Integrated Pest Management (IPM) for Biodiversity Enhancement

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Foreword

In the announcement of new Sustainable Farming Incentive (SFI) Standards (Defra 2023) - including a Standard for Integrated Pest Management (IPM) - Defra made 'support of biodiversity and species abundance' a key objective. IPM is also an integral part of the EU Directive 2009/128/EC (which remains part of UK legislation), promoting the use of pesticides only when all other reasonable preventative measures have been taken to achieve a sustainable use of pesticides. IPM is also a key component of the upcoming UK National Action Plan for the Sustainable Use of Pesticides. Underpinning all these principles is biodiversity.

As part of Environment Improvement Plan, the government has set targets to halt the decline in species abundance by 2030. With 63% of land in England being used for agriculture, actions in this area will be key for meeting this target.

While the primary aim of IPM practices is to reduce the reliance and use of chemical pesticides and so will have a benefit of reducing chemical pressures on wildlife, many of the IPM practices rely on natural solutions, which could improve biodiversity and species abundance.

In this review, Natural England aims to understand how the potential uptake of IPM practices across agricultural areas of England could affect biodiversity and species abundance. Recognizing the large variation both in agriculture/IPM practices and species abundance itself means that the impacts of IPM on biodiversity is complicated. However, the outputs from this review of evidence can be used to assist Natural England in future prioritisation of IPM practices and to gain a wider understanding of the impact new Environmental Land Management policy might have on species abundance targets and biodiversity in England.

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.

Executive summary

In the announcement of new Sustainable Farming Incentive (SFI) Standards (Defra 2023) - including a Standard for integrated pest management (IPM) - Defra made ‘support of biodiversity and species abundance’ a key objective. IPM is also an integral part of the EU Directive 2009/128/EC (which remains part of UK legislation), promoting the use of pesticides only when all other reasonable preventative measures have been taken to achieve a sustainable use of pesticides. This requires that eight principles of IPM are applied: prevention and suppression; monitoring; decisions based on monitoring and thresholds; non-chemical methods; pesticide selection; reduced pesticide use; anti-resistance strategies; and evaluation (Barzman *et al*., 2015). Underpinning all these principles is biodiversity. In conventional agricultural systems we have lost some of the resilience seen in natural biodiverse systems and the basis of natural resilience is biodiversity.

The purpose of this study is to provide an assessment of the evidence to help understand which IPM techniques deliver the most benefits for biodiversity, the opportunities for biodiversity enhancement and circumstances where there is a potential for negative impacts on biodiversity. Implementation of IPM on farm is not “one size fits all” but should be customised to an individual farm on a field-by-field basis.

This report covers a wide subject area, and its coverage has been limited by resources. A wide range of references have been consulted, but this was not exhaustive. In particular, there is little evidence on the effect of IPM on biodiversity in its strict sense. Most studies tested or observed effects on species abundance. We define in the report how this evidence has been interpreted and note that the conclusions should be interpreted with caution. Thirteen IPM techniques were covered in the arable sector, nine in outdoor horticulture and ten in grassland. The biodiversity categories covered were: birds; mammals; fish; amphibians; reptile; arthropods, annelids, molluscs; soil micro, meso and macro fauna; non-target plants and protected species. There was some crossover between the groups particularly with invertebrates as prey species and protected species.

The first part of the review summarises seven IPM projects done between 1981 and 2005. These projects were complicated and most tried to look at a whole system approach to improving biodiversity whilst reducing pesticide use and changing cultivations in crops. The reporting covered both the benefits and negatives to biodiversity. In IPM there is much crossover between techniques and whilst some biodiversity groups profit from the changes there are some negative impacts for other groups.

The greatest percentage of references concerning biodiversity covered arthropods, annelids and molluscs, followed by non-target plants and birds. There was a lack of information relating to the other categories, such as fish, amphibians and reptiles, possibly reflecting the difficulty of monitoring these species and other factors.

An assessment was made of references that had a positive and negative impact on biodiversity within the text. The majority of techniques had a positive impact on biodiversity with crop rotation, field margins, cover crops and companion crops, stubble management, varietal choice and seed mixtures, and bioprotectants having the most positive references. The techniques that had the greatest negative impact on biodiversity were cultivations (arable), harvesting (arable) and mowing and topping (grassland).

There are several techniques that received less research including hygiene and pruning, physical protection, soil amendments, sowing date and a weed tolerant approach.

The review has shown that there is an extensive amount of evidence on the effects of IPM on species abundance, but there are many knowledge gaps, and these are detailed in the individual sections. Previous UK IPM projects have been large, covering many hectares and multiple farms, these projects are expensive and generally target specific practices and species.

We recommend that the effects on biodiversity and species abundance of the paid actions within the new SFI IPM Standard, should be monitored. This would ensure the actions are delivering a key area of public good.

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General introduction

Defra have announced new Sustainable Farming Incentive (SFI) Standards (Defra, 2023) – including a Standard with paid actions to incentivise integrated pest management (IPM). Defra made 'support of biodiversity and species abundance' a key objective within SFI, and biodiversity is specifically noted as an intended public good from the IPM paid actions. IPM is also an integral part of the EU Directive 2009/128/EC[1], promoting the use of pesticides only when all other reasonable preventative measures have been taken. The eight principles of IPM are: prevention and suppression; monitoring; decisions based on monitoring and thresholds; non-chemical methods; pesticide selection; reduced pesticide usage; anti-resistance strategies; and evaluation (Barzman *et al*., 2015; who précised Annex III of EUR-Lex - 32009L0128 - EN - EUR-Lex (europa.eu)). Underpinning all these principles is biodiversity. Kogel (2022) stated that biodiversity is the basis for integrated pest management. In conventional agricultural systems we have lost some of the resilience seen in natural biodiverse systems and the basis of natural resilience is biodiversity.

The purpose of this study is to assess the evidence to help understand which IPM techniques deliver the most benefits for biodiversity and opportunities for biodiversity enhancement. Also identified are those circumstances where there exists a potential for negative impacts on biodiversity.

The main objectives of this report are:

1. To collate and **evaluate recent published evidence** from the UK, Europe, and other temperate regions **on the beneficial biodiversity outcomes of IPM programmes** for the three farm systems under consideration (arable, outdoor horticulture and grassland).

2. To itemise the **typical components** or elements of an IPM approach in arable, grassland and outdoor horticultural situations and provide an assessment of the potential for **biodiversity benefits** or **negative impacts** for each of the elements.

3. To undertake a **gap analysis** of the evidence and provide **recommendations** on priority research areas.

[1] Although Britain has left the European Union, EU legislation prior to 31 December 2020 is still part of UK legislation

Materials and methods

A text mining-based, systematic, literature review has been conducted to assemble the readily available, recent evidence on the impact of the chosen IPM techniques on biodiversity. Search terms used consisted of crop, IPM technique and biodiversity characteristics. The search parameters were confined to Europe, New Zealand, and North America, where the same crop species are grown. Literature searches were not date specific due to considerable significant IPM research e.g., Greig-Smith *et al., 1992*, Young *et al.,* 2001 not being recent. The search results have been screened, duplications removed and then classified into 'relevant', 'clearly not relevant' or 'uncertain' categories of evidence. The second phase of screening involved reading the abstract or the first paragraph of the 'clearly relevant' and 'uncertain' publications. Relevant evidence was then obtained in full and listed in the review. A further review of other sources of literature and evidence from unpublished but peer reviewed grey literature was undertaken.

