regime is similar to that reported on a national scale. The difference in use from the national figures may reflect a regional difference due to harvest dates, with crops ripening earlier in Sussex than the rest of the UK, as the analysis we undertook adjusted for crop type.

Most of the recent changes in timing and types of pesticides used within the Sussex Study area appear to reflect changes in the cropping regime. The observed move away from winter-sown to spring-sown cereals explains a decline in the use of herbicides and insecticides in autumn/winter, as well as a slight decline in the use of residual herbicides. The most obvious effects of EU legislation on changes in the active substances available for use (EU 1991, Karabelas et al. 2009, Hillocks 2012, Anderson 2014) are the lack of recent use of non-systemic organophosphates (particularly Demeton-methyl, Ewald & Aebischer 1999). Legumex Extra, a herbicide commonly used in the past to control broad-leaved weeds in undersown cereals (Ewald & Aebischer 1999), is also absent from the list of herbicides used since 2005 because one of its components, Benazolin, is no longer approved for use due to this EU legislation.

Use of insecticide seed treatments on the Sussex Study area was consistently higher than the national average, on average 9% greater percentage treated area across the study area when compared to the national figure. In fact the difference could be bigger because the value for the national figure is a worst-case national estimate (see Methods). With the data for foliar insecticides showing consistently similar values for Sussex and the national figures and assuming that seed treatments followed a similar pattern, it seems likely that the higher end of the estimate for national insecticide seed treatment area is closer to the true figure. When considering the higher estimate for the national figures, the percentage treated area for insecticide seed treatment was higher on the Sussex Study in all but two years. This indicates that any effects of insecticide seed treatment on invertebrate abundance in the Sussex Study are likely to be a 'worst case' scenario. The greater use of these seed treatments in Sussex may reflect regional differences in pest risk or timings of sowing of seed in this southern county. It could also be a local perception in risk or in the local availability of seed. Although there is no consistent recording of the exact timing of crop sowing and establishment in the Sussex Study, the more southerly location of the study area would suggest a tendancy for earlier sowing of cereal crops compared to the whole of the UK. This might mean that farmers are more likely to use insecticide seed treatments as earlier autumn sowing would take place when insect pests are still likely to be active, compared to later autumn sowing, when insect pests are less likely to be active.

4.2 Conservation headlands and pesticide applications

Conservation headlands were originally designed to provide chick-food resources for game birds (Sotherton 1991). They have been shown to increase the abundance of some cereal invertebrate taxa (Frampton & Dorne 2007) as well as arable flora (Walker et al. 2007) and are included as options in English agri-environment schemes (Entry Level Scheme – NE 2013a; Higher Level Scheme

– NE, 2013b). It is possible that using fewer pesticide applications on the field margin may encourage farmers to apply more pesticides to the middle of fields. We found that not to be the case for spring cereal and winter wheat crops when considering herbicide and fungicide use, with those fields with conservation headlands having fewer herbicide and fungicide applications. The opposite was found for insecticide use in winter wheat and winter barley/oats crops with conservation headlands which were more likely to have been treated with insecticides. Other research on factors describing pesticide use on arable crops found that pesticide use is driven by farm-to-farm variation in decision making which reflected the "quality of the farmland and the management system adopted by the farmer in question" – i.e. the pattern of use by each farmer (Burger et al. 2012). As the majority of the conservation headlands were found on two of the six large farms in the Sussex Study area, it may be that these findings reflect the individual decision making of these two farmers so these results may not hold for all farmers establishing conservation headlands throughout the UK.

4.3 Use of foliar pesticide applications following neonicotinoid seed treatments

We found a greater propensity for the use of autumn foliar herbicide and insecticide applications on winter cereals treated with neonicotinoid seed treatments and again this may reflect an eaerlier sowing date on the Sussex Study area for those crops treated with these types of seed treatments. It may also indicate that the farmers and agronomists managing these fields may be more risk adverse than those who choose not to use neonicotinoid seed treatments on their cereal crops.

It has been suggested that the use of neonicotinoid seed treatments would lead to a reduction in the use of foliar insecticides (Syngenta 2013). We found little evidence to support this claim within the Sussex Study data on winter cereal crops as fields sown with a neonicotinoid-dressed seed were more likely to receive an autumn foliar insecticide application than fields without such seeds. Budge et al. (2015) have found that autumn-sown oilseed rape treated with neonicotinoid seed treatments have fewer autumn foliar insecticide treatments and our results for this crop in particular support this. One difference in our results with those of other published findings was that Budge et al, (2015) found no difference in spring foliar applications in autumn-sown oilseed rape crops with or without neonicotinoid seed treatment treatment while in the Sussex Study autumn-sown oilseed rape treated with neonicotinoid seed treatments was more likely to be treated with foliar insecticide applications in the spring. This may be further evidence that those farmers on the Sussex Study who do not use neonicotinoid seed treatments are also less likely to use insecticides in general, i.e. are less risk adverse in terms of insect pests.

4.4 Invertebrate abundance and pesticide use

Across all the analyses undertaken on the Sussex dataset (Ewald & Aebischer 1999, GCT 2007 and this work), foliar insecticide use reduced invertebrate abundance consistently and significantly. Both autumn/winter and spring/summer insecticide use were associated with lower invertebrate abundances, for eight of the nine groups we examined, with some evidence to suggest that spring/summer use was slightly more damaging. Organophosphate (both systemic and non-systemic) and pyrethroid insecticides significantly negatively affected the abundance of a broad suite of the invertebrate groups examined, indicating that, in spite of the low amounts of pyrethroid active substances commonly used, these compounds can significantly reduce chick-food abundance. It is therefore encouraging to note that systemic organophosphate use has declined across the study area. As in previous work, we found that foliar insecticide use 'carried-over' into the following year, with the consequences lasting beyond the year in which they were first used.

The effects of herbicide or fungicide use were not as clear-cut as those for insecticide use. Earlier analyses (Ewald & Aebischer 1999, GCT 2007) highlighted the negative effect of spring/summer herbicide use on invertebrate abundance, but from 2005 to 2012 we found that autumn/winter applications of herbicides reduced abundance more than spring/summer ones. Use of broad-spectrum and monocotyledon-specific herbicides was associated with reduced invertebrate abundance, while herbicides applied pre-cultivation as well as those that worked through a combination of contact and residual activity were more damaging to chick-food numbers. Fungicide use overall was not particularly damaging to chick-food invertebrates, but the use of fungicides that were multi-site non-penetrative was associated with lower invertebrate abundance. The use of these types of fungicides has increased across the Sussex Study area. Although our results cannot pinpoint a mechanism, negative effects of fungicides on invertebrate abundance are commonly thought to involve decreases in invertebrate food resources, in particular reduction in food resources for mycophage invertebrates (Aebischer 1991, Potts 1986), although see Sotherton & Moreby (1988) for a direct effect on invertebrates of pyrazophos – which has not been used in the Sussex Study. Interestingly recent research suggests that chlorothalonil (the most commonly used multi-site non-penetrative fungicide used on the Sussex Study area) has a detrimental effect on bee larvae (Zhu et al. 2014), is associated with an increased risk of *Nosema ceranae* infection in bees (Pettis et al., 2013) and it is harmful to *Typhlodromus pyri* in laboratory tests - but harmless to *Aphidius rhopalosiphi* (http://sitem.herts.ac.uk/aeru/ppdb/en/atoz.htm).

The conservation headlands that were used in fields from 2005 to 2012 meant that there were multiple invertebrate sampling locations where no herbicides had been used, allowing us to compare invertebrate abundance on areas with and without herbicide use. We found that aphid abundance was significantly higher where herbicides had been used. Considering the mechanism behind this finding, it should be borne in mind that some invertebrate sampling locations with conservation headlands may still have had a restricted suite of herbicide applied so not all conservation headlands fell into the 'no herbicide' category. This would tend to discount a possible effect of higher insecticide use in the middle of field with conservation headlands leading to this result through spray-drift. Other researchers have found similar results for aphid abundance and herbicide use, suggesting that it is a decline in aphid predators in herbicide-treated fields that leads to an increase in aphids (Sadeghi Namaghi 2007, Michaud & Vargus 2010), similar to effects seen with broad-spectrum insecticide use (Duffield & Aebischer 1994). Our research here centred on the abundance of chick-food invertebrates, of which only two groups contain predators of aphids, Araneae & Opiliones and Carabidae & Elateridae. There were no significant effects of overall herbicide use on the abundance of Araneae & Opiliones, and the abundance of Carabidae & Elateridae was higher in herbicide-treated fields, a response identified previously (Ewald & Aebischer 1999, GCT 2007). It has been surmised that increases in Carabidae particularly may be due to ease of establishment of some species moving into herbicide-treated fields from the field boundary, with other researchers finding similar effects (Powell et al. 1985, Holland & Luff 2000). This result could be examined further by considering invertebrates in these groups grouped according to their function. For example, it would be possible to examine the abundance of aphid-specific versus more generalist predators (Aebischer 1991, Brewer & Elliott 2004), look at the effect of herbicide use on individual Carabidae species abundance and compare with results from pitfall traps, which sample large-bodied Carabidae more efficiently than D-vac sampling (Holland & Luff 2000).

One thing to consider regarding the lower aphid abundance where no herbicides were used is the possible confounding effect of nitrogen fertiliser. Some conservation headlands in our sample (it is unknown what proportion of these were untreated with herbicides) had restricted nitrogen applications. Research into the effect of nitrogen fertiliser applications on aphid abundance indicates that added nitrogen has the potential to increase aphid abundance on winter wheat especially when conditions are favourable (Duffield et al. 1997, Aqueel & Leather 2011). It may be that the difference in herbicide versus none herbicide treated fields is more to do with difference in nitrogen treatment, which would be supported by comparing our results from 2005 to 2012 to results from 1970 to 1995 (Ewald & Aebischer 1999) where no significant difference was found in aphid abundance in herbicide vs. non-herbicide treated fields.

Our results support earlier work on the influence of pesticide use (particularly insecticide use) on the productivity of farmland birds through negative effects on chick-food resources. Although the indirect effect of insecticide **and** herbicide use on grey partridges *Perdix perdix* is well established (Potts 1986, Campbell et al. 1997, Boatman et al. 2004, Newton 2004), most recent research on other species has indicated that insecticide use, rather than herbicide use, is behind most indirect effects of pesticides identified recently. Examples include work on yellowhammer *Emberiza citrinella* (Hart et al. 2006) and corn bunting *Miliaria calandra* (Brickle et al. 2000), which showed that food resources were negatively impacted by insecticide applications. Research on skylark *Alauda arvensis* (Boatman et al. 2004) indicated an effect of insecticide use on chick body condition but no significant effect on food resources.

4.5 Invertebrate abundance and neonicotinoid use

We found few significant effects of neonicotinoid seed treatments on the invertebrate taxa that we examined, taking into consideration the effects of other pesticides commonly applied to crops. In two instances invertebrate abundance on fields treated with neonicotinoid seed treatments did show a significant effect. The abundance of Araneae & Opiliones on fields treated with neonicotinoids did not differ from the abundance on fields with no seed treatment. Conversely, aphid abundance was lower in fields that were treated with neonicotinoid seed treatments compared to fields treated with other seed treatments but did not differ from fields with no seed treatment. These results were not clear-cut but do reflect the difficulty of trying to tease out the effect of seed treatments in a real-life situation with the multitude of pesticide combinations applied to cereal fields. The take-home message from our work must be that foliar insecticide use poses a greater threat overall to the chick-food invertebrate abundance that we examined here during the avian breeding season than do neonicotinoid seed treatments on cereal crops in a field situation. Of course the results of monitoring farmer's pesticide reported use must be compared to the results from experiments designed to examine a specific aspect of pesticide use and at other invertebrate taxa. It does highlight the need for policy-makers and scientists to ensure that restrictions on the use of neonicotinoid seed treatments do not result in increased use of foliar insecticides that are known to have detrimental effects on invertebrates providing chick-food resources (Connolly 2013). We also found that opportunities to limit foliar insecticide use in cereal crops through the use of neonicotinoid seed treatments (Jeschke et al. 2010, Syngenta 2013) did not appear to be exploited across the study area as a whole. Further analysis on the abundance of the other invertebrate taxa identified in the Sussex Study invertebrate monitoring would allow the comparison of the detrimental effects of foliar pesticides and seed treatments, providing further information on the use of these pesticides and non-target invertebrates other than chick-food components.