This report is split in to four parts, Synopsis of historical IPM projects, Arable (winter cereals, winter oilseed rape, sugar beet), Outdoor horticulture (top fruit, root vegetables, brassicas) and Grassland.

IPM Techniques

The IPM techniques reviewed were chosen by evaluation of the techniques highlighted as priority areas in the Agriculture and Horticulture Development Board (AHDB) IPM review (Blake *et al.,* 2021) and input from Natural England. Searches were be made for the techniques listed and evidence from further manual searches was also used. The IPM techniques discussed are listed in Table 1.

Table 1. The IPM techniques contained in the report and their location. Note: some cells have been deliberately left blank.

IPM techniques	Arable	Horticulture	Grassland
Cultivations	6.1	See arable	8.1
Crop rotation	6.2	7.1	8.2
Field margins and in-field strips	6.3		
Monitoring of crops, DSS, forecasting and pest thresholds	6.4	7.2	8.3
Non-chemical weed control	6.5	7.3	
Sowing date	6.6		
Precision application	6.7		8.4
Bioprotectants	6.8	7.4	
Selective and/or narrow spectrum pesticides	6.9		
Cover crops, companion cropping, intercropping, undersowing, trap crops, banker plants and floral strips	6.10	7.5	
Varietal choice and diverse seed mixtures	6.11		8.5
Genetic modification	6.12	See arable	
Stubble management	6.13		
Soil amendments		7.6	
Hygiene and pruning		7.7	
Physical protection of crops (crop covers, artificial shelters, barriers)		7.8	
Mowing and topping			8.6
Grazing management			8.7
Weed tolerant approach			8.8
ELM options and Agri-environment schemes			8.9

There are other IPM techniques available, and other options in Countryside Stewardship, but these are outside the scope of this work so not included in the report.

Biodiversity

The components of biodiversity can be considered at different levels:

Species abundance: refers to the number of individuals per species.

Species richness: refers to the number of species in a community.

Species diversity: includes a measure of the number of species and the abundance of each species.

Biodiversity: includes species diversity, and genetic and ecosystem diversity.

A thorough assessment of biodiversity is resource intensive and current evidence on the biodiversity implications of different IPM techniques is sparse. Studies tend to focus on the effects of IPM on the abundance of single species or a few species, mainly beneficials and pests. Therefore, restricting this review to studies which assessed effects on biodiversity, in its strict sense, would have yielded little insight.

In broad terms, if species, or groups of species, decline in abundance to the point where they become sparsely and patchily distributed, then biodiversity is reduced. The UK biodiversity indicators 2022 report (Defra, 2022) shows long term declines of pollinators, insects and birds in the wider countryside, and UK priority species. Due to the lack of scientific evidence on the biodiversity implications of IPM techniques, the information from the different studies has been used to comment on potential overall biodiversity implications for each technique. Where an IPM technique shows potential to increase the abundance of a species in the categories outlined below then we have considered this to be advantageous to biodiversity and therefore assessed as a positive impact. The authors recognise that such a conclusion could be erroneous, for example where an increase in one species results in a decrease of another. Hence, this analysis provides only a partial picture and the conclusions should therefore be interpreted with caution.

Comprehensive, in-depth research, focusing on biodiversity implications of IPM techniques would be required to provide a more accurate picture. To maximise efficiency, future research would best be focused on biodiversity indicator or keystone species for each IPM technique. This would support assessment of Defra's objective (Defra 2023) to 'halt the decline in species abundance by 2030 and ensure species abundance in 2042 is greater than in 2022'.

There are further areas of interpretation that need to be considered:

- IPM techniques are intended to reduce the need for pesticide treatment and then ensure that pesticides are applied according to need. Pesticides can have direct or indirect effect on non-target species. Hence, if an IPM technique results in reduced pesticide use, this has been reported as being beneficial to biodiversity. The authors recognise that such effects vary by product, dose, timing and location and will, in many cases, be transient. Pesticides causing persistent negative effects on non-target organisms would be unlikely to meet the regulatory requirements for registration.

- Biodiversity includes species which can be agricultural pests, weeds or pathogens, when they are in the wrong place at the wrong time. The purpose of IPM is to control these species and reduce their abundance in the crop at critical times to avoid economic, yield, quality or ongoing impacts. However, these species can be important food sources for other species. For example, some weed species are important for seed eating birds and herbivorous insects, and invertebrate pests sustain predators. Effective IPM control could therefore be characterised as negative for biodiversity. In this review we have adopted a more balanced approach, whereby:

- Effective control of invertebrate pests, weeds and pathogens is interpreted generally as a desirable outcome.
- The desired level of control is to an abundance below the economically damaging level, but not (in most cases) complete eradication.
- Taking the example of weeds; different species may combine low competitiveness to the crop with high biodiversity benefits, or *vice versa* (Storkey and Westbury, 2007; Marshall *et al*., 2003). The acceptable or desired population abundance varies accordingly. This review only considers control of weeds to be negative for biodiversity if it overly suppresses weed species which combine low competitiveness and high value for supporting biodiversity.

- A positive or negative biodiversity effect is a relative assessment compared to a 'standard'. In the numerous studies reviewed here, IPM practices were variously compared against a range of other management practices. For policy purposes, the question is whether adoption of more IPM methods would improve biodiversity compared to current practice (which is predominantly a combination of IPM methods and the use of conventional chemical plant protection products). The text of the review summarises 'what was compared with what' in each study. The summary tables attempt to interpret whether increased adoption of IPM practices would be positive or negative for biodiversity, compared against current practice. This is the most practically relevant comparison but introduces considerable subjective expert judgement into the analysis.

The following search terms were used for the purpose of identifying different components of biodiversity in the literature searches:

- Birds Invertebrates as prey species
- Mammals
- Fish
- Amphibians
- Reptiles
- Arthropods, annelids, molluscs
- Soil micro, meso and macro fauna
- Non-target plants
- Protected species

Impacts on fungi, algae, protozoa, archaea, chromista and bacteria are not well described in the literature, despite their ecological importance.

For the purpose of this report protected species are defined as:

- Protected species listed in 'The conservation of Habitats and Species Regulations 2010' https://www.legislation.gov.uk/uksi/2010/490/signature/made.

- Species listed under Section 41 (S41) of the 2006 Natural Environment and Rural Communities (NERC) Act.

There was some crossover between sections, particularly with invertebrates as prey species and protected species. Where this has occurred, the evidence has been cited in the original section and then cross referenced in the protected species section. Evidence for bumblebee species was not always species specific, however they are cross-referenced to the protected species section. All other groups have only been cross-referenced where the specific species has been named.

IPM and pesticide usage

IPM techniques that help to reduce pesticide usage can help to reduce both the direct and indirect impacts of pesticides on the environment. An over reliance on pesticides can lead to resistant pest populations, the suppression of beneficial pollinators and natural enemies (Bommarco *et al.,* 2011; Bass *et al.*, 2014) and the decline in other farmland species. The landscape diversity in the surrounding habitats influences the abundance and diversity of non-target farmland species. The use of buffer zones, well timed pesticide applications and the use of drift reduction technology can protect habitats adjacent to crops. Providing additional habitats and resources for non-pest species improves the abundance and diversity of farmland species (Norton *et al.*, 2009; Gabriel *et al.*, 2013; Puech *et al.*, 2014; UKCEH, 2022)). The provision of resources for beneficial species and natural enemies of crop pests can help reduce the likelihood of pest populations exceeding economic thresholds (Ramsden *et al.*, 2017). The use of field margins and in-field measures such as beetle banks (a permanent grass strip within an arable field that provides refuge for invertebrates) can provide additional resources and refuge from crop treatments (Griffiths *et al* 2018, Ramsden *et al.*, 2016). These techniques provide the most benefit when managed at a landscape level, providing a diverse, robust population of natural enemies (Griffith *et al.*, 2018). Encouraging natural enemies through additional habitat resources within the landscape is an important part of the IPM strategy, promoting the use of pesticides only when all other reasonable preventative measures have been taken. Pesticides have been shown to have negative indirect effects on farmland biodiversity (Mann *et al.*, 2009; McKenzie and Whittingham, 2009; Gilburn *et al.*, 2015). Pesticide usage can be reduced whilst maintaining high yields, through decision support systems and changes in attitude to risk (Ramsden *et al.*, 2017).

Deytieux et al (2012) found Integrated weed management (IWM) based systems reduced aquatic ecotoxicity impact per cultivated area by 89-93% and resulted in a 70-80% reduction in terrestrial ecotoxicity compared to a standard, non-IWM system, when compared in a six-year field experiment. Most of the differences between systems were due to the impact of herbicides, which were used at very low levels in the IWM cropping systems. Fungicides and insecticides also have ecotoxicological effects, but many effects have not been effectively quantified to date.

Stroda and Garthwaite (2020) surveyed farmers on integrated pest management (IPM). 90% of respondents had completed an IPM plan, 47% alone and 43% alongside an agronomist. Farmers were asked which management techniques they carried out to reduce risk. Techniques used by ≥70% of respondents included crop rotation, cultivation of seeds beds before and after sowing, varietal/seed choice to reduce pest risk, catch/cover/trap cropping to reduce pest risk and enhance beneficial organisms.

Synopsis of main IPM projects in the UK

The Boxworth project was conceived in the 1970s and began in 1981, to study the impact of pesticides on non-target species and was followed by many more projects (Figure 1).

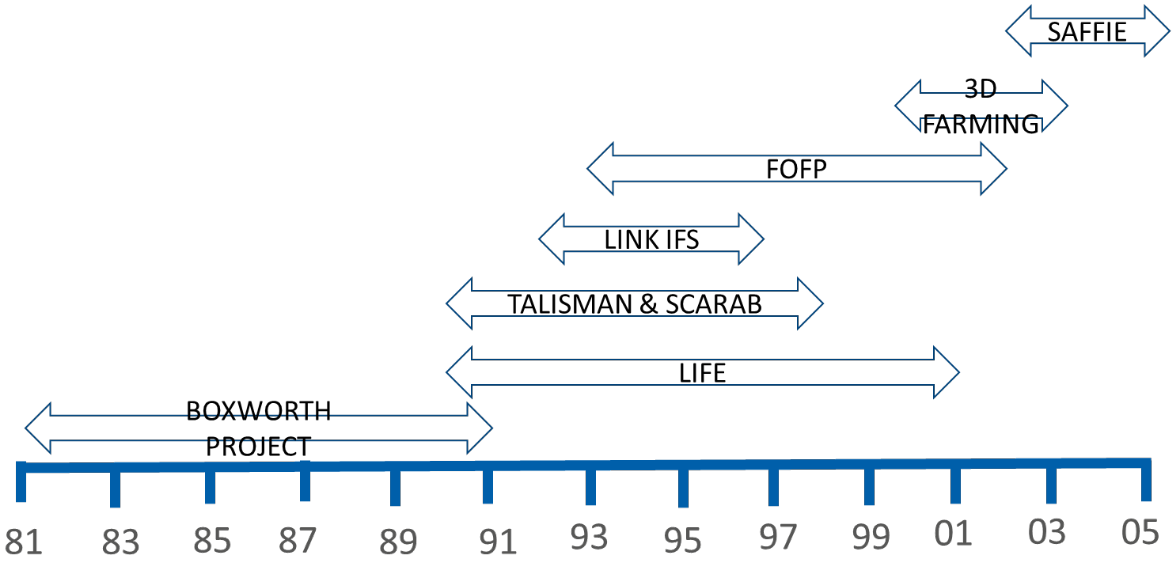

Figure 1. The timeline of integrated farming projects

The Boxworth project

The Boxworth Project (1981–1991) (Greig-Smith *et al.*, 1992) was commissioned and funded by Defra to investigate the effects of pesticide use in cereals on a range of wildlife, including plants, birds, small mammals, and arthropods (e.g. insects, mites and spiders). The project was not conceived or designed with an Integrated Pest Management (IPM) remit. The Project was the first large scale, multi-disciplinary study in the UK to provide a long-term comparison of different farming systems and included many elements which form part of IPM. The Boxworth Project was an ecological study with incidental monitoring of economic inputs and outputs. The following aims were central to the Project:

- To examine and compare the environmental and ecological side effects of contrasting pesticide regimes.
- To monitor the economics of crop production under contrasting pesticide regimes and to establish the commercial viability of reduced input farming.
- To identify any difficulties that might arise in the practical management of reduced input farming systems, with particular reference to pesticide use.

The project was sited at ADAS Boxworth where the farm was split into three areas. After two years (1982 & 1983) of baseline monitoring of flora and fauna, three pesticide regimes were applied to the field areas for a period of five years continuous cropping (1984-1988.

1. A ‘Full Insurance’ regime which involved high inputs and prophylactic treatments, imitating an intensive cereal production system of the late 1970s.
2. A ‘Supervised’ regime whereby pesticides were applied only if weeds, diseases or pests exceeded economic thresholds.

3. An ‘Integrated’ regime using economic thresholds and husbandry practices which further reduce the need for pesticides.

In reality there was little difference in pesticide inputs between the ‘supervised’ and ‘integrated’ regimes.

The main conclusions were:

- Populations of birds and mammals were apparently resilient to the effects of the high input approach. But within-season effects on small mammals were shown. Avian studies showed exposure to pesticides, but it was not likely to see impact on population size at the scale of the study.
- Patterns of weed densities reflected the efficacy of weed control measures. Changes in flora were slow to occur due to the buffering effects of the seedbank and also allowed for the reintroduction of rare arable species. Greater changes in flora were attributable to physical disturbance rather than herbicides.
- Some beneficial arthropods were vulnerable to pesticides.
- Lower input systems of crop protection are not necessarily less economically viable.

The overarching conclusion was that very high inputs of pesticides are unlikely to be required in a well-managed crop but are likely to result in adverse environmental side-effects and are unlikely to result in additional economic benefits.

The TALISMAN and SCARAB projects

The TALISMAN and SCARAB projects (1990–1998) (Young *et al.*, 2001) were commissioned and funded by Defra and specifically designed as follow on studies to address many of the issues raised by the Boxworth Project. TALISMAN (Towards A Lower Input System Minimising Agrochemicals and Nitrogen) and SCARAB (Seeking Confirmation About Results at Boxworth) complemented each other in their aims and objectives; TALISMAN focused primarily on the economic issues of reducing pesticide and fertiliser use, whilst SCARAB examined in detail many of the questions surrounding the ecological side effects of pesticides. Neither TALISMAN nor SCARAB was conceived or designed with an Integrated Pest Management (IPM) remit, the Projects lacked many of the cultural elements of weed, pest and disease control. TALISMAN and SCARAB share many common features with IPM, particularly in relation to achieving economically sustainable reductions in pesticide use.