4.5.1 Comparing our results for neonicotinoid seed treatments to other research

There has been little research into the effect of neonicotinoid seed treatments on chick-food resources within cereal fields (Goulson 2013, Gibbons et al. 2014), beyond the scope of regulatory studies (see **http://www.efsa.europa.eu/en/publications** for regulatory publications), with most research into the effects of neonicotinoid seed treatment examining the effect on bees (Pisa et al. 2014). Research into predatory invertebrates, that provide an essential ecosystem service of pest management, is applicable to the abundance of some of the chick-food invertebrates that we have considered (Chagnon et al. 2014). However, there is little published research relating to an on-farm situation, where exposure is through crops grown from dressed seed and through the soil in which the seed was planted (Hopwood et al. 2013). For maize, studies of the effect of neonicotinoid seed treatment on predatory invertebrates found significant negative effects on the abundance of Heteroptera (Anthocoridae) when measured by visual searching but not when measured via pitfalls, while there were no negative effects on Araneae, Coccinellidae and Dermaptera (Albajes et al. 2003). Laboratory work on neonicotinoid treatment of maize seed has shown a negative effect on the abundance of Carabidae in microcosm bioassays (Mullin et al. 2005). The use of neonicotinoid seed treatment in sugar beet fields was associated with lowered activity of some species of Carabidae and Lyniphiid spiders, but no difference in species composition (Weber et al. 2008). The use of neonicotinoid (imidacloprid- or thiamethoxam-treated soybean seed) was found to significantly reduce overall numbers of predators, particularly Nabidae (Hemiptera) and Chrysopidae (Neuroptera); no effect of seed treatment was detected on the abundance of soybean aphids, thrips, grasshoppers, spiders and harvestmen (Seagreaves & Lundgren 2012). Our results on the decrease in aphid abundance may reflect those of other researchers who found evidence of sub-lethal effects of neonicotinoids on aphids, given that invertebrate sampling in Sussex takes place past the time that neonicotinoids applied through seed treatments are likely to have a lethal effect on aphids (Elbert et al. 2008). Neonicotinoids taken up through seed treatments do persist within treated plants, often at levels lower than those expected to have a lethal effect on invertebrates for some time (see review by Bonmatin et al. 2014). This varies between different crops and within different plants tissues, with most research on neonicotinoids applied through seed being undertaken on maize or oil seed rape, looking at the effect of neonicotinoids or their breakdown products on honeybees and bumblebees (see review by Pisa et al. 2014). Other researchers have found sub-lethal effects on aphid feeding behaviour and reproduction associated with low concentrations of neonicotinoids applied to wheat seeds (Daniels et al. 2009, Miao et al. 2014). Of note in our results may be the increased abundance of Araneae & Opiliones in fields with neonicotinoid seed treatments which may have had a negative effect on aphid abundance as Araneae (spiders) are known to predate aphids. Our findings overall though are in contrast to those of Hallmann et al. (2014), who hypothesized a connection between declines in farmland birds and increases in concentrations of neonicotinoid pollution in water bodies acting through a deleterious effect of neonicotinoids on invertebrate food resources across the Netherlands (van Dijk et al. 2013). Our research covers a localised area where seed treatments are the only source of neonicotinoids in the environment, which differs from the one described in Hallmann et al. (2014), where the highest concentrations of neonicotinoids in the environment was found in areas predominated by glasshouses and bulb growing (van Dijk et al. 2013). Our findings that foliar insecticide applications are more damaging to chick-food invertebrates than neonicotinoid seed treatments would support the need to consider the effects of other chemicals concurrent with neonicotinoid use as suggested by Vijver and van den Brink (2014).

Most of the research on the effect of neonicotinoid seed treatments on invertebrates has concentrated on pollinators, particularly bees, with some researchers finding effects on feeding rate (Cresswell et al. 2012), foraging behaviour (Gill et al. 2012) and negative effects on colony growth and survival (Whitehorn et al. 2012), while others do not (Pilling et al. 2013). Discussion continues (Walters 2013, Godfray et al. 2014, Pisa et al. 2014), with a need for more work looking at effects in the field at a large-enough scale to detect a difference (Cresswell 2011), reflecting the management decisions taken by farmers, as is the case in the Sussex Study.

4.6 Research and management considerations

The EU restriction on the use of three types of neonicotinoid seed treatment on flowering crops (EC 2013) provided the impetus for research into the effects of pesticides on non-target invertebrates. The renewed interest into the effects of pesticide use on non-target invertebrates in particular and arable management in general should provide an opportunity to reconsider the balance between Integrated Pest Management (IPM) and pesticide use (Mole et al. 2013, Walters 2013). How neonicotinoid seed treatments fit into IPM of cereals is uncertain. Our results do not indicate that the use of neonicotinoid seed treatments has led to a decline in foliar insecticides applications in cereal crops which this work, previous analyses of the Sussex Study dataset, and other researchers have indicated are damaging to chick-food invertebrates and chicks of declining farmland birds. Compared to the results for foliar insecticides, we did not find similar broad-scale declines in chick-food invertebrates when neonicotinoid seed treatments were used as compared to other seed treatments, with declines for specifically neonicotinoid treatments found only for aphids, a group that contains cereal pests as well as functioning as a food resource for farmland bird chicks. These results seem to indicate that foliar insecticide applications are more of a threat to the abundance of chick-food invertebrates examined here than the use of neonicotinoid seed treatments, in a cereal ecosystem (although see caveats below on all seed dressings). This indicates that it may be possible to limit the use of foliar applications (particularly those directed at controlling Aphididae and BYDV) with targeted use of neonicotinoid seed treatments, together with changes to cereal management. The use of conservation tillage, in combination with neonicotinoid seed treatments for winter cereals and reduced foliar insecticide applications, may be worthy of further investigation, although results on this so far have been equivocal (Kennedy et al. 2010, 2012). Since we found that seed treatments as a whole were associated with lower abundances of several groups of invertebrates, namely Carabidae & Elateridae, Chrysomelidae & Curculionidae and CFI, further research is definitely needed before a combination of seed treatments and minimum tillage could be advocated as a means of minimising foliar insecticide applications. The caveat to this is to bear in mind that most of the fields that were not treated with seed treatments of any kind in our study were on one farm. Further research is urgently needed into designing a control programme for BYDV in cereals that includes practical thresholds for using seed treatments and foliar insecticides, in combination with the development of resistant varieties of cereals, similar to what has been done for Wheat Orange Blossom Midge *Sitodiplosis mosellana* (Oakley et al. 2005, HGCA 2009). It would fit in with the move to IPM across Europe (EC 2008, 2009). Based on our results showing the negative effect of foliar insecticide applications on chick-food insects, there is a need to avoid an increase in the use of foliar insecticides when seeking to limit any negative effects of neonicotinoid-based seed treatments. Active research into this trade-off, involving the crop protection industry, farmers and policymakers, would help ensure that professional users of pesticides have the knowledge necessary to follow the principals of integrated pest management, as required by the Sustainable Use Directive (Directive 2009/128/EC).

Since 2003, one farm on the Sussex Study area, which has used neonicotinoid seed treatments on cereals, has undertaken management to restore a wild grey partridge shoot (Ewald et al. 2012). This includes agri-environmental options from the Higher Level Schemes (HLS) agri-environmental schemes (NE 2013b), in particular, conservation headland (HF14) and reduced input cereal (HG7) options. Not only have grey partridges increased but so have other farmland birds, particularly those that are red-listed (Eaton et al. 2009, Potts 2012), indicating it is possible to recover farmland birds on farms using neonicotinoid seed treatments and specifically limited foliar pesticides by applying agri-environmental options designed to benefit the food resources of breeding farmland birds (Sotherton 1991, Frampton & Dorne 2007). Decreasing foliar insecticides increases the quantity of chick-food resources within cereal ecosystems. Less foliar insecticide use results in more chick-food resources within a cereal ecosystem.

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7. Tables

Table 1. Foliar/residual herbicide use (percentage fields treated) in relation to whether crops were grown with and without neonicotinoid seed treatments for five broad types of crops from 2003 to 2012, as well as the specific type of break crop grown. Results are chi-square analysis (with Yates' correction) of the proportions of fields treated with herbicides.

Crop	Autumn herbicide			Spring herbicide		
	No neonicotinoid seed treatment (N)	Neonicotinoid seed treatment (N)	Chi-square	No neonicotinoid seed treatment (N)	Neonicotinoid seed treatment (N)	Chi-square
Spring cereal				99.0% (397)	100% (3)	-
Winter wheat	72.4% (196)	96.7% (184)	40.31***	93.4% (196)	94.0% (184)	0.01
Winter barley/oats	50.0% (10)	100% (72)	30.10***	100% (10)	72.2% (72)	2.32
Autumn break crops	92.3% (13)	100% (52)	0.02	61.5% (13)	96.2% (52)	16.59***
Winter oilseed rape	100% (9)	100% (50)	-	44.4% (9)	100% (50)	23.61***
Winter beans	75% (4)	100% (2)	-	100% (4)	0% (2)	-
Spring break crops				90.7% (43)	100% (41)	2.22
Spring oilseed rape				55.6% (9)	100% (14)	4.76*
Fodder beet				100% (3)	100% (10)	-
Peas				100% (30)	-	-
Linseed				100% (1)	100% (17)	-

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Table 2. Foliar fungicide use (percentage fields treated) in relation to whether crops were grown with and without neonicotinoid seed treatments for five broad types of crops from 2003 to 2012, as well as the specific type of break crop grown. Results are chi-square analysis (with Yates' correction) of the proportions of fields treated with fungicides.

Crop		Fungicide		
		No neonicotinoid seed treatment (N)	Neonicotinoid seed treatment (N)	Chi-square
Spring cereal		99.2% (397)	100% (3)	-
Winter wheat		99.0% (196)	100% (184)	0.44
Winter barley/oats		100% (10)	100% (72)	-
Autumn break crops		100% (13)	94.2% (52)	0.02
	Winter oilseed rape	100% (9)	94.0% (50)	0.01
	Winter beans	100% (4)	100% (2)	-
Spring break crops		76.7% (43)	65.9% (41)	0.74
	Spring oilseed rape	0% (9)	85.7% (14)	12.88*
	Fodder beet	100% (3)	90.0% (10)	-
	Peas	100% (30)	-	-
	Linseed	0% (1)	35.3% (17)	-

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Table 3. Foliar insecticide use (percentage fields treated) in relation to whether crops were grown with and without neonicotinoid seed treatments for five broad types of crops from 2003 to 2012, as well as the specific type of break crop grown. Results are chi-square analysis (with Yates' correction) of the proportions of fields treated with insecticides.

Crop	Autumn insecticide			Spring insecticide		
	No neonicotinoid seed treatment (N)	Neonicotinoid seed treatment (N)	Chi-square	No neonicotinoid seed treatment (N)	Neonicotinoid seed treatment (N)	Chi-square
Spring cereal				8.8% (397)	0% (3)	-
Winter wheat	62.8% (196)	82.6% (184)	17.73***	30.6% (196)	23.4% (184)	2.17
Winter barley/oats	20.0% (10)	93.1% (72)	29.87***	0% (10)	2.8% (72)	0.31
Autumn break crops	69.2% (13)	50.0% (52)	0.87	61.5% (13)	80.8% (52)	1.22
Winter oilseed rape	100% (9)	52.0% (50)	5.43*	44.4% (9)	84.0% (50)	4.83*
Winter beans	0% (4)	0% (2)	-	100% (4)	0% (2)	-
Spring break crops				88.4% (43)	68.3% (41)	3.90*
Spring oilseed rape				100% (9)	100% (14)	-
Fodder beet				100% (3)	0% (10)	-
Peas				86.7% (30)	-	-
Linseed				0% (1)	82.4% (17)	-

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Table 4. Foliar/residual herbicide use. The effect of herbicide use (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant (*P* < 0.05) difference in the slope between time periods (as shown by the F-ratio which tested for an interaction between time period and herbicide use), that is invertebrate density responded differently to herbicide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate abundance decreased with the use of herbicides and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,2534}$)	1970-2012
Araneae & Opiliones	14	-13	**5.44***	0
Carabidae & Elateridae	0	24***	**7.00****	7
Symphyta & Lepidoptera	0	14	1.75	8
Chrysomelidae & Curculionidae	-11*	-9	0.07	-12**
Non-aphid Hemiptera	6	-16	2.79	-1
Aphididae	-12	88***	**28.67*****	22**
Chick-food Index	-3	4	**3.92***	-1
Four-food Index	-2	-1	0.01	-4
Yellowhammer Index	-6	22*	**5.90***	6

* *P* < 0.05, ** *P* < 0.01, *** *P* < 0.001.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 5. Foliar/residual herbicide applications. The effect of increasing numbers of herbicide applications (controlling for crop, year and the increasing numbers of applications of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tests for an interaction between time period and herbicide applications), that is invertebrate density responded differently to herbicide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative slope shows that invertebrate abundance decreased with the number of herbicide applications and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,2534}$)	1970-2012
Araneae & Opiliones	0.0711**	-0.0290	**9.62****	0.0313*
Carabidae & Elateridae	0.0116	0.0567***	3.69	0.0298**
Symphyta & Lepidoptera	-0.0063	0.0406	2.56	0.0144
Chrysomelidae & Curculionidae	-0.0254	0.0456	**6.34***	0.0078
Non-aphid Hemiptera	0.0310	-0.1405***	**19.60*****	-0.0537**
Aphididae	-0.0606*	0.0856**	**12.84*****	0.0283
Chick-food Index	-0.0067	0.0161	**4.82***	0.0030
Four-food Index	-0.0125	0.0316	3.25	0.0096
Yellowhammer Index	-0.0201	0.0216	1.87	0.0126

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 6. Timing of foliar/residual herbicide use. The effect of the timing of herbicide use (controlling for crop, year and the use of other pesticide types, grouped by timing of application) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant (*P* < 0.05) difference in the slope between time periods (as shown by the F-ratio which tests for an interaction between time period and herbicide use), that is invertebrate density responded differently to herbicide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate abundance decreased with the use of herbicides and vice versa. In each time period we tested whether or not the effects of autumn application differed from those of spring application, on an herbicide by herbicide basis.

Invertebrate group[1]	1970-2004			2005-2012			Comparison of slopes between time periods ($F_{1,2531}$)		1970-2012		
	Autumn/ winter	Spring/ summer	Test of differences $F_{1,1125}$	Autumn/ winter	Spring/ summer	Test of differences $F_{1,345}$	Autumn/ winter	Spring/ summer	Autumn/ winter	Spring/ summer	Test of differences $F_{1,1476}$
Araneae & Opiliones	1	10	2.43	5	-18***	7.39**	0.28	**13.32*** **	2	-2	0.03
Carabidae & Elateridae	14**	-1	5.26*	-3	17***	3.85	**6.82** **	**8.75** **	8**	5	1.35
Symphyta & Lepidoptera	4	-2	2.53	0	0	0.89	0.22	0.10	2	-2	4.49*
Chrysomelidae & Curculionidae	-1	-14***	8.55**	-18**	1	3.48	**5.82* **	**7.86** **	-6	-10***	1.41
Non-aphid Hemiptera	9	2	0.47	-17*	-28***	3.31	**5.87* **	**13.50*** **	-3	-12**	4.37*
Aphididae	0	-7	0.03	-32***	92***	27.33***	**12.14*** **	**63.26*** **	-8	22***	7.09**
Chick-food Index	4*	-4**	12.27***	-7**	3	1.49	**15.53*** **	**7.39** **	0	-3*	5.04*
Four-food Index	1	-4	1.04	1	-7	0.61	0.01	0.59	1	-6*	2.14
Yellowhammer Index	0	-4	0.11	-24***	27***	9.03**	**10.12** **	**18.07*** **	-7	6	1.90

* *P* < 0.05, ** *P* < 0.01, *** *P* < 0.001.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all year

Table 7. Herbicide specificity. The effect of the type of herbicide used grouped by specificity (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tests for an interaction between time period and type of herbicide), that is invertebrate densities responded differently to either broad-spectrum or specific herbicide applications in 2005-2012 compared to 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate densities decreased with herbicide use and vice versa. In each time period we tested whether or not the effects of broad-spectrum herbicide applications differed from those for specific herbicide application.