The TALISMAN project ran over six years at three locations in England (Cambridgeshire, Warwickshire and North Yorkshire), measuring the economic and agronomic implications of reducing inputs of pesticides and nitrogen fertilisers to arable crops. The study looked at low and high input pesticide regimes in two contrasting arable crop rotations. The ‘Standard Rotation’ contained autumn sown cereals and break crops. The ‘Alternative Rotation’ contained a high proportion of spring-sown cereals and break crops. The main pesticide regimes applied to these rotations were either: Current Commercial Practice (CCP), with nitrogen fertiliser and pesticides applied according to manufacturers' recommended rates; or a Low Input Approach (LIA) in which nitrogen rates were applied at 50 per cent below CCP and pesticide applications omitted or applied at no more than 50 per cent of the rates used in CCP.

Within the SCARAB project in depth observations were made on the ecological effects of pesticides. The impacts of the two levels of pesticide use were assessed over a six-year period at three sites in England. Current Farm Practice (CFP) was the practice followed by a typical, technically competent and financially aware farmer, with pesticides applied at manufacturers' recommended rates. In comparison the Reduced Input Approach (RIA) received no insecticides, molluscicides or nematicides. Fungicides and herbicides were applied at reduced or full rates only where required to avoid a significant reduction in crop yield or value.

The main conclusions of TALISMAN were:

- In terms of the number and timing of pesticide applications, the TALISMAN conventional regime was fully representative of commercial practice at the time.
- Whilst reducing inputs alone may not be the complete answer to ensuring a sustainable farming system, the results demonstrated that lower input pesticide use can be profitable.
- The Alternative Rotation (mainly spring-sown crops) had a lower overall demand on pesticide use than the Standard Rotation (mainly winter-sown crops).
- Pesticides were seen to affect pitfall trap catches reducing carabid beetles, and linyphiid spiders. These catches recovered within three months.
- Arthropod abundance was significantly affected by year-to-year differences and crop rotation

The main conclusions of SCARAB were:

- Short-lived effects of insecticides occurred among different groups of the nontarget arthropods examined in all fields and all years. However, recovery usually followed within the same season.
- Long-term negative effects of the conventional pesticide regime on arthropods were detected only in one out of eight fields, which was under a grass and wheat rotation, and related to certain species of soil-dwelling springtails (collembola) which include beneficial species.
- Pesticide effects on the soil bacteria and fungi species examined showed no clear-cut pattern (using the methods available at the time) and impacts were highly dependent on soil type and soil condition at the time of application.
- There were no apparent long-term trends in earthworm populations, or individual species of earthworm, which could be related to pesticide use.

- The complete absence of insecticides and nematicides in the SCARAB reduced input treatment gave a commercial disadvantage and led to reduced profits in some cases, most noticeably in the high-value crops of potatoes and sugar beet.

LIFE

The Less Intensive Farming and Environment (LIFE) project began in 1989 and continued for 12 years (Defra 2002, 2003). The project occupied approximately 23 ha at Long Ashton, near Bristol and compared integrated arable cropping (IFS) with standard farm practice (SFP). Plot size was relatively large (1 hectare). The objectives were as follows:

- To reduce agrochemical inputs and costs and increase the environmental safety of growing arable crops; to decrease carry over of pests, diseases and weeds by modifying cropping sequences and agronomic practices.
- To conserve nitrogen in the system, reduce demand for external nitrogen and diminish the potential for nitrate leaching; to protect and conserve natural enemies of key pests and diseases and reduce the potential need for pesticides.
- To encourage more active soil flora and fauna, including earthworms, by the use of alternative soil management methods, e.g. non-inversion tillage.
- To specifically target weed control as one of the main limiting factors, by integration of chemical and mechanical methods of control with crop rotation.
- To assess the impact of integrated production systems on the environment by monitoring changes in functions and densities of a number of bio-indicators: epigeal arthropods (carabid and staphylinid beetles, linyphiid spiders), earthworm biomass and impacts on soils (soil erosion, diffuse pollution/emissions of nutrients and pesticides.

The project was initially divided into two phases, phase I (1990-1994), phase II (1995-2001). After harvest 2001, 12 of the 14 previously non-inversion tilled (NIT) plots were split and one half ploughed whilst the other remained in non-inversion tillage.

The SFP plots were ploughed annually and received inputs according to Good Agricultural Practice (GFP) aiming to imitate a conventional farming system. The IFS plots had crops established annually with non-inversion tillage and received crop inputs according to crop needs and disease/pest thresholds.

The main biodiversity outcomes were:

- Earthworm populations were higher in the integrated fields, equivalent to 38% increase in earthworm biomass over the 12-year period when compared to conventionally farmed soil.
- Greater populations of polyphagous predators were present in the integrated crops than in the conventional system.

- In the follow-on experiment where cultivation regimes were reversed earthworm populations decreased where the plough was used. Earthworm populations began to increase when ploughing stopped.

LINK Integrated Farming Systems

The LINK Integrated Farming Systems (IFS) project (Ogilvy, 2000) was established in 1992 on six farms situated in the UK covering Hampshire (Manydown), Cambridgeshire (Boxworth and Sacrewell), Herefordshire (Lower Hope), Yorkshire (High Mowthorpe) and Midlothian (Pathhead). The five-year study was completed in 1997. The aim of the project was to develop an arable integrated system of production that maintained profitability with a different balance of inputs and reduced environmental impact than current conventional systems. There were no specific targets for nitrogen or pesticide use. The integrated system was designed to grow crops in ways that minimised the need for pesticide and fertiliser inputs.

At each site, approximately 50 ha of land was divided into five main blocks. Each block was sub-divided into two field plots and the integrated system of production was compared with a conventional reference. A five-year crop rotation relevant to each location was adopted at each site. Practices adopted in the integrated system included: targeted and selective pesticide use at appropriate rates based on crop monitoring; nutrient inputs balanced with crop requirements; soil reserves and uptakes; a range of cultural control measures including the use of resistant varieties and cultivation techniques to minimise weeds. At some sites, field margins were also managed to encourage biodiversity, especially in relation to beneficial predators and parasites of crop pests.

The main conclusion of IFS was:

- There is no fixed ‘blueprint’ for integrated systems, methods must instead be adopted to fit local, site-specific, circumstances. To make best use of the IFS results it was suggested that farmers would need to identify trial sites most appropriate to their own farming situation in order to identify which integrated techniques they could successfully adopt.

- There were no significant differences in spider and beetle numbers when comparing the integrated and conventional farming system. The effects of different farming practises on invertebrate activity and abundance were relatively small, in this study, compared with other external influences. Differences between the farming systems were often due to a difference in crop grown.

FOFP

Focus on Farming practice (FOFP) started in 1993 in response to the anticipated decline in farm profitability and increasing awareness of environmental concerns about agriculture. It was sponsored by Agrovista UK Ltd, Farmcare and Hydro Agro (UK) Ltd and located on a 60ha site at the Stoughton Estate in Leicestershire (Anon, 2002). The project compared integrated farming directly with conventional farming systems over a nine-year rotation that included grass leys to reflect mixed farming as well as all arable systems. The rotation comprised of a two-year grass ley, winter wheat, set-aside, winter wheat, winter beans and winter wheat. Comparisons were also made with adjacent organic land.