Invertebrate group[1]	1970-2004				2005-2012				Comparison of slopes between time periods ($F_{1,1839}$)			1970-2012			
	Dicot specific	Monocot specific	Broad-spectrum	Test of differences $F_{2,533}$	Dicot specific	Monocot specific	Broad-spectrum	Test of differences $F_{2,171}$	Dicot specific	Monocot specific	Broad-spectrum	Dicot specific	Monocot specific	Broad-spectrum	Test of differences F_{710}
Araneae & Opiliones	20**	1	9	1.13	-8	-21***	15*	2.87	**10.25****	**8.14****	0.37	5	-11**	8	0.8
Carabidae & Elateridae	5	6	2	0.23	13**	4	6	2.11	1.45	0.18	0.03	9**	5	4	0.93
Symphyta & Lepidoptera	-1	-3	-6	0.23	2	-7	6	3.34*	0.06	0.18	**5.08***	1	-7	-1	1.61
Chrysomelidae & Curculionidae	-3	-3	-1	0.55	0	0	-7	1.66	0.39	0.15	1.78	-3	1	-3	0.69
Non-aphid Hemiptera	10	1	1	1.27	-15*	-24***	-12	2.40	**6.71****	**6.70****	1.07	-4	-17***	-9	0.64
Aphididae	17*	-10	-3	2.83	60***	13	-30***	10.54***	**8.22****	**7.16****	1.78	35***	3	-10*	8.08***
Chick-food Index	-1	0	-1	0.03	2	-1	-2	3.22*	1.28	0.20	0.17	0	0	-1	0.98
Four-food Index	-6	-2	-5	0.79	-3	-5	11	1.15	0.16	0.30	**5.57***	-4	-2	1	2.49
Yellowhammer Index	15*	-6	-2	2.57	21***	-1	-20***	3.74*	0.21	1.43	0.45	18***	-4	-8*	3.81*

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1129 from 1970 to 2004, 766 from 2005 to 2012 and 1895 over all years.

Table 8. Herbicide mode of action. The effect of the type of herbicide used grouped by mode of action (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant (P < 0.05) difference in the slope between time periods (as shown by the F-ratio, which tests for an interaction between time periods and type of herbicide), that is invertebrate densities responded differently to either pre-cultivation, contact, residual or contact + residual herbicide applications in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate densities decreased with herbicide use and vice versa. In each time period we tested whether or not the effects of different types of herbicide applications differed from each other.

Invertebrate group[1]	1970-2004					2005-2012					Comparison of slopes between time periods ($F_{1,1797}$)				2005-2012				
	Pre-cultivation	Contact	Residual	Contact + residual	Test of differences $F_{3,525}$	Pre-cultivation	Contact	Residual	Contact + residual	Test of differences $F_{3,206}$	Pre-cultivation	Contact	Residual	Contact + residual	Pre-cultivation	Contact	Residual	Contact + residual	Test of differences $F_{3,738}$
Araneae & Opiliones	0	15*	-3	-7	0.92	-17**	-12*	15*	-1	4.82**	4.55*	9.63**	2.91	0.39	-10*	1	3	-5	0.49
Carabidae & Elateridae	-9*	1	7	4	0.80	-7	18***	16***	-10*	0.35	0.12	7.46**	0.85	6.04*	-7*	8**	11**	-1	1.20
Symphyta & Lepidoptera	-7	5	-10	-4	0.13	-11	5	23	-10**	0.92	0.27	0.01	19.20***	0.33	-8	5	3	-6	0.03
Chrysomelidae & Curculionidae	-11*	-6	0	-5	0.28	-10	-1	7	-13	1.01	0.01	0.73	0.02	1.77	-9*	-4	3	-10*	0.31
Non-aphid Hemiptera	-14*	6	-3	-20**	1.43	-38***	-21**	1	11	4.56**	9.61**	7.32**	0.24	8.36**	-28***	-8	-2	-7	1.18
Aphididae	-10	18*	-11	-7	2.35	-22**	99***	-26***	-19*	8.61***	0.99	25.60***	0.13	0.24	-10	48***	-18***	-11*	6.05***
Chick-food Index	-5**	-6***	-1	-2	0.75	-7**	4	6*	-5	0.10	0.70	3.1	5.35*	2.01	-6***	0	1	-2	0.59
Four-food Index	-7	-1	-8	-4	0.48	-2	-5	22***	-11*	1.15	0.55	0.85	15.40***	1.24	-4	-3	4	-7	0.80
Yellowhammer Index	-9	12*	-10	-8	4.22**	-21***	33***	-19**	-13*	2.01	1.62	5.31*	0.58	0.01	-12***	21***	-14***	-9*	4.70**

* P < 0.05, ** P < 0.01, *** P < 0.001.

1. The sample size for all groups is 1089 from 1970 to 2004, 766 from 2005 to 2012 and 1855 over all years.

Table 9. Foliar/residual herbicide use in previous year. The effect of herbicide use in the previous year (controlling for crop, year, pesticide treatment in the current year and for crop and the application of other pesticide types in the previous year) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio, which tests for an interaction between time period and pesticide use), that is invertebrate densities responded differently to pesticide use in the previous year in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate densities decreased with the use of herbicides in the previous year and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,1983}$)	1970-2012
Araneae & Opiliones	19**	-9	3.81	9
Carabidae & Elateridae	6	2	0.24	7
Symphyta & Lepidoptera	-1	-6	0.01	0
Chrysomelidae & Curculionidae	3	-3	0.09	-1
Non-aphid Hemiptera	4	0	0.18	1
Aphididae	13	29	**4.20***	19**
Chick-food Index	2	0	0.05	2
Four-food Index	3	-3	0.22	1
Yellowhammer Index	10	11	0.83	9

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1466 from 1970 to 2004, 578 from 2005 to 2012 and 2044 over all years.

Table 10. Foliar/residual fungicide use. The effect of fungicide use (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tested for an interaction between time period and fungicide use), that is invertebrate density responded differently to fungicide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate abundance decreased with the use of fungicides and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,2534}$)	1970-2012
Araneae & Opiliones	-15**	-5	0.59	-13**
Carabidae & Elateridae	8	-4	1.37	7*
Symphyta & Lepidoptera	0	-2	0.01	-2
Chrysomelidae & Curculionidae	-6	7	1.19	-2
Non-aphid Hemiptera	-11	-11	0.01	-13*
Aphididae	-7	-1	0.13	-4
Chick-food Index	1	-5	1.80	1
Four-food Index	3	-9	1.47	1
Yellowhammer Index	-8	6	1.13	-6

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 11. Foliar/residual fungicide applications. The effect of increasing numbers of fungicide applications (controlling for crop, year and the increasing numbers of applications of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tests for an interaction between time period and fungicide applications), that is invertebrate density responded differently to fungicide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative slope shows that invertebrate abundance decreased with the number of fungicide applications and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,2534}$)	1970-2012
Araneae & Opiliones	-0.0967***	-0.0588	0.86	-0.0913***
Carabidae & Elateridae	0.0448*	-0.0287	**6.13***	0.0211
Symphyta & Lepidoptera	-0.0504*	-0.0339	0.20	-0.0409*
Chrysomelidae & Curculionidae	-0.0205	-0.0660*	1.63	-0.0372*
Non-aphid Hemiptera	-0.0654*	-0.0131	1.14	-0.0540*
Aphididae	-0.0420	0.0546	3.51	0.0031
Chick-food Index	0.0017	-0.0265*	**4.62***	-0.0083
Four-food Index	-0.0266	-0.0476	0.46	-0.0346*
Yellowhammer Index	-0.0559*	0.0166	3.55	-0.0267

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 12. Fungicide mode of action. The effect of the type of fungicide used grouped by mode of action (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio, which tests for an interaction between the two time periods and the type of fungicide), that is invertebrate densities responded differently to either site-specific/penetrative or multi-site/non-penetrative fungicide applications in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density of treated v. untreated. A negative value shows that invertebrate densities decreased with fungicide use and vice versa. In each time period we tested whether or not the effects of different types of fungicide applications differed from each other.

Invertebrate group[1]	1970-2004			2005-2012		Comparison of slopes between time periods ($F_{1,2436}$)		1970-2012		
	Site-specific/ penetrative	Multi-site/ non-penetrative	Test of differences $F_{1,753}$	Site-specific/ penetrative	Multi-site/ non-penetrative	Site-specific/ penetrative	Multi-site/ non-penetrative	Site-specific/ penetrative	Multi-site/ non-penetrative	Test of differences $F_{1,1045}$
Araneae & Opiliones	-22	-31***	0.82	51	-11	2.63	**7.65****	-1	-21***	0.14
Carabidae & Elateridae	-2	-9*	0.14	0	18***	0.01	**15.71*****	2	0	1.02
Symphyta & Lepidoptera	18	-11*	2.86	24	2	1.22	**4.62***	13	-7*	2.38
Chrysomelidae & Curculionidae	-5	-9*	0.41	-5	-18**	0.49	0.16	-2	-9*	0.25
Non-aphid Hemiptera	-14	-24***	1.41	5	-19*	0.05	0.34	-2	-19***	1.10
Aphididae	1	-15*	0.50	22	50***	2.95	**31.78*****	1	4	0.51
Chick-food Index	2	-5**	1.54	10	2	0.09	**5.79***	5	-2	1.12
Four-food Index	4	-12***	0.04	28	-3	0.20	1.92	14	-9**	0.01
Yellowhammer Index	1	-20***	2.94	18	21**	2.23	**29.81*****	4	-6	2.53

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1724 from 1970 to 2004, 766 from 2005 to 2012 and 2490 over all years.

Table 13. Foliar/residual fungicide use in previous year. The effect of fungicide use in the previous year (controlling for crop, year, pesticide treatment in the current year and for crop and the application of other pesticide types in the previous year) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F ratio, which tests for an interaction between the two time periods and pesticide use), that is invertebrate densities responded differently to pesticide use in the previous year in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density of treated v. untreated. A negative value shows that invertebrate densities decreased with the use of fungicide in the previous year and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,1983}$)	1970-2012
Araneae & Opiliones	-3	0	1.35	-1
Carabidae & Elateridae	-1	5	0.86	2
Symphyta & Lepidoptera	3	13	0.03	5
Chrysomelidae & Curculionidae	4	-2	0.05	3
Non-aphid Hemiptera	-1	-18	0.54	-5
Aphididae	12	-12	1.08	7
Chick-food Index	1	4	0.71	1
Four-food Index	-5	5	0.33	-3
Yellowhammer Index	5	-5	0.02	4

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1466 from 1970 to 2004, 578 from 2005 to 2012 and 2044 over all years.

Table 14. Foliar/residual insecticide use. The effect of insecticide use (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tested for an interaction between time period and insecticide use), that is invertebrate density responded differently to insecticide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate abundance decreased with the use of insecticides and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,2534}$)	1970-2012
Araneae & Opiliones	-12*	-3	1.26	-11**
Carabidae & Elateridae	-4	-10*	1.15	-6*
Symphyta & Lepidoptera	-27***	-14*	**4.41***	-21**
Chrysomelidae & Curculionidae	-10*	-17**	1.38	-14***
Non-aphid Hemiptera	-33***	-30***	0.12	-31***
Aphididae	-42***	-23**	**7.21****	-35***
Chick-food Index	-7***	-9***	0.51	-8***
Four-food Index	-17***	-12*	0.95	-16***
Yellowhammer Index	-36***	-15*	**12.88*****	-29***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 15. Foliar/residual insecticide applications. The effect of increasing numbers of insecticide applications (controlling for crop, year and the increasing numbers of applications of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tests for an interaction between time period and insecticide applications), that is invertebrate density responded differently to insecticide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative slope shows that invertebrate abundance decreased with the number of insecticide applications and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,2534}$)	1970-2012
Araneae & Opiliones	-0.2128***	-0.0906*	**5.41***	-0.1813***
Carabidae & Elateridae	-0.0765***	-0.0670*	0.06	-0.0747***
Symphyta & Lepidoptera	-0.1481***	-0.1839***	0.56	-0.1570***
Chrysomelidae & Curculionidae	-0.0920***	-0.1461***	1.38	-0.1105***
Non-aphid Hemiptera	-0.4026***	-0.3110***	2.10	-0.3648***
Aphididae	-0.3220***	-0.2733***	0.54	-0.3314***
Chick-food Index	-0.0637***	-0.0744***	0.41	-0.0672***
Four-food Index	-0.1002***	-0.1269***	0.45	-0.1110***
Yellowhammer Index	-0.3210***	-0.2229***	**3.92***	-0.3055***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 16. Timing of foliar/residual insecticide use. The effect of the timing of insecticide use (controlling for crop, year and the use of other pesticide types, grouped by timing of application) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio which tests for an interaction between time period and insecticide use), that is invertebrate density responded differently to insecticide use in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density in treated v. untreated fields. A negative value shows that invertebrate abundance decreased with the use of insecticides and vice versa. In each time period we tested whether or not the effects of autumn application differed from those of spring application, on an insecticide by insecticide basis.

Invertebrate group[1]	1970-2004			2005-2012			Comparison of slopes between time periods ($F_{1,2531}$)		1970-2012		
	Autumn/ winter	Spring/ summer	Test of differences $F_{1,495}$	Autumn/ winter	Spring/ summer	Test of differences $F_{1,281}$	Autumn/ winter	Spring/ summer	Autumn/ winter	Spring/ summer	Test of differences $F_{1,782}$
Araneae & Opiliones	-10	-27***	1.04	5	-33***	2.84	2.23	0.60	-9	-29***	4.29*
Carabidae & Elateridae	-12**	-8	5.45*	-6	-5	0.03	0.09	0.15	-11**	-6	4.57*
Symphyta & Lepidoptera	-27***	-19***	0.10	-9	-29***	0.59	**5.94***	1.76	-20***	-23***	0.85
Chrysomelidae & Curculionidae	-9	-19***	3.68	2	-28***	6.37*	1.39	1.41	-9*	-20***	8.70**
Non-aphid Hemiptera	-26***	-53***	8.39**	3	-66***	21.83***	**7.38****	**6.58***	-15**	-59***	23.02***
Aphididae	-39***	-38***	10.16**	22*	-45***	10.22***	**28.28*****	0.74	-27***	-37***	13.18***
Chick-food Index	-10***	-9***	0.02	0	-15***	8.89**	**10.50****	**4.64***	-8***	-10***	3.03
Four-food Index	-17***	-15***	0.43	-11	-19**	1.01	1.02	0.58	-16***	-16***	0.06
Yellowhammer Index	-32***	-42***	14.65***	16	-42***	13.28***	**29.34*****	0.01	-21***	-40***	21.68***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1822 from 1970 to 2004, 766 from 2005 to 2012 and 2588 over all years.

Table 17. Insecticide mode of action. The effect of the type of insecticide used grouped by mode of action (controlling for crop, year and the use of other pesticide types) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio, which tests for an interaction between the two time periods and the type of insecticide), that is invertebrate densities responded differently to either pyrethroid, systemic or non-systemic organophosphates or pirimicarb applications in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density of treated v. untreated. A negative value shows that invertebrate densities decreased with insecticide use and vice versa. In each time period we tested whether or not the effects of different types of insecticide applications differed from each other.

Invertebrate group[1]	1970-2004					2005-2012				Comparison of slopes between time periods ($F_{1,2499}$)			1970-2012				
	Pyrethroids	Systemic organo-phosphates	Non-systemic organo-phosphates	Pirimicarb	Test of differences $F_{3,417}$	Pyrethroids	Non-systemic organo-phosphates	Pirimicarb	Test of differences $F_{3,297}$	Pyrethroids	Non-systemic organo-phosphates	Pirimicarb	Pyrethroids	Systemic organo-phosphates	Non-systemic organo-phosphates	Pirimicarb	Test of differences $F_{3,720}$
Araneae & Opiliones	-7	-27**	-44***	11	3.64*	0	-32***	0	0.12	0.26	2.42	0.15	-8	-28**	-40***	7	2.13
Carabidae & Elateridae	-4	-8	-12*	8	1.31	-11**	-4	-8	0.30	0.78	1.04	0.50	-6*	-6	-9*	5	0.86
Symphyta & Lepidoptera	-26***	-8	-22***	-3	0.61	-15*	-26**	-13	2.39	3.86	0.19	0.14	-20***	-8	-23***	-6	0.52
Chrysomelidae & Curculionidae	-8	-16*	-17**	1	0.5	-16**	-18*	-15	0.34	1.32	0.00	0.38	-13***	-15	-17***	-2	0.28
Non-aphid Hemiptera	-23***	-44***	-62***	3	3.37*	-17*	-66***	-21	4.40*	0.27	0.60	0.53	-19***	-47***	-64***	-4	6.44***
Aphididae	-37***	-3	-53***	44*	4.74**	-21**	-35***	60	2.04	**7.27****	**5.19***	0.15	-32***	5	-47***	44*	2.82*
Chick-food Index	-7***	-7*	-12***	7	0.63	-9***	-11***	-6	0.21	0.06	0.07	1.46	-8***	-6	-12***	4	0.65
Four-food Index	-16***	-12	-15**	4	0.61	-14**	-15	-20	1.88	0.17	0.00	1.23	-15***	-11	-15***	-2	0.42
Yellowhammer Index	-30***	-19*	-54***	46**	9.59***	-11	-40***	37	2.61	**10.21****	**5.94***	0.02	-24***	-17	-50***	40**	7.03***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1790 from 1970 to 2004, 766 from 2005 to 2012 and 2556 over all years.

Table 18. Foliar/residual insecticide use in previous year. The effect of insecticide use in the previous year (controlling for crop, year, pesticide treatment in the current year and for crop and the application of other pesticide types in the previous year) on invertebrate densities on a field-by-field basis for 1970-2004, 2005-2012 and the full length of the study, 1970-2012. Results should be viewed with caution for areas shaded in grey: there was a significant ($P < 0.05$) difference in the slope between time periods (as shown by the F-ratio, which tests for an interaction between time period and pesticide use), that is invertebrate densities responded differently to pesticide applications in the previous year in 2005-2012 compared with 1970-2004. Results are the percentage difference in mean density of treated v. untreated. A negative value shows that invertebrate densities decreased with the use insecticides in the previous year and vice versa.

Invertebrate group[1]	1970-2004	2005-2012	Comparison of slopes between time periods ($F_{1,1983}$)	1970-2012
Araneae & Opiliones	-20***	-17**	1.76	-19***
Carabidae & Elateridae	-7	-19***	2.85	-11***
Symphyta & Lepidoptera	-10*	-10	0.49	-10*
Chrysomelidae & Curculionidae	-1	-4	2.04	-2
Non-aphid Hemiptera	-27***	-20*	1.71	-24***
Aphididae	-21***	-19*	0.08	-21***
Chick-food Index	-4*	-7*	1.79	-5***
Four-food Index	-2	-6	0.45	-4
Yellowhammer Index	-18***	-18**	0.01	-18***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 1466 from 1970 to 2004, 578 from 2005 to 2012 and 2044 over all years.

Table 19. Seed treatment use. The effect of seed treatments (controlling for crop, year and the use of foliar/residual pesticides as well as other types of seed treatment) on invertebrate densities on a field-by-field basis where information on seed treatment use was available (2003-2012). Results are the percentage difference in mean density of treated v. untreated. A negative value shows that invertebrate abundance decreased with the use of seed treatments and vice versa. We tested whether or not the effects of different types of seed treatments differed.

Invertebrate group[1]	Fungicide seed treatment	Neonicotinoid seed treatment	Pyrethroid seed treatment	Test of differences ($F_{2,621}$)
Araneae & Opiliones	-25**	-6	-28*	3.74*
Carabidae & Elateridae	-28***	-31***	-21**	2.94
Symphyta & Lepidoptera	-22**	-20*	-24*	0.03
Chrysomelidae & Curculionidae	-22**	-26**	-29**	0.82
Non-aphid Hemiptera	-21	-14	-37**	2.36
Aphididae	2	-23	20	4.59*
Chick-food Index	-13***	-15***	-13**	0.50
Four-food Index	-5	-5	-5	0.07
Yellowhammer Index	-4	-15	6	1.79

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

1. The sample size for all groups is 700.

Appendix

Appendix: Table 1 Chemical compounds used as herbicides, fungicides and insecticides on break crops in the Sussex Study Area, 1970-1995 (taken from Ewald & Aebischer, 1999).

Year	Herbicide	Fungicide	Insecticide
1970	dinoseb, simazine		demeton-s-methyl
1971	diquat, prometryn, simazine		gamma-HCH
1972	chlorotoluron, paraquat, prometryn, simazine, TCA, terbutryn		gamma-HCH
1973	chlorotoluron, dalapon, desmetryn, paraquat, simazine, TCA		demeton-s-methyl, gamma-HCH
1974	simazine		DDT, disulfoton, gamma-HCH, phorate
1975	chlorotoluron, dinitramine, simazine	captafol, carbendazim	azinphos-methyl, DDT, gamma-HCH, phorate, pirimicarb
1976	dinoseb, simazine, TCA		azinophos-methyl, DDT, demeton-s-methyl, endosulfan, fenitrothion, gamma-HCH, phorate
1977	chlorotoluron, dalapon, isoproturon, paraquat, propyzamide, simazine		fenitrothion, triazophos
1978			
1979	paraquat, TCA		triazophos
1980	TCA, trifluralin		triazophos
1981	paraquat, simazine		pirimicarb
1982	chlorotoluron		
1983	propachlor		
1984			
1985		iprodione, propiconazole	pirimicarb, triazophos
1986			
1987	desmetryn, paraquat		
1988	desmetryn, glyphosate, paraquat, simazine, trietazine	carbendazim	cypermethrin
1989	simazine, trietazine		cypermethrin, pirimicarb
1990			dimethoate
1991	atrazine, desmetryn, fluazifop-P-butyl, metsulfuron-methyl, paraquat		
1992	atrazine, benazolin, clopyralid, desmetryn, glyphosate, paraquat		alpha-cypermethrin, pirimicarb
1993	atrazine, benazolin, clopyralid, desmetryn fluazifop-P-butyl, glyphosate, metsulfuron-methyl, paraquat, simazine, trietazine		alpha-cypermethrin, cyhalothrin, deltamethrin, pirimicarb
1994	atrazine, benazolin, bentazone, bromoxynil, clopyralid, cyanazine, cycloxydim, desmetryn, diquat, fluazifop-P-butyl, fluroxypyr, glyphosate, glufosinate-ammonium, metazachlor, metsulfuron-methyl, paraquat, propaquizapop-methyl, pyridate, quizalofop-ethyl, trifluralin	carbendazim, iprodione, prochloraz, sulfur, thiophanate-methyl, tridemorph, vinclozolin	cyhalothrin, cypermethrin, deltamethrin, triazophos
1995	atrazine, benazolin, clopyralid, glyphosate, metazachlor, metsulfuron-methyl, pendimethalin, propaquizafoppyridate, quizalopop-methyl, trifluralin	carbendazim, prochloraz, vinclozolin	deltamethrin, gamma-HCH, lambda-cyhalothrin, triazophos