The key findings were:

- Under the Integrated farming system cultivation costs were 16% lower with an average of 1.3 less passes and comparable profits to the conventional system.
- Fertiliser costs were similar between the two systems, but efficiency of nitrogen use was improved, and nitrogen rates decreased under the integrated system.
- Crop protection costs were 30% lower in the integrated system, even under a minimum cultivation regime.
- Management time inputs were highest in the integrated system.
- Pesticide inputs were nearly halved in the integrated system and nitrogen leaching reduced. This was reflected in higher earthworm, beetle and bird numbers.
- The importance of hedge and field margin management was highlighted as they accounted for 80% of the biodiversity within the farmed environment.

In the early years of the project the integrated system benefitted from lower cultivation and operational costs and targeted use of inputs. In more recent years the costs of the two systems converged as the conventional system adopted many of the integrated techniques to reduce costs.

The main biodiversity outcomes were:

- Significant positive effects on bird, beetle and earthworm numbers. Most of these changes were attributed to the use of minimum tillage. The changes in earthworm populations were complex, but populations responded positively to changes in cultivation, direct drilling and the inclusion of grass leys, overall populations were higher in the integrated fields.
- Bird sightings were increased by the increased retention of stubble through minimum tillage and direct drilling; this was attributed to increased food availability.

3-D FARMING

The aim of the project was to use field margin management techniques to increase the abundance and diversity of beneficial insects and spiders and manipulate their distribution and dispersal on farmland for the control of aphid pests (Powell *et al*., 2004). The specific objectives were as follows:

- To provide farmers with advice on field margin management to optimise integrated pest management whilst maintaining biodiversity benefits and profitability.
- To test and further develop a novel aphid control strategy involving the manipulation of parasitoids using aphid sex pheromones in field margins.
- To develop and evaluate the use of specific native flowering plants in field margins to enhance the abundance and diversity of aphid-eating hoverflies in adjacent crops.
- To measure the effects of margin and crop management on aphid and beneficial insect abundance, dispersal and spatial distribution in both the margin and adjacent crops.
- To measure the spatial and temporal distribution of cereal aphids and the extent to which these are controlled by predatory and parasitic species.
- To measure the impact of recently introduced field margin management options on the biodiversity of aphids and their natural enemies.

Manipulation of parasitoid and hoverfly abundance, and the factors affecting aphid and beneficial insect abundance, dispersal and spatial distribution were done on large scale field sites. Further work on aphid predation using Polymerase Chain Reaction (PCR) techniques and hoverfly behaviour were done in controlled conditions.

The main conclusions from the project were as follows:

- Field margins containing wildflower/grass mixtures can help to reduce aphid densities in adjacent cereal crops.
- Field margins and other non-crop habitats provide valuable reservoirs of aphid parasitoids.
- Umbellifer flowers, such as cow parsley and hogweed, as well as yarrow and white campion, provide the best food resources for adult hoverflies, whose larvae feed on aphids. These should be incorporated into field margin seed mixes or conserved in other non-crop habitats such as hedge bottoms and track verges, as appropriate.
- Hoverfly activity in fields with appropriate wildflower margins can result in substantial reductions in aphid numbers in cereal crops.

- The distribution of carabid beetles, which are valuable pest predators, varies through both space and time and is influenced by crop type and by crop and margin management.
- Field margins support ground-dwelling predatory invertebrates that subsequently distribute themselves through the crop. Large fields will be more slowly colonised than small fields, and the diversity of these predators will be lower in the centre of large fields. No optimum field size was given as colonisation would vary according to margin: field ratio and crop manipulation factors such as weed cover.
- Large numbers of predatory invertebrates overwinter within the soil and autumn cultivations can reduce their numbers.
- Some species of generalist invertebrate predators, such as carabid beetles, have localised distribution patterns across and amongst fields and broad-scale insecticide applications should be avoided wherever possible if the chances of reinvasion are to be maximised.
- Ground dwelling predatory invertebrates are encouraged by weeds.10-14% weed cover was deemed optimal, considering total predator numbers, however this may vary where species composition is different.
- Set-aside strips sown with game cover can encourage predatory invertebrates within the crop, but sown mixtures need to be developed for this purpose.
- Ground-active invertebrate predators can contribute to pea aphid control.
- Money spiders are important predators of aphids, feeding on cereal and pea aphids for at least 100m into the crop even when aphid densities are low.
- Field margins provide valuable habitats for money spiders, which can rapidly spread into crops by 'ballooning' on silk threads.
- Maintaining biodiversity on the farm aids natural aphid control, especially if a range of invertebrate predators and parasitoids are encouraged.
- Encouraging a diverse natural enemy community in agricultural ecosystems provides stability for natural biocontrol systems.
- A diverse range of field margins should be maintained on the farm as this adds to the diversity of invertebrate predators. There is not a single margin design that will suit all purposes.
- A dual margin consisting of a narrow strip of grassy uncut vegetation against the field boundary (around 1m), with a broader (at least 2m) flower-rich strip, cut in late summer, would probably benefit the greatest range of beneficial invertebrates.

SAFFIE

The Sustainable Arable Farming For an Improved Environment (SAFFIE) project (2002-2006) (Clarke *et al.*, 2007) was developed during a period of competing economic and environmental pressures. Arable farmers were moving towards optimising inputs and improving efficiency, but the UK had a commitment to increase biodiversity, especially farmland bird populations. The SAFFIE project, located over 26 sites in the UK, aimed to reconcile these pressures by quantifying costs and environmental benefits of new techniques for farmers and policymakers. The following objectives were central to the project:

- To manipulate agronomy of wheat to increase biodiversity.
- To manage field margin vegetation to benefit biodiversity.
- To assess the integrated effects of 'best' crop and margin management practices.
- To conduct a cost: benefit analysis of the best practices.
- To interact with the farming community to focus the work and promote findings.

The project evaluated practical techniques to improve biodiversity in the cropping environment by quantifying the impact of the techniques on key species of birds, grasses and flowering plants, bees, butterflies, beetles, bugs, flies, grasshoppers, subsoil invertebrates and spiders and the economics of the techniques.

The project was divided into four experiments:

Experiment 1.1

This investigated the impacts of novel habitat management on the in-crop biodiversity of winter-sown wheat crops at 10 sites during 2002 and 2003.

On each site, wheat crops were established with three treatments:

- CONV: The experimental control, conventional husbandry with normal row spacing and management.
- UP: Undrilled Patches established at a density of two undrilled patches per ha; with the dimensions of each individual undrilled patch (PA) being approximately 4 m x 4 m.
- WSR: Wide-spaced drill rows sown at double the normal width.

The key findings from this experiment were as follows:

- The experimental treatments generally failed to deliver consistent increases in bird-food abundance or biomass, although a few invertebrate species or families were more abundant in the UP treatment.
- At the field-scale, treatments had few effects on vegetation. However, at a local level within the UP treatments, differences in vegetation cover, structure and seed production were often marked, although there was variation between sites and years. Compared to the surrounding crop, the vegetation in PAs was shorter, sparser and patchier, with higher weed cover including species important in the diet of birds. The vegetative structure of PAs was likely to have substantially increased access to the chick-food resources that were present. Probably as a result of this, in the UP treatment, skylark (*Alauda arvensis)* territory densities were higher (particularly in the crucial late season breeding period) and the number of skylark chicks reared was nearly 50% greater than in the CONV treatment. Siting patches 50m from a margin and away from tramlines was recommended to reduce predation and further increase skylark numbers.
- The WSR treatment provided some wildlife benefits (particularly for skylarks) but effects were not as consistent or as pronounced as for the UP treatment and a yield decrease was noted on some sites.