Appendix: Table 1 (continued). Chemical compounds used as herbicides, fungicides and insecticides on break crops in the Sussex Study Area, 1996-2012. Areas shaded in grey inidicate where no information was available for break crops in this year.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
1996	atrazine, benazolin, bromoxynil, chlorotoluron, clopyralid, cycloxydim, desmetryne, diquat, fluazifop-P-butyl, glyphosate, ioxynil, linuron, MCPA, mecoprop-P, metazachlor, paraquat, propaquizafop, quizalofop-ethyl, trifluralin	carbendazim, chlorothalonil, prochloraz	alpha-cypermethrin, deltamethrin, gamma-HCH, lambda-cyhalothrin, triazophos	
1997	atrazine, benazolin, bromoxynil, clopyralid, cycloxydim, diquat, glyphosate, ioxynil, metazachlor, paraquat, propaquizafop, pyridate, simazine, triasulfuron, trifluralin	carbendazim, chlorothalonil, fenpropidin, iprodione, procholoraz, thiophanate-methyl	alpha-cypermethrin, cyhalothrin, deltamethrin, gamma-HCH, lambda-cyhalothrin	
1998	amidosulfuron, atrazine, benazolin, bromoxynil, clopyralid, diquat, glyphosate, metazachlor, metsulfuron-methyl, propaquizafop, pyridate, terbuthylazine, terbutryn, trifluralin	carbendazim, chlorothalonil, flusilazole, iprodione, procholoraz, tebuconazole, thiophanate-methyl	cyhalothrin, deltamethrin, lambda-cyhalothrin, pirimicarb	
1999	atrazine, bentazone, carbetamide, cyanazine, diquat, glyphosate, MCPB, metazachlor, metsulfuron-methyl, propaquizafop, pyridate, trifluralin	carbendazim, chlorothalonil, flusilazole, iprodione, procholoraz, thiophanate-methyl	deltamethrin, lambda-cyhalothrin, pirimicarb	
2000	amidosulfuron, atrazine, bromoxynil, clopyralid, cycloxydim, glyphosate, pyridate, quizalofop-P-ethyl, terbuthylazine, terbutryn, trifluralin	carbendazim, chlorothalonil, flusilazole, tebuconazole, vinclozolin	alpha-cypermethrin, cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb	
2001	atrazine, bentazone, bromoxynil, clodinafop-propargyl, cyanazine, cycloxydim, diflufenican, glyphosate, isoproturon, MCPB, metazachlor, pendimethalin, propaquizafop, prosulfuron, quinmerac, terbuthylazine, terbutryn, trifluralin	carbendazim, chlorothalonil, flusilazole, iprodione, tebuconazole, thiophanate-methyl, vinclozolin	deltamethrin, lambda-cyhalothrin, pirimicarb	
2002	atrazine, bentazone, cyanazine, cycloxydim, glyphosate, MCPB, metazachlor, pendimethalin, propaquizafop, pyridate, quinmerac, tepraloxydim, terbuthylazine, terbutryn, trifluralin	azoxystrobin, benzimidazole, carbendazim, chlorothalonil, difenoconazole, flusilazole, iprodione, tebuconazole, vinclozolin	cypermethrin, deltamethrin, dimethoate, lambda-cyhalothrin, pirimicarb	beta-cyfluthrin (I), imidacloprid (I), thiram (F)
2003	amidosulfuron, clopyralid, propaquizafop, trifluralin, glyphosate, pendimethalin, cyanazine, MCPB, cycloxydim, quinmerac, propaquizafop, bromoxynil, bentazone, metazachlor, trifluralin	azoxystrobin, carbendazim, chlorothalonil, epoxiconazole, flusilazole, iprodione, sulfur, tebuconazole, thiophanate-methyl	cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb	beta-cyfluthrin (I), imidacloprid (I), iprodione (F), thiram (F)
2004	amidosulfuron, bentazone, bromoxynil, carbetamide, cyanazine, glyphosate, metazachlor, metsulfuron-methyl, pendimethalin, propaquizafop, quinmerac, simazine, tepraloxydim, trifluralin	azoxystrobin, carbendazim, chlorothalonil, flusilazole, iprodione, prochloraz, tebuconazole, thiophanate-methyl	cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb	beta-cyfluthrin (I), imidacloprid (I)
2005	amidosulfuron, bromoxynil, clomazone, diquat, glyphosate, linuron, metazachlor, pendimethalin, propaquizafop, propyzamide, quinmerac, simazine, tepraloxydim, trifluralin	azoxystrobin, carbendazim, chlorothalonil, flusilazole, iprodione, tebuconazole, thiophanate-methyl	cypermethrin, deltamethrin, permethrin, zeta-cypermethrin	
2006	bromoxynil, carbetamide, clomazone, clopyralid, cyanazine, cycloxydim, diquat, fluazifop-P-butyl, glufosinate-ammonium, glyphosate, metazachlor, oxadiazon, picloram, propaquizafop, propyzamide, quinmerac, simazine, tepraloxydim, trifluralin	azoxystrobin, carbendazim, chlorothalonil, flusilazole, iprodione, metconazole, prothioconazole, tebuconazole, thiophanate-methyl	alpha-cypermethrin, cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb, tau-fluvalinate	beta-cyfluthrin (I), imidacloprid (I), iprodione (F)
2007	bentazone, bifenox, carbetamide, chloridazon, clomazone, clopyralid, cyanazine, cycloxydim, ethofumesate, fluazifop-P-butyl, glyphosate, lenacil, MCPB, metamitron, metazachlor, pendimethalin, phenmedipham, picloram, picloram, propaquizafop, quinmerac, simazine, terbuthylazine, terbutryn, trifluralin, triflusulfuron-methyl	azoxystrobin, boscalid, carbendazim, chlorothalonil, difenocoazole, fenpropidin, flusilazole, iprodione, metconazole, prothioconazole, tebuconazole, thiophanate-methyl	alpha-cypermethrin, cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb, tau-fluvalinate, zeta-cypermethrin	beta-cyfluthrin (I), imidacloprid (I), iprodione (F), thiram (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 1 (continued). Chemical compounds used as herbicides, fungicides and insecticides on break crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment
2008	amidosulfuron, bentazone, bifenox, bromoxynil, clomazone, clopyralid, cycloxydim, diquat, ethofumesate, fluazifop-P-butyl, glyphosate, imazamox, lenacil, MCPB, mesotrione, metamitron, metazachlor, nicosulfuron, pendimethalin, phenmedipham, propaquizafop, propyzamide, quinmerac, tepraloxydim, trifluralin, triflusulfuron-methyl	azoxystrobin, carbendazim, chlorothalonil, cyproconazole, difenocoazole, famoxadone, fenpropidin, fenpropimorph, flusilazole, iprodione, metconazole, sulphur, tebuconazole, thiophanate-methyl	alpha-cypermethrin, cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb, tau-fluvalinate, zeta-cypermethrin	beta-cyfluthrin (I), imidacloprid (I), iprodione (F), prochloraz (F), thiram (F)
2009	amidosulfuron, bentazone, bifenox, bromoxynil, carbetamide, chloridazon, clomazone, clopyralid, cycloxydim, diquat, ethofumesate, fluazifop-P-butyl, glyphosate, imazamox, lenacil, MCPB, mesotrione, metamitron, metazachlor, nicosulfuron, pendimethalin, phenmedipham, propaquizafop, quinmerac, quizalofop-P-tefuryl, tepraloxydim, triflusulfuron-methyl	azoxystrobin, carbendazim, chlorothalonil, cyproconazole, difenocoazole, famoxadone, fenpropidin, flusilazole, iprodione, metconazole, quinoxyfen, sulphur, tebuconazole, thiophanate-methyl	alpha-cypermethrin, chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb, tau-fluvalinate, thiacloprid, zeta-cypermethrin	beta-cyfluthrin (I), cymoxanil (F), fludioxonil (F), imidacloprid (I), iprodione (F), metalaxyl-M (F), methiocarb (I) prochloraz (F)
2010	amidosulfuron, bentazone, bromoxynil, carbetamide, chloridazon, clomazone, clopyralid, cycloxydim, desmedipham, diquat, ethofumesate, fluazifop-P-butyl, glyphosate, imazamox, lenacil, MCPB, mesotrione, metamitron, metazachlor, metsulfuron-methyl, nicosulfuron, pendimethalin, phenmedipham, picloram, propaquizafop, propyzamide, quinmerac, quizalofop-P-tefuryl, tepraloxydim, triflusulfuron-methyl	azoxystrobin, carbendazim, chlorothalonil, cyproconazole, difenocoazole, famoxadone, fenpropidin, fenpropimorph, flusilazole, metconazole, prothioconazole, pyraclostrobin, tebuconazole	alpha-cypermethrin, cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb, tau-fluvalinate, zeta-cypermethrin	beta-cyfluthrin (I), clothianidin (I), cymoxanil (F), fludioxonil (F), imidacloprid (I), iprodione (F), metalaxyl-M (F) methiocarb (I), prochloraz (F)
2011	amidosulfuron, bentazone, bifenox, carbetamide, chloridazon, clomazone, clopyralid, cycloxydim, desmedipham, diquat, ethofumesate, fluazifop-P-butyl, glyphosate, imazamox, iodosulfuron-methyl-sodium, lenacil, MCPB, mesotrione, metamitron, metazachlor, nicosulfuron, pendimethalin, phenmedipham, picloram, propaquizafop, quinmerac, tepraloxydim, triflusulfuron-methyl	azoxystrobin, boscalid, carbendazim, chlorothalonil, cyproconazole, difenocoazole, famoxadone, fenpropidin, fenpropimorph, flusilazole, metconazole, propiconazole, prothioconazole, tebuconazole, thiophanate-methyl	alpha-cypermethrin, lambda-cyhalothrin, pirimicarb, deltamethrin, cypermethrin, tau-fluvalinate, pymetrozine, thiacloprid, zeta-cypermethrin	beta-cyfluthrin (I), clothianidin (I), imidacloprid (I), prochloraz (F), thiamethoxam (I), thiram (F)
2012	amidosulfuron, bentazone, bifenox, bromoxynil, carbetamide, chloridazon, clomazone, clopyralid, cycloxydim, desmedipham, diquat, ethofumesate, fluazifop-P-butyl, glyphosate, imazamox, iodosulfuron-methyl-sodium, lenacil, MCPB, metamitron, metazachlor, pendimethalin, phenmedipham, picloram, propaquizafop, propyzamide, prosulfuron, quinmerac, quizalofop-P-tefuryl, S-metolachlor, tepraloxydim, triflusulfuron-methyl	azoxystrobin, boscalid, carbendazim, chlorothalonil, cyproconazole, difenocoazole, famoxadone, fenpropidin, flusilazole, iprodione, prochloraz, propiconazole, prothioconazole, tebuconazole, thiophanate-methyl	cypermethrin, deltamethrin, lambda-cyhalothrin, pirimicarb, pymetrozine, tau-fluvalinate	beta-cyfluthrin (I), clothianidin (I), imidacloprid (I), prochloraz (F), thiamethoxam (I), thiram (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 2 Chemical compounds used as herbicides, fungicides and insecticides on spring cereal crops in the Sussex Study Area, 1970-1995 (taken from Ewald & Aebischer, 1999).

Year	Herbicide	Fungicide	Insecticide
1970	benazolin, 2,4-DB, di-allate, dicamba, dichlorprop, MCPA, mecoprop	ethirimol	
1971	benazolin, bromoxynil, 2,4-DB, dicamba, dichlorprop, ioxynil, MCPA, mecoprop, simazine, 2,3,6-TBA	chlorquinox, tridemorph	
1972	benazolin, bromoxynil, 2,4-DB, dicamba, dichlorprop, ioxynil, MCPA, mecoprop, paraquat, TCA		
1973	benazolin, bromofenoxim, chlorotoluron, 2,4-DB, dicamba, dichlorprop, diquat, MCPA, mecoprop, terbuthylazine		
1974	benazolin, bromofenoxim, 2,4-DB, dicamba, dichlorprop, diquat, MCPA, mecoprop, simazine, terbuthylazine	carbendazim, captafol, ethirimol, triadimefon	
1975	benazolin, bromofenoxim, bromoxynil, 2,4-DB, dicamba, dichlorprop, glyphosate, ioxynil, MCPA, mecoprop, terbuthylazine	carbendazim, tridemorph	DDT, demeton-s-methyl
1976	benazolin, 2,4-DB, dicamba, MCPA, mecoprop, paraquat, simazine	benomyl, copper, maneb, tridemefon	
1977	benazolin, bromofenoxim, 2,4-DB, dicamba, dichlorprop, dinoseb, glyphosate, ioxynil, MCPA, mecoprop, paraquat, 2,3,6-TBA, terbuthylazine	benomyl, ethirimol, maneb, triadimefon, tridemorph	
1978	benazolin, chlorotoluron, 2,4-DB, dicamba, dichlorprop, glyphosate, MCPA, mecoprop	triadimefon	aldrin
1979	benazolin, bromoxynil, 2,4-DB, dicamba, dichlorprop, glyphosate, ioxynil, MCPA, mecoprop, methabenzthiazuron, paraquat	captafol, triadimefon	
1980	benazolin, chlorotoluron, 2,4-DB, dicamba, dichlorprop, MCPA, mecoprop, paraquat	triadimefon	
1981	benazolin, bromoxynil, 2,4-DB, dicamba, dichlorprop, ioxynil, isoproturon, linuron, MCPA, mecoprop, paraquat	carbendazim, captafol, ethirimol, mancozeb, triadimefon	
1982	benazolin, 2,4-DB, dicamba, MCPA, mecoprop, paraquat	prochloraz, propiconazole, triadimefon	
1983	benazolin, 2,4-DB, dicamba, MCPA, mecoprop, paraquat	propiconazole, triadomefon	
1984	benazolin, chlorotoluron, clopyralid, 2,4-DB, dicamba, dichlorprop, glyphosate, MCPA, mecoprop	captafol, fenpropimorph, fuberidazole, propiconazole, triadimefon, triadimenol	
1985	benazolin, clopyralid, 2,4-DB, dicamba, MCPA, mecoprop	triadimenol	
1986	benazolin, chlorotoluron, 2,4-DB, glyphosate, MCPA, mecoprop, metsulfuron-methyl	triadimenol	
1987	benazolin, chlorotoluron, 2,4-DB, dicamba, glyphosate, isoproturon, MCPA, mecoprop	flutriafol	
1988	benazolin, 2,4-DB, dicamba, dichlorprop, glyphosate, isoproturon, MCPA, mecoprop, metsulfuron-methyl	fenpropimorph, flutriafol, propiconazole, triadimenol	gamma-HCH
1989	benazolin, 2,4-DB, dicamba, glyphosate, isoproturon, MCPA, mecoprop	fenpropimorph, propiconazole	
1990	benazolin, 2,4-DB, dicamba, glyphosate, MCPA, mecoprop, mecoprop-p	flutriafol, propiconazole	gamma-HCH
1991	benazolin, bromoxynil, 2,4-DB, dicamba, ioxynil, MCPA, mecoprop, metasulfuron-methyl, thifensulfuron-methyl	fenpropimorph, flutriafol	
1992	benazolin, bromoxynil, 2,4-DB, dicamba, fluroxypyr, glyphosate, ioxynil, MCPA, mecoprop, metasulfuron-methyl, thifensulfuron-methyl	flutriafol	
1993	benazolin, 2,4-DB, dicamba, difenzoquat, glyphosate, MCPA, mecoprop, metsulfuron-methyl, thifensulfuron-methyl	flutriafol	
1994	benazolin, bromoxynil, 2,4-DB, dicamba, fluroxypyr, glyphosate, ioxynil, MCPA, mecoprop, metsulfuron-methyl, thifensulfuron-methyl	carbendazim, cyproconazole, fenpropimorph, flutriafol, prochloraz, propiconazole, tridemorph	
1995	benazolin, bromoxynil, 2,4-DB, dicamba, diflufenican, fluroxypyr, ioxynil, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, paraquat, thifensulfuron-methyl	carbendazim, chlorothalonil, cyproconazole, fenpropidin, fenpropimorph, flutriafol, mancozeb, prochloraz, propiconazole, tebuconazole	