Experiment 1.2

Experiment 1.2 looked at the combination of herbicide treatments, row spacing and mechanical hoeing at three sites between 2002 and 2004. The aim was to maximise the diversity of plant species and associated insects within wheat crops without compromising yield.

The study combined a range of herbicide treatments according to the weed spectrum present, with three row spacing and cultivation treatments. The range of herbicide treatments applied included 'untreated', 'full weed control' and a range of pre-emergence, post-emergence and spring herbicides which were applied in combination or individually. Assessments were made of vegetation cover, arthropod abundance and yield.

The key findings were as follows:

- The use of wide-spaced rows reduced yield by 4% compared to conventional spacing. Using a spring cultivation with the wide-spaced rows significantly reduced yield by 4% over wide-spaced rows alone.
- There were few effects of the spacing/cultivation treatments on either vegetation or arthropods. Where differences were recorded, the effects were not consistent across sites or years.
- Herbicide treatment had a significant effect on all individual weed species and groupings analysed. Generally, single product applications left more plant cover than sequences. Generally different sequences-controlled weeds equally effectively.

- There was variation in the degree to which arthropod groups were affected by differences in vegetation cover under differing herbicide regimes, but untreated plots usually supported greatest arthropod populations, and herbicide sequences the lowest.
- Weed cover and arthropod abundance were only related where weed cover was relatively high (>25% on untreated plots), as were the species assemblages. The species composition of the weed assemblage was affected by herbicide application; most applications reduced the complexity of the weed spectrum. In contrast with the weed community, the species assemblage of the arthropods responded to row spacing and cultivation.
- It is possible to increase weed cover by the use of selective herbicides and this can result in positive benefits for wider biodiversity. However, in the context of IPM, management must be site specific, reactive and use of narrow spectrum herbicides is not appropriate where pernicious weeds are common or where herbicide resistance is present.

Experiment 2

This looked at the margin management needed to optimise biodiversity.

Three grass seed mixtures, a simple Countryside Stewardship mixture (CS), a mixture of tussock grasses and flowers (TG) and a mixture of fine-leafed grasses and flowers (FG) were sown as 6 m wide margins, at three sites between October 2001 and March 2002. Three different spring management treatments (cutting, scarification and a low rate of a selective graminicide) were applied annually in March between 2003 and 2006. Invertebrates, plants and birds were monitored both in the margins and in the crop adjacent to the margins.

The key findings were as follows:

- Weeds and pests did not move from the margin into the adjacent crop.
  Plant species diversity in margins decreased over the five years, regardless of seed mix and treatment.
- Plots sown with the FG mix generally had the greatest abundance of reproductive resources (buds, flowers, seed/fruit) and plots sown with a grass seed mix (CS) generally had the lowest levels.
  Compared with other margin management treatments, margins scarified in March/April had:
  - the greatest percentages of bare ground,
  - enhanced plant species diversity at some sites,
  - plant diversities converging between margins sown with different seed mixes,
  - lower values of architectural complexity (especially of the dead litter, fine grass and legume components),

- reduced values of reproductive resources.

- In margins that had an application of a graminicide, plant communities included more sown wildflower species than margins that were scarified or cut, although wildflower species and abundance varied according to season, seed mix sown, time of sowing, soil type, field history and aspect of the margin (compass direction) relative to sunshine hours/warmth/hedge shading etc.

Invertebrates

- The grass seed mix (CS) provided a good resource for those invertebrate species that are dependent on sward architectural complexity. However, it is a poor resource for phytophagous species, particularly where their host plants are wildflowers.
- A seed mix of tussocky grasses and wildflowers (TG) provided an architecturally complex sward and host plants vital for the feeding, safety and shelter of many invertebrate species.
- For a variety of invertebrate taxa there was evidence that abundance and species richness will reach a maximum 2–3 years after margin establishment.
- Sowing a diverse seed mixture of perennial wildflowers was the most effective means of creating foraging habitat for bees and butterflies on arable field margins. Inclusion of forbs in the seed mixture resulted in increases in abundance and diversity of pollen and nectar resources, bumblebees and butterflies.
- Invertebrate species that required either an architecturally complex sward or dense grass responded poorly to scarification, e.g. planthoppers, spiders and Symphyta/Lepidoptera larvae. In contrast, improved establishment of some wildflower species in response to scarification benefited some phytophagous invertebrates, e.g. weevils and leaf beetles.
- In scarified margins there were fewer and lower abundances of isopods (woodlice) than in other margins. Species assemblages in the scarified plots consisted of species commonly associated with cropped or exposed habitats.
- Across all the sites the scarified plots had the greater diversity in 2004 and 2006, however in 2003 diversity values were similar.
- Graminicide application is a practical option for enhancing the value of the large area of species-poor grass margins for pollinators.

Birds

- For birds, margin sward content in terms of the grass/flower mix, was best managed to encourage beetles (especially Carabidae) and spiders (Arachnida).

Experiment 3

This looked at the best combination of crop and margin management.

The best treatments from Experiments 1.1 and Experiment 2 were evaluated in winter wheat crops on 26 commercial farms in England and Scotland, beginning in 2004. Undrilled patches were established on all sites as the best within-crop option from Experiment 1.1. Two margin types, tussock grasses + flowers (TG) and fine grasses + flowers (FG) were used on each site in equal lengths. The best margin management treatment from Experiment 2, scarification, was tested in the spring, in 2005 and 2006.

On each of 26 farms, typical arable farms in England and Scotland, four treatments were established: (1) Conventional wheat and no margins; (2) Wheat with undrilled patches and margins; (3) Conventional wheat and margins; (4) Wheat with undrilled patches and no margins. Experiment 3 covered a total area of 856 ha, located on predominantly clay-based soil types, with between 25 and 45 ha on each individual farm. Crop rotations were predominantly winter cropped (70%) with first and second wheat the most common crops. A range of break crops was grown including, winter oilseed rape, barley, peas, onions and potatoes. Set-aside was included in some rotations. All crops were managed by the host farmer, using typical management for the location and season.

Scarification was done in the spring 2004 by cultivation with a power harrow to a depth of 2.5 cm to achieve a target of 60% disturbance of the soil surface area.

The key findings were as follows:

- There was no evidence of adverse effects on crop weed, pest or disease levels from incorporating margins and undrilled patches into a winter dominated arable rotation.
- For all species and species groups (See section 7.4.5.1 and Appendix 1 of SAFFIE report for full species list and data), bird densities and territories were consistently higher (1.3 - 2.8 times) in fields with margins (4% of field area) and two undrilled patches per hectare than in fields with a conventional crop. This response was also consistent for Farmland Bird Index species and Biodiversity Action Plan species, for which farmland recovery is particularly desirable. Factors that affected these increases in density and population size included: (a) In margins, the combined elements of higher beetle and spider abundances, and more complex swards, and (b) In wheat crops, the presence of undrilled patches (large-scale open ground) and bare ground at a fine-scale and at foraging locations. In crops, there were only weak links to invertebrate abundance.
- Creating bare ground and foraging access in dense crops and field margins was the single most important management treatment giving a 1.3–2.8 times increase in bird densities and breeding territories for both field and boundary nesting species. Open ground can be achieved at relatively low cost by scarification in margins, and by creating undrilled patches in wheat crops. For birds, margin sward content in terms of the grass/flower mix, was best managed to encourage beetles (especially Carabidae) and spiders (Arachnida).