Appendix: Table 2 (continued). Chemical compounds used as herbicides, fungicides and insecticides on spring cereal crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
1996	2,4-DB, benazolin, bromoxynil, diflufenican, fluazifop-P-butyl, glyphosate, ioxynil, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl, triasulfuron	carbendazim, epoxiconazole, fenpropidin, fenpropimorph, flusilazole, propiconazole, tebuconazole, tridemorph	lambda-cyhalothrin	bitertanol (F), fuberidazole (F), gamma-HCH (I), tebuconazole (F), triazoxide (F)
1997	2,4-DB, benazolin, bromoxynil, difenzoquat, glyphosate, ioxynil, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl	cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, prochloraz, propiconazole		gamma-HCH (I), tebuconazole (F), triazoxide (F)
1998	2,4-DB, benazolin, bromoxynil, dicamba, diflufenican, ioxynil, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, paraquat, thifensulfuron-methyl, tralkoxydim, triasulfuron	cyproconazole, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, flutriafol, kresoxim-methyl, prochloraz, propiconazole, spiroxamine,	chlorpyrifos	gamma-HCH (I), tebuconazole (F), triazoxide (F)
1999	2,4-DB, benazolin, bentazone, bromoxynil, cyanazine, diquat, glyphosate, ioxynil, MCPA, mecoprop, metsulfuron-methyl, paraquat	azoxystrobin, cyproconazole, cyprodinil, fenpropidin, flusilazole, prochloraz, spiroxamine		gamma-HCH (I), guazatine (F), tebuconazole (F), triazoxide (F)
2000	2,4-DB, benazolin, bentazone, bromoxynil, cyanazine, glyphosate, ioxynil, MCPA, mecoprop, metsulfuron-methyl, thifensulfuron-methyl	azoxystrobin, cyproconazole, cyprodinil, fenpropidin, prochloraz, spiroxamine		bitertanol (F), fuberidazole (F), guazatine (F), tebuconazole (F), triazoxide (F)
2001	2,4-DB, benazolin, bromoxynil, dicamba, diclofop-methyl, fenoxaprop-P-ethyl, glyphosate, MCPA, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl, tralkoxydim	azoxystrobin, chlorothalonil, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, kresoxim-methyl, trifloxystrobin		carboxin (F), fluquinconazole (F), prochloraz (F), tebuconazole (F), tefluthrin (I), thiram (F), triazoxide (F)
2002	2,4-DB, benazolin, bromoxynil, dicamba, dichlorprop, glyphosate, ioxynil, MCPA, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl, tralkoxydim	azoxystrobin, cyprodinil, epoxiconazole, fenpropimorph, picoxytrobin, spiroxamine, trifloxystrobin		bitertanol (F), fuberidazole (F), imidacloprid (I), tebuconazole (F), triazoxide (F)
2003	2,4-DB, benazolin, bromoxynil, dicamba, dichlorprop, diclofop-methyl, fenoxaprop-P-ethyl, glyphosate, ioxynil, MCPA, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl, tralkoxydim	azoxystrobin, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, kresoxim-methyl, picoxytrobin, tebuconazole, trifloxystrobin	deltamethrin	bitertanol (F), carboxin (F), fludioxonil (F), fuberidazole (F), tebuconazole (F), thiram (F), triazoxide (F)
2004	2,4-DB, amidosulfuron, bromoxynil, dicamba, dichlorprop, diclofop-methyl, fenoxaprop-P-ethyl, ioxynil, linuron, MCPA, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl, tralkoxydim	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, kresoxim-methyl, picoxytrobin, trifloxystrobin		carboxin (F), fludioxonil (F), tebuconazole (F), thiram (F), triazoxide (F)
2005	amidosulfuron, bentazone, bromoxynil, clodinafop-propargyl, clopyralid, diclofop-methyl, diflufenican, fenoxaprop-P-ethyl, florasulam, flufenacet, fluroxypyr, glyphosate, ioxynil, MCPA, MCPB, mecoprop-P, metsulfuron-methyl, pendimethalin, thifensulfuron-methyl, tralkoxydim, trifluralin	azoxystrobin, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, picoxystrobin, prothioconazole, quinoxyfen, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin	tebuconazole (F), triazoxide (F)
2006	2,4-DB, bentazone, bromoxynil, glyphosate, ioxynil, isoproturon, linuron, MCPA, MCPB, mecoprop-P, metsulfuron-methyl, pinoxaden, propaquizafop, thifensulfuron-methyl	azoxystrobin, chlorothalonil, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, picoxystrobin, prothioconazole, quinoxyfen, trifloxystrobin	chlorpyrifos, cypermethrin	fludioxonil (F), prothioconazole (F), tebuconazole (F), triazoxide (F)
2007	2,4-DB, bentazone, bromoxynil, dicamba, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, ioxynil, isoproturon, linuron, MCPA, MCPB, mecoprop-P, metsulfuron-methyl, pinoxaden, thifensulfuron-methyl, tralkoxydim, tribenuron-methyl	azoxystrobin, chlorothalonil, epoxiconazole, fenpropimorph, fluoxastrobin, prothioconazole, quinoxyfen, trifloxystrobin	chlorpyrifos	fludioxonil (F), prothioconazole (F), tebuconazole (F), tefluthrin (I), triazoxide (F)
2008	bentazone, bromoxynil, dicamba, florasulam, fluroxypyr, glyphosate, ioxynil, isoproturon, MCPA, MCPB, mecoprop-P, metsulfuron-methyl, pinoxaden, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, chlorothalonil, cyproconazole, epoxiconazole, fenpropimorph, fluoxastrobin, picoxystrobin, proquinazid, prothioconazole, quinoxyfen, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin	fludioxonil (F), flutriafol (F), prothioconazole (F), tebuconazole (F), tefluthrin (I), triazoxide (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 2 (continued). Chemical compounds used as herbicides, fungicides and insecticides on spring cereal crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
2009	2,4-DB, amidosulfuron, bromoxynil, cycloxydim, dicamba, dichlorprop-P, diflufenican, flufenacet, fluroxypyr, glyphosate, ioxynil, linuron, MCPA, MCPB, mecoprop-P, metazachlor, metsulfuron-methyl, pendimethalin, pinoxaden, propaquizafop, quinmerac, quizalofop-P-tefuryl, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, fluoxastrobin, picoxystrobin, proquinazid, prothioconazole, quinoxyfen, trifloxystrobin	cypermethrin, zeta-cypermethrin	clothianidin (I), fludioxonil (F), prothioconazole (F), tebuconazole (F), tefluthrin (I), triazoxide (F)
2010	2,4-DB, amidosulfuron, bentazone, bromoxynil, dicamba, diflufenican, fenoxaprop-P-ethyl, flufenacet, fluroxypyr, flurtamone, glyphosate, ioxynil, linuron, MCPA, MCPB, mecoprop-P, metsulfuron-methyl, pendimethalin, pinoxaden, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fluoxastrobin, isopyrazam, metrafenone, picoxystrobin, proquinazid, prothioconazole, quinoxyfen, trifloxystrobin	zeta-cypermethrin	fludioxonil (F), prochloraz (F), prothioconazole (F), tebuconazole (F), tefluthrin (I), triazoxide (F), triticonazole (F)
2011	2,4-DB, bromoxynil, dicamba, fluazifop-P-butyl, fluroxypyr, glyphosate, ioxynil, linuron, MCPA, MCPB, mecoprop-P, metsulfuron-methyl, pendimethalin, pinoxaden, propaquizafop, prosulfocarb, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, bixafen, boscalid, chlorothalonil, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, isopyrazam, prothioconazole, pyraclostrobin, quinoxyfen, trifloxystrobin	deltamethrin, lambda-cyhalothrin	fludioxonil (F), prochloraz (F), prothioconazole (F), tebuconazole (F), tefluthrin (I), triazoxide (F), triticonazole (F)
2012	2, 4-DB, bromoxynil, dicamba, diflufenican, diquat, florasulam, fluazifop-P-butyl, fluroxypyr, glyphosate, imazamox, ioxynil, MCPA, mecoprop-P, metsulfuron-methyl, pendimethalin, pinoxaden, prosulfocarb, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, bixafen, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, isopyrazam, kresoxim-methyl, prothioconazole, quinoxyfen, tebuconazole, trifloxystrobin	cypermethrin, deltamethrin, pirimicarb	fludioxonil (F), prochloraz (F), tebuconazole (F), tefluthrin (I), thiram (F), triazoxide (F), triticonazole (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 3 Chemical compounds used as herbicides, fungicides and insecticides on winter wheat crops in the Sussex Study Area, 1970-1995 (taken from Ewald & Aebischer, 1999).

Year	Herbicide	Fungicide	Insecticide
1970	2,4-D, dicamba, dichlorprop, MCPA, mecoprop, metoxuron, paraquat, 2,3,6-TBA		
1971	clopyralid, 2,4-D, dicamba, dichlorprop, mecoprop, MCPA, metoxuron, propanex, propanil, 2,3,6-TBA, terbutryn		
1972	chlorotoluron, 2,4-D, dicamba, MCPA, mecoprop, metoxuron, paraquat, simazine, 2,3,6-TBA, terbutryn		
1973	chlorotoluron, dicamba, MCPA, mecoprop, metoxuron, paraquat, simazine, 2,3,6-TBA		
1974	chlorotoluron, dicamba, MCPA, mecoprop, metoxuron, paraquat, simazine, 2,3,6-TBA		
1975	chlorotoluron, dicamba, MCPA, mecoprop, methoprotryne, metoxuron, paraquat, simazine, 2,3,6-TBA	carbendazim, captafol, tridemorph	demeton-s-methyl, metasystox, pirimicarb
1976	chlorotoluron, dicamba, isoproturon, MCPA, mecoprop, metoxuron, paraquat, simazine, 2,3,6-TBA	benomyl, captafol, triadimefon	demeton-s-methyl, pirimicarb
1977	chlorotoluron, 2,4-D, dalapon, dicamba, dichlorprop, glyphosate, ioxynil, isoproturon, MCPA, mecoprop, 2,3,6-TBA	benomyl, captafol, carbendazim, ethirimol, maneb	demeton-s-methyl, pirimicarb
1978	chlorotoluron, dicamba, glyphosate, isoproturon, MCPA, mecoprop, 2,3,6-TBA	carbendazim	
1979	chlorotoluron, dicamba, glyphosate, isoproturon, MCPA, mecoprop, methabenzthiazuron, paraquat	carbendazim, triadimefon	
1980	bromoxynil, chlorotoluron, dicamba, diclofop-methyl, dinoseb, ioxynil, isoproturon, linuron, MCPA, mecoprop, paraquat, 2,3,6-TBA, trifluralin	benomyl, captafol, carbendazim, ethirimol, propineb, triadimefon	demeton-s-methyl, pirimicarb
1981	bromoxynil, chlorotoluron, dicamba, dichlorprop, glyphosate, ioxynil, isoproturon, linuron, MCPA, mecoprop, methabenzthiazuron, paraquat	benomyl, captafol, carbendazim, chlorothalonil, cyproconazole, ethirimol, mancozeb, maneb, procholoraz, propineb, triadimefon, tridemorph	demeton-s-methyl
1982	bromoxynil, chlorotoluron, glyphosate, ioxynil, isoproturon, linuron, mecoprop, paraquat	benomyl, captafol, carbendazim, ethirimol, propiconazole	
1983	bifenox, bromoxynil, chlorotoluron, clopyralid, dicamba, glyphosate, ioxynil, isoproturon, MCPA, mecoprop, paraquat, tralkoxydim	captafol, carbendazim, propiconazole, triadimefon	
1984	bifenox, bromoxynil, chlorotoluron, clopyralid, glyphosate, ioxynil, isoproturon, MCPA, mecoprop	captafol, carbendazim, fuberadazole, propiconazole, thiophanate, triadimefon, triadimenol	chlorpyrifos, cypermethrin, demeton-s-methyl, gamma-HCH, pirimicarb
1985	bifenox, chlorotoluron, clopyralid, fluroxypyr, ioxynil, isoproturon, MCPA, mecoprop	captafol, flutriafol, propiconazole, triadimefon, triadimenol	cypermethrin
1986	atrazine, chlorosulfuron, chlorotoluron, clopyralid, dichlorprop, diclofop-methyl, fluroxypyr, glyphosate, isoproturon, MCPA, mecoprop, metsulfuron-methyl, 2,4,5-T, terbutryn	captafol, carbendazim, flutriafol, procholoraz, propiconazole, triadimefon	cypermethrin
1987	bifenox, chlorosulfuron, chlorotoluron, cyanazine, dichlorprop, fluroxypyr, glyphosate, isoproturon, MCPA, me coprop, metsulfuron-methyl	captafol, carbendazim, fenpropimorph, flutriafol, maneb, procholaraz, propiconazole, triadimefon, triadimenol, tridemorph	cypermethrin
1988	chlorotoluron, diflufenican, fluroxypyr, glyphosate, isoproturon, MCPA, mecoprop, metsulfuron-methyl, paraquat	captafol, carbendazim, flutriafol, prochloraz, propiconazole, triadimefon	cypermethrin, dimethoate
1989	chlorotoluron, diflufenican, fluroxypyr, glyphosate, imazamethabenz-methyl, isoproturon, mecoprop, metsulfuron-methyl, paraquat, thifensulfuron-methyl	carbendazim, fenpropidin, fenpropimorph, flusilazole, flutriafol, prochloraz, propiconazole	cypermethrin, demeton-s-methyl, dimethoate
1990	chlorotoluron, diclofop-methyl, difenzoquat, diflufenican, fenoxaprop-P-ethyl, flamprop-M-isopropyl, fluroxypyr, glyphosate, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, thifensulfuron-methyl	carbendazim, fenpropimorph, flutriafol, prochloraz, propiconazole	cypermethrin, dimethoate, gamma HCH, pirimicarb
1991	bromoxynil, chlorotoluron, diflufenican, diquat, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, paraquat, simazine, thifensulfuron-methyl	carbendazim, chlorothalonil, fenpropidin, fenpropimorph, flutriafol, mancozeb, maneb, prochloraz, propiconazole, triadimenol, tridemorph	chlorpyrifos, cypermethrin, dimethoate, pirimicarb
1992	bromoxynil, chlorotoluron, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, ioxynil, isoproturon, mecoprop, metasulfuron-methyl, pendimethalin, thifensulfuron- methyl	carbendazim, chlorothalonil, cyproconazole, fenpropidin, fenpropimorph, flutriafol, mancozeb, maneb, prochloraz, propiconazole, tridemorph	chlorpyrifos, cypermethrin, dimethoate
1993	bromoxynil, chlorotoluron, diclofop-methyl, diflufenican, fenoxaprop-P-ethyl, flamprop-M-isopropyl, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, MCPA, mecoprop-p, metsulfuron-methyl, paraquat, thifensulfuron-methyl, tralkoxydim	carbendazim, chlorothalonil, fenpropidin, fenpropimorph, flutriafol, maneb, propiconazole, tebuconazole	cypermethrin, gamma HCH
1994	amidosulfuran, benazolin, bromoxynil, cyanazine, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, pendimethalin, thifensulfuron-methyl, trifluralin	carbendazim, chlorothalonil, cyproconazole, fenpropidin, fenpropimorph, flusilazole, flutriafol, mancozeb, maneb, prochloraz, tebuconazole	chlorpyrifos, cypermethrin, triazophos
1995	amidosulfuron, benazolin, bromoxynil, chlorotoluron, clodinafop-propargyl, cyanazine, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, MCPA, mecoprop, mecoprop-p, metsulfuron-methyl, tralkoxydim, trifluralin	carbendazim, chlorothalonil, cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, flusilazole, flutriafol, mancozeb, prochloraz, propiconazole, tebuconazole	chlorpyrifos, cypermethrin, lambda-cyhalothrin, deltamethrin, esfenvalerate