- Overall, the sown margins and UPs had relatively few effects on the numbers of invertebrates within the crop and, therefore, the abundance of food available to farmland birds. There was some evidence that invertebrates were remaining within the margins rather than dispersing into the adjacent crop. The low levels of weeds within the crop may also have limited colonisation by phytophagous invertebrates and their associated predators. Conversely, invertebrate predation may have been higher where margins and patches were present, so that the effects of the margins were obscured.
- There were indications that where undrilled patches and margins were present in the same field, skylarks experienced reduced breeding success and productivity than in conventionally managed wheat. This was attributed to increased mammalian predator activity. It is recommended that undrilled patches should not be situated within 50 m of a margin, intersecting tramlines, nor close to 'perching poles' for avian predators.

Ecotoxicity

This section outlines the relevant regulations for plant protection products (PPPs), the data requirements to ensure the safety of an active substance and where this data can be accessed.

Regulation (EC) No 1107/2009 (the Regulation) provides statutory powers to control PPPs, including all herbicides, fungicides, insecticides, soil sterilants and, where used to protect plants, rodenticides. The Regulation is underpinned by the Plant Protection Products Regulations 2011 (as amended) and together these regulations mean that only authorised products can be sold, supplied, stored, advertised or used. PPPs must only be used in situations for which their use is currently authorised by the Health and Safety Executive (HSE).

Active substance data requirements are presented in Regulation (EC) No 283/2013 and product data requirements in Regulation (EC) No 284/2013. The data requirements cover the following sectors, and up to 100 specific tests are done to ensure the safety of an active substance.

- Physical and chemical properties of the active substance and the components and 'recipe' of the pesticide product.
- Analytical methods - methods of testing for the substance.
- Toxicology – includes effects on mammals.
- Residues - to support all pesticide uses which could result in pesticide residues in food or animal feed.
- Consumer exposure - through dietary intake.
- Non-dietary human exposure - exposure via non-dietary routes, including inhalation, dermal absorption and ingestion.
- Environmental fate and behaviour - how substances behave in soil, surface water, sediment, groundwater and air including:
    - What the active substance breaks down into
    - How quickly the active substance and metabolites break down
    - Where the active substance and metabolites move to in the environment
    - Whether the substances accumulate in the environment
    - What levels of active substances or metabolites are likely to occur in the environment
- Ecotoxicology - the risk to non-target organisms, to ensure that there are no significant long-term changes to the population nor to the function of the ecosystem. Including other unacceptable effects such as vertebrate mortalities. Specific groups of organisms covered are:
    - Birds and mammals.
    - Aquatic organisms.
    - Bees and non-target arthropods.

    - Soil organisms.
    - Non-target plants.
- Efficacy - the effectiveness of a substance, including identifying the appropriate dose and mode of action, and identifying any adverse or unintended negative impacts.

The complete dossier is a very extensive set of documentation comprising the required tests and studies, and a series of supporting documents providing background information on the active substance and its uses.

This data can be found within three databases developed and maintained by the University of Hertfordshire's Agriculture and Environment Research Unit (AERU). These databases relate to chemical (natural and synthetic) substances used in agriculture: pesticides (Pesticide Properties Database[2] (PPDB)) and bio-pesticides (Bio-Pesticides Database[3] (BPDB)). The databases are comprehensive and relational of pesticide physicochemical, toxicological, eco-toxicological, human health and other related data as provided when a pesticide registration is submitted. The primary data sources used to populate the databases are mainly public domain sources (regulatory bodies), peer-reviewed literature and private databases.

[2] https://sitem.herts.ac.uk/aeru/ppdb/

[3] https://sitem.herts.ac.uk/aeru/bpdb/index.htm

Arable

This section covers information relating to IPM techniques when used in crops of winter wheat, oilseed rape and sugar beet. The term 'no evidence of positive/negative biodiversity effects found' is used where no relevant evidence of biodiversity effects was found on the specific IPM technique.

Cultivations - Plough/non-inversion tillage/no-till/direct drilling

Ploughing is a cultivation that inverts the soil. The aim of ploughing is to turn the surface of the soil including vegetation, seeds and other organisms and aims to place them at a depth of 15-30cm. Ploughing is used to manage weeds and crop residues prior to planting the following crop and provides a 'clean' seedbed for establishing the following crop.

Non-inversion tillage mixes the upper layers of the soil to the working depth of the implement. Generally, vegetation, seeds and organisms are mixed within this layer. The type of implement used can include discs and tines.

No-till/direct drilling only moves soil where the drill passes, the majority of the soil surface remains unmoved.

Benefits - cultivations

Birds: Skylarks, granivorous passerines and gamebirds were found more regularly on fields established with non-inversion tillage than conventional tillage where 121 fields were surveyed during winter 2000 to 2003 (Cunningham *et al.*, 2003). Gulls, corvids and other birds are often seen at the time of ploughing, and many invertebrate feeding bird species will visit ploughed fields, even if they prefer grassland, with greater food abundance.

Invertebrates as prey species: Cultivation techniques can have different impacts on certain pests. Avoidance of ploughing, and adoption of direct drilling and no-till techniques can lead to a decrease in aphids and pest fly species in cereals, but an increase in slug populations, especially when stubble and straw residues are left (Glen, 2000). Slugs are prey for a range of generalist predators including invertebrates and birds (South, 1992; O'Hanlon *et al*., 2019), thus cultivation methods can reduce some pests and encourage a greater richness of ground nesting birds that may act as predators of slugs. However, more research is needed to provide a robust link between cultivation techniques and greater slug control by birds.

Mammals: No evidence of positive biodiversity effects found.

Fish: An effect of min-tillage is to reduce the amount of sediment lost as turbid water from field drains (Simpson, N., pers. comm).

Amphibians: No evidence of positive biodiversity effects found.

Reptile: No evidence of positive biodiversity effects found.

Arthropods, annelids, molluscs: Only 14% of invertebrate taxonomic groups (e.g., small carabid beetles) were more numerous in ploughed areas (Boinot *et al.*, 2019). Other studies suggest smaller carabid beetles are able to tolerate ploughing events and can even thrive under these conditions (Pretorius *et al.*, 2018; Hatten *et al.*, 2007). Arthropod pest species decline in ploughed fields (Jabbour *et al.*, 2016). Approximately the same number of adult beetles were found in ploughed plots compared to non-inversion tillage plots in studies in Germany. However, beetle larvae were more sensitive to soil cultivation, with more in the unploughed plots. Although adult numbers were similar in ploughed and unploughed plots, species richness was higher in the reduced cultivation plots (Krooss and Schaefer, 1998). Thorbek & Bilde *(*2004) suggested reduced tillage is less detrimental to soil-inhabiting arthropods than inversion tillage as less habitat is disrupted, reducing potential arthropod emigration.

Epigeic (surface dwelling) earthworm species that live in the organic matter in the topsoil layer can benefit from ploughing. As they do not form burrows, they suffer less habitat disruption from mouldboard ploughing and benefit from the incorporation of organic matter (Ernst & Emmerling, 2009; Roger-Estrade *et al.*, 2010).

Van Groenigen *et al*., 2014 showed that a positive effect of earthworms on plant growth through their effect on soil structure is likely to be a transient effect after soil tillage operations.