Appendix: Table 3 (continued). Chemical compounds used as herbicides, fungicides and insecticides on winter wheat crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
1996	amidosulfuron, bromoxynil, chlorotoluron, CMPP, di-allate, diclofop-methyl, diflufenican, fenoxaprop-P-ethyl, flamprop-M-isopropyl, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, linuron, MCPA, mecoprop, mecoprop-P, metsulfuron-methyl, paraquat, pendimethalin, simazine, tralkoxydim, trifluralin	carbendazim, chlorothalonil, cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, flusilazole, flutriafol, mancozeb, prochloraz, propiconazole, tebuconazole	chlorpyrifos, cypermethrin, deltamethrin, dimethoate, gamma-HCH, lambda-cyhalothrin	carboxin (F), fludioxonil (F), fuberidazole (F), gamma-HCH (I), thiabendazole (F), triadimenol (F)
1997	amidosulfuron, chlorotoluron, clodinafop-propargyl, di-allate, diflufenican, diquat, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, imazamethabenz-methyl, isoproturon, mecoprop-P, metsulfuron-methyl, paraquat, pendimethalin, trifluralin	carbendazim, chlorothalonil, cyproconazole, difenoconazole, epoxiconazole, fenpropidin, fenpropimorph, flutriafol, mancozeb, prochloraz, propiconazole, tebuconazole	chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin	bitertanol (F), fuberidazole (F), gamma-HCH (I)
1998	amidosulfuron, benazolin, bromoxynil, carfentrazone-ethyl, clodinafop-propargyl, cyanazine, di-allate, diflufenican, fenoxaprop-P-ethyl, flupyrsulfuron-methyl-sodium, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, linuron, mecoprop, mecoprop-P, metosulam, metsulfuron-methyl, paraquat, pendimethalin, tralkoxydim, trifluralin	azoxystrobin, carbendazim, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, flusilazole, flutriafol, kresoxim-methyl, prochloraz, propiconazole, tebuconazole	chlorpyrifos, cypermethrin, deltamethrin, gamma-HCH	bitertanol (F), fuberidazole (F), gamma-HCH (I)
1999	amidosulfuron, bromoxynil, diflufenican, flurtamone, glyphosate, ioxynil, isoproturon, mecoprop, metsulfuron-methyl, pendimethalin	azoxystrobin, chlorothalonil, epoxiconazole, fenpropimorph, fluquinconazole, flutriafol, kresoxim-methyl, tebuconazole	deltamethrin, lambda-cyhalothrin	bitertanol (F), fuberidazole (F), gamma-HCH (I)
2000	amidosulfuron, bromoxynil, clodinafop-propargyl, diflufenican, fenoxaprop-P-ethyl, flamprop-M-isopropyl, florasulam, flupyrsulfuron-methyl-sodium, fluroxypyr, flurtamone, ioxynil, isoproturon, mecoprop, mecoprop-p, metsulfuron-methyl, pendimethalin, propaquizafop, tralkoxydim, tribenuron-methyl, trifluralin	azoxystrobin, carbendazim, chlorothalonil, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, fluquinconazole, flutriafol, kresoxim-methyl, mancozeb, metconazole, propiconazole, quinoxyfen, spiroxamine, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, esfenvalerate, lambda-cyhalothrin	bitertanol (F), fuberidazole (F), imidacloprid (I)
2001	amidosulfuron, bromoxynil, chlorotoluron, clodinafop-propargyl, dichlorprop, diflufenican, diquat, florasulam, flupyrsulfuron-methyl-sodium, fluroxypyr, glyphosate, ioxynil, isoproturon, mecoprop, mecoprop-p, metsulfuron-methyl, pendimethalin, sulfosulfuron, thifensulfuron-methyl, tri-allate, trifluralin	azoxystrobin, chlorothalonil, cyproconazole, epoxiconazole, fenpropimorph, fluquinconazole, kresoxim-methyl, quinoxyfen, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin,	bitertanol (F), carboxin (F), fluquinconazole (F), fuberidazole (F), imidacloprid (I), prochloraz (F), thiram (F)
2002	amidosulfuron, chlorotoluron, clodinafop-propargyl, diflufenican, florasulam, flufenacet, flupyrsulfuron-methyl-sodium, fluroxypyr, flurtamone, glyphosate, isoproturon, MCPA, mecoprop-p, metsulfuron-methyl, pendimethalin, terbutryn, thifensulfuron-methyl, trifluralin	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluquinconazole, kresoxim-methyl, metconazole, pyraclostrobin, quinoxyfen, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin, permethrin	bitertanol (F), carboxin (F), fuberidazole (F), imidacloprid (I), tefluthrin (I), thiram (F)
2003	amidosulfuron, bromoxynil, carfentrazone-ethyl, chlorotoluron, clodinafop-propargyl, dicamba, dichlorprop, diflufenican, florasulam, flufenacet, flupyrsulfuron-methyl-sodium, fluroxypyr, flurtamone, glyphosate, ioxynil, isoproturon, mecoprop-P, metsulfuron-methyl, pendimethalin, propoxycarbazone-sodium, terbutryn, thifensulfuron-methyl, trifluralin	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, fluquinconazole, kresoxim-methyl, pyraclostrobin, quinoxyfen, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin	bitertanol (F), carboxin (F), fluquinconazole (F), fuberidazole (F), imidacloprid (I), prochloraz (F), thiram (F)
2004	amidosulfuron, bromoxynil, carfentrazone-ethyl, chlorotoluron, clodinafop-propargyl, dichlorprop, diflufenican, florasulam, flufenacet, flupyrsulfuron-methyl-sodium, fluroxypyr, flurtamone, glyphosate, iodosulfuron-methyl-sodium, ioxynil, isoproturon, linuron, mecoprop, mecoprop-p, mesosulfuron-methyl, metsulfuron-methyl, pendimethalin, picolinafen, propoxycarbazone-sodium, terbutryn, thifensulfuron-methyl, trifluralin	azoxystrobin, carbendazim, chlorothalonil, cyproconazole, cyprodinil, dimoxystrobin, epoxiconazole, fenpropimorph, fluquinconazole, kresoxim-methyl, metrafenone, prochloraz, pyraclostrobin, quinoxyfen, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin, permethrin, pirimicarb, tau-fluvalinate	bitertanol (F), carboxin (F), fuberidazole (F), imidacloprid (I), thiram (F), triticonazole (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 3 (continued). Chemical compounds used as herbicides, fungicides and insecticides on winter wheat crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
2005	amidosulfuron, bromoxynil, chlorotoluron, clodinafop-propargyl, diflufenican, fenoxaprop-P-ethyl, florasulam, flufenacet, flupyrsulfuron-methyl-sodium, fluroxypyr, flurtamone, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, mecoprop-P, mesosulfuron-methyl, metsulfuron-methyl, pendimethalin, picolinafen, propoxycarbazone-sodium, thifensulfuron-methyl, trifluralin	azoxystrobin, boscalid, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, kresoxim-methyl, metrafenone, prothioconazole, pyraclostrobin, quinoxyfen, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, zeta-cypermethrin	bitertanol (F), clothianidin (I), fluoxastrobin (F), fuberidazole (F), imidacloprid (I), prothioconazole (F), tebuconazole (F) triazoxide (F), triticonazole (F)
2006	bromoxynil, clodinafop-propargyl, clomazone, diflufenican, ethylene glycol, fenoxaprop-P-ethyl, florasulam, flufenacet, flupyrsulfuron, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, ioxynil, isoproturon, mecoprop-P, mesosulfuron-methyl, metazachlor, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, sulfosulfuron, tri-allate, tribenuron-methyl, trifluralin	azoxystrobin, boscalid, chlorothalonil, cyproconazole, cyprodinil, dimoxystrobin, epoxiconazole, fenpropimorph, kresoxim-methyl, metrafenone, propiconazole, prothioconazole, pyraclostrobin, tebuconazole, triadimenol	chlorpyrifos, cypermethrin, deltamethrin, lambda-cyhalothrin, permethrin, zeta-cypermethrin	bitertanol (F), clothianidin (I), fluoxastrobin (F), fuberidazole (F), imidacloprid (I), prochloraz (F), prothioconazole (F) tebuconazole (F), tefluthrin (I), triadimenol (F), triazoxide (F), triticonazole (F)
2007	bromoxynil, carfentrazone-ethyl, chlorotoluron, clodinafop-propargyl, clomazone, diflufenican, fenoxaprop-P-ethyl, florasulam, flufenacet, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, ioxynil, isoproturon, mecoprop-P, mesosulfuron-methyl, metazachlor, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, propyzamide, quizalofop-P-tefuryl, simazine, thifensulfuron-methyl, tribenuron-methyl, trifluralin	azoxystrobin, boscalid, chlorothalonil, cyproconazole, dimoxystrobin, epoxiconazole, fenpropidin, fenpropimorph, flutriafol, metrafenone, prothioconazole, pyraclostrobin, quinoxyfen, tebuconazole, triadimenol, trifloxystrobin	cypermethrin, deltamethrin, permethrin, zeta-cypermethrin	bitertanol (F), clothianidin (I), fuberidazole (F), imidacloprid (I), prochloraz (F), prothioconazole (F), triticonazole (F)
2008	amidosulfuron, bromoxynil, chlorotoluron, clodinafop-propargyl, clomazone, diflufenican, fenoxaprop-P-ethyl, florasulam, flufenacet, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, ioxynil, isoproturon, mecoprop-P, mesosulfuron-methyl, metazachlor, metsulfuron-methyl, pendimethalin, picolinafen, thifensulfuron-methyl, tribenuron-methyl, trifluralin	azoxystrobin, boscalid, chlorothalonil, cyproconazole, epoxiconazole, fenpropimorph, fluoxastrobin, kresoxim-methyl, metconazole, metrafenone, picoxystrobin, prochloraz, propiconazole, proquinazid, prothioconazole, pyraclostrobin, tebuconazole	chlorpyrifos, cypermethrin, lambda-cyhalothrin, zeta-cypermethrin	clothianidin (I), fuberidazole (F), imidacloprid (I), prochloraz (F), prothioconazole (F), triadimenol (F), triticonazole (F)
2009	bromoxynil, carfentrazone-ethyl, chlorotoluron, clodinafop-propargyl, diflufenican, florasulam, flufenacet, flupyrsulfuron-methyl-sodium, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, ioxynil, isoproturon, mecoprop-P, mesosulfuron-methyl, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, thifensulfuron-methyl, tribenuron-methyl, trifluralin	azoxystrobin, boscalid, chlorothalonil, cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, fluoxastrobin, metconazole, metrafenone, prochloraz, propiconazole, proquinazid, prothioconazole, pyraclostrobin, quinoxyfen, tebuconazole	cypermethrin, zeta-cypermethrin	clothianidin (I), fuberidazole (F), imidacloprid (I), prochloraz (F), prothioconazole (F), triadimenol (F), triticonazole (F)
2010	bromoxynil, chlorotoluron, clodinafop-propargyl, diflufenican, fenoxaprop-P-ethyl, florasulam, flufenacet, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, ioxynil, mecoprop-P, mesosulfuron-methyl, metsulfuron-methyl, pendimethalin, picolinafen, pyroxsulam, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, boscalid, carbendazim, chlorothalonil, cyproconazole, dimoxystrobin, epoxiconazole, fenpropimorph, fluoxastrobin, kresoxim-methyl, metconazole, metrafenone, prochloraz, propiconazole, proquinazid, prothioconazole, pyraclostrobin	chlorpyrifos, cypermethrin, zeta-cypermethrin	clothianidin (I), fuberidazole (F), imidacloprid (I), prochloraz (F), prothioconazole (F), silthiofam (F), triadimenol (F) triticonazole (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 3 (continued). Chemical compounds used as herbicides, fungicides and insecticides on winter wheat crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
2011	amidosulfuron, bromoxynil, chlorotoluron, clodinafop-propargyl, diflufenican, florasulam, flufenacet, flupyrsulfuron-methyl, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, lignin sulfonic acid, MCPA, mecoprop-P, mesosulfuron-methyl, methanol, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, pyroxsulam, thifensulfuron-methyl, tribenuron-methyl	azoxystrobin, boscalid, chlorothalonil, cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, kresoxim-methyl, metconazole, metrafenone, prochloraz, propiconazole, proquinazid, prothioconazole, pyraclostrobin, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, lambda-cyhalothrin, pirimicarb, zeta-cypermethrin	clothianidin (I), fluquinconazole (F), prochloraz (F), prothioconazole (F), triticonazole (F)
2012	chlorotoluron, clodinafop-propargyl, diflufenican, diquat, florasulam, flufenacet, flupyrsulfuron-methyl, fluroxypyr, glyphosate, iodosulfuron-methyl-sodium, mecoprop-P, mesosulfuron-methyl, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, pyroxsulam, tribenuron-methyl	azoxystrobin, bixafen, boscalid, chlorothalonil, cyproconazole, epoxiconazole, fenpropimorph, fluoxastrobin, fluxapyroxad, isopyrazam, kresoxim-methyl, metconazole, prochloraz, propiconazole, proquinazid, prothioconazole, pyraclostrobin, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, lambda-cyhalothrin, zeta-cypermethrin	clothianidin (I), fluquinconazole (F), prochloraz (F), prothioconazole (F), triticonazole (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 4 Chemical compounds used as herbicides, fungicides and insecticides on winter barley/oats crops in the Sussex Study Area, 1970-1995 (taken from Ewald & Aebischer, 1999).

Year	Herbicide	Fungicide	Insecticide
1970	dicamba, MCPA, mecoprop, paraquat, 2,3,6-TBA		
1971	dicamba, MCPA, mecoprop, 2,3,6-TBA	chloraniformethan, tridemorph	
1972	dalapon, dicamba, MCPA, mecoprop, paraquat, 2,3,6-TBA		
1973	desmetryne, mecoprop	ethirimol	dimethoate
1974	chlorotoluron, mecoprop, metoxuron, paraquat, simazine	captafol, ethirimol	
1975	chlorotoluron, mecoprop, metoxuron, simazine	captafol, carbendazim	pirimicarb, demeton-s-methyl
1976	MCPA, mecoprop, metoxuron, simazine	captafol, carbendazim, ethirimol, tridemorph	demeton-s-methyl
1977	2,4-D, MCPA, mecoprop, metoxuron, simazine	benomyl, triadimefon, tridemorph	
1978	dicamba, MCPA, mecoprop, paraquat	tridemefon	demeton-s-methyl
1979	chlorotoluron, isoproturon, MCPA, mecoprop, methabenzthiazuron, paraquat	carbendazim, maneb, triadimefon, tridemorph, zinc ammoniate ethylenebis mixture	
1980	dicamba, isoproturon, MCPA, mecoprop, methabenzthiazuron, paraquat	carbendazim, maneb, triadimefon, tridemorph	
1981	bromoxynil, chlorotoluron, ioxynil, isoproturon, linuron, MCPA, mecoprop, methabenzthiazuron, paraquat, trifluralin	carbendazim, triadimefon, tridemorph	pirimicarb
1982	chlorotoluron, glyphosate, linuron, MCPA, mecoprop, methabenzthiazuron, paraquat, trifluralin	propiconazole	
1983	bifenox, bromoxynil, chlorotoluron, clopyralid, diquat, glyphosate, ioxynil, isoproturon, MCPA, mecoprop, paraquat	carbendazim, propiconazole, triadimefon	demeton-s-methyl, gamma –HCH
1984	bifenox, bromoxynil, chlorotoluron, clopyralid, difenzoquat, ioxynil, isoproturon, MCPA, mecoprop, tri-allate	carbendazim, fuberadazole, propiconazole, triadimenol, thiophanate	cypermethrin, deltamethrin
1985	chlorotoluron, clopyralid, glyphosate, isoproturon, MCPA, mecoprop, paraquat	carbendazim, procholoraz, propiconazole	cypermethrin
1986	chlorotoluron, clopyralid, fluroxypyr, MCPA, mecoprop, paraquat	carbendazim, fenpropidin, prochloraz, propiconazole	cypermethrin
1987	chlorotoluron, chlorsulfuron, fluroxypyr, mecoprop, metsulfuron-methyl	carbendazim, flutriafol, maneb, propiconazole, triadimefon, tridemorph	cypermethrin
1988	chlorotoluron, fluroxypyr, isoproturon, paraquat	captafol, carbendazim, flutriafol, prochloraz, propiconazole, triadimefon	
1989	benazolin, bromoxynil, chlorotoluron, fluroxypyr, ioxynil, isoproturon, MCPA, mecoprop, paraquat	carbendazim, fenpropidin, fenpropimorph, flusilazole, flutriafol, prochloraz, propiconazole	cypermethrin
1990	chlorotoluron, diflufenican, glyphosate, isoproturon, mecoprop-p	carbendazim, fenpropimorph, flutriafol, prochloraz, propiconazole	cypermethrin
1991	chlorotoluron, difenzoquat, diflufenican, glyphosate, isoproturon	carbendazim, chlorothalonil, fenpropidin, fenpropimorph, flutriafol, mancozeb, maneb, prochloraz, propiconazole, triadimenol, tridemorph	cypermethrin
1992	benazolin, bromoxynil, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, ioxynil, isoproturon, metasulfuron-methyl	carbendazim, chlorothalonil, cyproconazole, fenpropidin, fenpropimorph, flutriafol, mancozeb, maneb, prochloraz, propiconazole, tridemorph	cypermethrin
1993	chlorotoluron, difenzoquat, diflufenican, fluroxypyr, isoproturon, mecoprop-p, metsulfuron-methyl, paraquat	carbendazim, chlorothalonil, fenpropidin, fenpropimorph, flutriafol, maneb, propiconazole, tebuconazole	cyhalothrin, cypermethrin
1994	amidosulfuron, benazolin, bromoxynil, diclofop-methyl, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, ioxynil, isoproturon, mecoprop, metsulfuron-methyl, tralkoxydim, trifluralin	carbendazim, chlorothalonil, cyproconazole, fenpropidin, fenpropimorph, flusilazole, flutriafol, mancozeb, maneb, prochloraz, tebuconazole	cypermethrin
1995	amidosulfuron, benazolin, bromoxynil, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, imazamethabenz-methyl, ioxynil, isoproturon, linuron, MCPA, mecoprop-p, metsulfuron-methyl, simazine, trifluralin	carbendazim, chlorothalonil, cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, flusilazole, flutriafol, mancozeb, prochloraz, propiconazole, tebuconazole	cypermethrin, deltamethrin, lambda-cyhalothrin

Appendix: Table 4 (continued). Chemical compounds used as herbicides, fungicides and insecticides on winter barley/oats crops in the Sussex Study Area, 1996-2012. Areas shaded in grey inidicate where no information was available for break crops in this year.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
1996	amidosulfuron, bromoxynil, di-allate, diflufenican, fluroxypyr, glyphosate, ioxynil, isoprotuon, isoproturon, mecoprop, mecoprop-P, metsulfuron-methyl, pendimethalin, trifluralin	carbendazim, chlorothalonil, cyproconazole, epoxiconazole, fenpropidin, fenpropimorph, propiconazole, tebuconazole, triadimenol, tridemorph	cypermethrin, deltamethrin, lambda-cyhalothrin	
1997	amidosulfuron, bromoxynil, di-allate, diflufenican, fluroxypyr, glyphosate, ioxynil, isoproturon, mecoprop, mecoprop-P, metoxuron, metsulfuron-methyl, pendimethalin, simazine, trifluralin	carbendazim, epoxiconazole, fenpropidin, fenpropimorph, procholoraz, propiconazole, triadimenol, tridemorph	cypermethrin, deltamethrin, lambda-cyhalothrin	
1998	amidosulfuron, diclofop-methyl, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, glyphosate, isoproturon, metsulfuron-methyl, pendimethalin, tralkoxydim, trifluralin	carbendazim, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, flusilazole, procholoraz, propiconazole, spiroxamine	cypermethrin, deltamethrin, gamma-HCH, lambda-cyhalothrin	
1999	amidosulfuron, diclofop-methyl, diflufenican, fenoxaprop-P-ethyl, fluroxypyr, flurtamone, glyphosate, isoproturon, metsulfuron-methyl, pendimethalin	azoxystrobin, cyprodinil, epoxiconazole, fenpropimorph	deltamethrin, lambda-cyhalothrin	tebuconazole (F), triazoxide (F)
2000	amidosulfuron, chlorotoluron, clodinafop-propargyl, diflufenican, florasulam, fluroxypyr, flurtamone, glyphosate, isoproturon, pendimethalin, tribenuron-methyl	azoxystrobin, cyprodinil, epoxiconazole, fenpropimorph, metconazole, propiconazole, tebuconazole, trifloxystrobin	chlorpyrifos, cypermethrin, deltamethrin, gamma-HCH, lambda-cyhalothrin	tebuconazole (F), triazoxide (F)
2001	amidosulfuron, diflufenican, florasulam, flufenacet, glyphosate, isoproturon, metazachlor, metsulfuron-methyl, propaquizafop, quinmerac, tralkoxydim, trifluralin	azoxystrobin, carbendazim, cyprodinil, epoxiconazole, fenpropimorph, flusilazole, kresoxim-methyl	lambda-cyhalothrin	bitertanol (F), fuberidazole (F), imidacloprid (I), tebuconazole (F), triazoxide (F)
2002	amidosulfuron, carfentrazone-ethyl, diflufenican, florasulam, flupyrsulfuron-methyl, fluroxypyr, flurtamone, glyphosate, isoproturon, metsulfuron-methyl, pendimethalin, tralkoxydim, trifluralin	azoxystrobin, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, kresoxim-methyl, picoxytrobin, spiroxamine, tebuconazole	cypermethrin, deltamethrin, lambda-cyhalothrin	carboxin (F), thiram (F)
2003	carfentrazone-ethyl, flupyrsulfuron-methyl-sodium, fluroxypyr, glyphosate	azoxystrobin, cyproconazole, cyprodinil, fenpropimorph, picoxytrobin, quinoxyfen, tebuconazole	lambda-cyhalothrin	carboxin (F), thiram (F)
2004	carfentrazone-ethyl, chlorotoluron, florasulam, flupyrsulfuron-methyl-sodium, fluroxypyr, pendimethalin, picolinafen	azoxystrobin, cyproconazole, cyprodinil, picoxystrobin, tebuconazole	cypermethrin, lambda-cyhalothrin	carboxin (F), imidacloprid (I), tebuconazole (F), thiram (F), triazoxide (F)
2005	diflufenican, florasulam, flufenacet, fluroxypyr, glyphosate, metsulfuron-methyl, pendimethalin, thifensulfuron-methyl, trifluralin	azoxystrobin, cyproconazole, cyprodinil, fluoxastrobin, prothioconazole	cypermethrin	imidacloprid (I), tebuconazole (F), triazoxide (F)
2006	bromoxynil, diflufenican, florasulam, flufenacet, fluroxypyr, glyphosate, ioxynil, isoproturon, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, thifensulfuron-methyl, tribenuron-methyl, trifluralin	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, kresoxim-methyl, penconazole, picoxystrobin, prothioconazole	cypermethrin, deltamethrin, zeta-cypermethrin	fuberidazole (F), imidacloprid (I), tebuconazole (F), triadimenol (F), triazoxide (F)
2007	diflufenican, florasulam, flufenacet, fluroxypyr, glyphosate, isoproturon, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden, thifensulfuron-methyl	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, kresoxim-methyl, picoxystrobin, prothioconazole, pyraclostrobin, spiroxamine	cypermethrin, zeta-cypermethrin	imidacloprid (I), tebuconazole (F), triazoxide (F)
2008	chlorotoluron, diflufenican, ethylene glycol, florasulam, flufenacet, fluroxypyr, isoproturon, mecoprop-P, metsulfuron-methyl, pendimethalin, picolinafen, pinoxaden	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, metrafenone, penconazole, picoxystrobin, proquinazid, prothioconazole	cypermethrin, lambda-cyhalothrin, zeta-cypermethrin	clothianidin (I), imidacloprid (I), prothioconazole (F), tebuconazole (F), triazoxide (F)

*(F) – fungicide, (I) – Insecticide.

Appendix: Table 4 (continued). Chemical compounds used as herbicides, fungicides and insecticides on winter barley/oats crops in the Sussex Study Area, 1996-2012.

Year	Herbicide	Fungicide	Insecticide	Seed treatment*
2009	chlorotoluron, clomazone, diflufenican, florasulam, flufenacet, fluroxypyr, glyphosate, isoproturon, mecoprop-P, metazachlor, metsulfuron-methyl, pendimethalin, pinoxaden, thifensulfuron-methyl	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, epoxiconazole, fenpropimorph, fluoxastrobin, kresoxim-methyl, metrafenone, picoxystrobin, proquinazid, prothioconazole, pyraclostrobin, quinoxyfen, tebuconazole	chlorpyrifos, cypermethrin, pirimicarb, zeta-cypermethrin	clothianidin (I), fluopyram (F), fuberidazole (F), imidacloprid (I), prothioconazole (F), tebuconazole (F), triadimenol (F) triazoxide (F)
2010	chlorotoluron, diflufenican, florasulam, flufenacet, fluroxypyr, glyphosate, mecoprop-P, pendimethalin, pinoxaden	azoxystrobin, chlorothalonil, cyproconazole, cyprodinil, fluoxastrobin, picoxystrobin, proquinazid, prothioconazole, quinoxyfen, trifloxystrobin	cypermethrin, lambda-cyhalothrin, zeta-cypermethrin	clothianidin (I), prothioconazole (F), tebuconazole (F), triazoxide (F)
2011	chlorotoluron, florasulam, flufenacet, fluroxypyr, glyphosate, mecoprop-P, metsulfuron-methyl, pendimethalin, pinoxaden, thifensulfuron-methyl	bixafen, cyprodinil, epoxiconazole, fenpropimorph, metrafenone, picoxystrobin, proquinazid, prothioconazole, pyraclostrobin, trifloxystrobin	cypermethrin	clothianidin (I), prothioconazole (F)
2012	chlorotoluron, diflufenican, florasulam, flufenacet, fluroxypyr, glyphosate, metsulfuron-methyl, pendimethalin, pinoxaden, prosulfocarb	bixafen, cyproconazole, cyprodinil, epoxiconazole, fenpropidin, fenpropimorph, isopyrazam, kresoxim-methyl, metrafenone, proquinazid, prothioconazole, pyraclostrobin	chlorpyrifos, cypermethrin, lambda-cyhalothrin, zeta-cypermethrin	clothianidin (I), prothioconazole (F), tebuconazole (F), triazoxide (F)

*(F) – fungicide, (I) – Insecticide.