Anecic (make permanent vertical burrows) earthworm biomass increases under no-till or conservation tillage when compared to plough-based systems (Prendergast-Miller *et al*., 2021; Petrovskii *et al*., 2014; Muoni *et al*., 2019; Roger-Estrade *et al*., 2010; Ernst and Emmerling, 2009; Cunningham *et al*., 2004). Briones & Schmidt (2017) conducted a meta-analysis of 165 publications over 65 years in 40 countries, found no-tillage and conservation agriculture increased earthworm abundance by 137% and 127% respectively, compared to conventional ploughing. Additional meta-analyses found that epigeic and the larger anecic earthworms were the most sensitive to conventional tillage.

Soil micro, meso and macro fauna: As ploughing completely inverts the soil, destroying the 'green bridge', this can disrupt the life cycles of certain pests and diseases (Morris *et al*., 2010).

Growth of certain fungal and bacterial species can be stimulated by ploughing. Saprotrophic fungi were reported to be unaffected by tillage (Van Groenigen *et al.*, 2010), and the bacterial phyla Acidobacteria, Actinobacteria, Chloroflexi, Verrucomicrobia and Nitrospirae were more abundant under ploughing (Legrand *et al.*, 2018).

Anderson (1999) ran five field experiments over four years and compared autumn ploughing and reduced tillage (no-tillage or spring harrowing) plots. Weed cover was denser in reduced tillage, and the author thought this accounted for most of the differences. Field slugs were most common in reduced tillage and were positively correlated with weed cover. Generally, more carabids and staphylinids were caught in reduced tillage, particularly *Amara*-species and *Loricera pilicornis*, *Philonthus cognatus* and *Tachinus signatus*, which were also positively correlated with weed cover. *Aloconota gregaria*, *Bembidion quadrimaculatum*, *B. lampros*, *Harpalus rufipes* and *Trechus quadristriatus* were more common in autumn ploughed than in reduced tillage plots, several of them preferring open soil.

Beetles and spiders were noted in greater numbers in minimum tillage plots compared to ploughed (Holland and Reynolds, 2003)

Non-target plants: Where the seed bank has been reduced ploughing can help bring up seed from a deeper level (Plantlife, n.d). Ploughing reduces herbicide use (Cannell *et al*., 2003, Cannell, 1985).

The use of non-inversion tillage has led to lower levels of broad-leaved species in comparison with ploughing (Froud-Williams *et al*., 1983).

Protected species: See Cunningham *et al.*, 2003 cited in the birds section evidencing skylarks found more regularly on non-inversion tillage compared to conventional tillage.

Negative impacts - cultivations

The burial of weed seeds and crop residues has a negative impact on invertebrate and vertebrate species which feed on them. Thus, the biodiversity of organisms further up the food chain is detrimentally affected due to ploughing (Cunningham *et al*., 2005).

Birds: Between October to December, there were no differences in field occupancy by birds under ploughing or reduced tillage. However, by January-March, there were significantly fewer game birds and granivorous passerines occupying fields which had been ploughed compared to crops established by non-inversion tillage (Cunningham *et al.*, 2004).

The removal of crop residues can be detrimental to ground-nesting birds, as reduced vegetative cover, alongside reduced seed availability, results in low density nesting on ploughed fields and increased distance required for foraging (Field *et al*., 2007).

Granivores are more likely to be impacted by ploughing rather than birds with a more diverse diet (Barré *et al.*, 2018).

Reductions in arthropod populations will have impacts further up the food chain (Cunningham *et al.*, 2004; 2005) for example, on bird and rodent species.

Invertebrates as prey species: Invertebrate abundance decreases under ploughing (Barré *et al.*, 2018). Ploughing showed a greater effect on E*pigeic collembola*, an important prey for generalist arthropod predators, than non-inversion tillage (Møller Marcussen, Axelsen and Toft, 1999; Bilde, Axelsen and Toft 2000; Petersen 2002 cited by Thorbek and Bilde, 2004).

Mammals: Ploughing buries seeds and crop residues out of reach of birds and small mammals (e.g., voles, mice, shrews), thereby decreasing food availability for these species (Mérő *et al.*, 2015).

Fish and Amphibians: Ploughing can have indirect impacts on aquatic organisms and water quality (Holland, 2004). Ploughing removes surface residue, reducing the surface stability of the soil, leaving the soil bare and exposed to wind and rain. This can lead to soil erosion and runoff (Morris *et al*., 2010). Runoff water following ploughing is often contaminated with soil, silt, sediment, nutrients and pesticides that leach into watercourses, polluting waterways, causing eutrophication and sedimentation (Morris *et al*., 2010). The removal of anecic earthworms can also lead to reduced soil porosity (Prendergast-Miller *et al*., 2021). Ploughing heavily disturbs soil which can directly injure or kill arthropods in the soil, as well as affecting them through habitat destruction (Alyokhin *et al*., 2020).

Reptiles: No evidence of negative biodiversity effects found

Arthropods, annelids, molluscs: Populations of spiders, beetles and earthworms are reduced by cultivation (Holland and Reynolds, 2003). Bee species which nest above-ground in agricultural fields, are nine times more negatively affected by tillage, than the larger number of bee species which do not nest in these areas and therefore, remain unaffected by tillage (Williams *et al*., 2010).

Terrestrial arthropods and arthropods that have a larval stage in soil can be directly affected by ploughing. Cunningham *et al.* (2004) reported a 50% reduction in sawfly emergence under ploughing, as the larval stage is directly affected by soil disturbance. Boinot *et al*. (2019) found that 55% of invertebrate taxonomic groups (e.g., large carabid beetles, butterflies and moths) were more abundant in vegetative areas which do not experience ploughing.

Ploughing can reduce the diversity and number of arthropods which can increase the likelihood of pest outbreaks, due to the reduction in natural predator species which act as a form of biocontrol (Hatten *et al.*, 2007). Parasitism can also be reduced under ploughing (Tamburini *et al*., 2016).

Anecic earthworm species that form burrows are at greater risk of habitat disruption from ploughing. Anecic earthworm biomass increases under no-till or conservation tillage when compared to plough-based systems (Prendergast-Miller *et al*., 2021; Perego *et al*., 2019; Muoni *et al*., 2019; Roger-Estrade *et al*., 2010; Ernst and Emmerling, 2009; Cunningham *et al*., 2004). Sugar beet field trials across 19 sites in Germany during 2008-2009 showed ploughing reduced earthworm abundance by 80% compared to a mulching system. Despite a strong increase in the earthworm population during the vegetation stage in the ploughed plots this did not compensate for the initial differences (Marwitz *et al.,* 2012).

Ploughing loosens topsoil compaction (Daraghmeh *et al*., 2009; Y. Li *et al*., 2019), and can increase sub-soil compaction which restricts the movement of earthworms and can limit plant rooting (Holland, 2004; Morris *et al*., 2010). Compaction can be equally caused by discs, power harrows or trafficking in unsuitable soil conditions.

As ploughing inverts the soil, it exposes earthworms of all species to direct mechanical damage, predation and/or desiccation (if the weather conditions are dry or frosty) (Holland, 2004). The impact of ploughing on earthworm population estimates ranges from a six-fold decrease to a 36% decrease in fields that undergo ploughing compared to non-ploughing systems (Holland, 2004). Large numbers of predatory invertebrates, such as centipedes, overwinter within the soil and autumn cultivations can reduce their numbers (Powell *et al*., 2004).

Soil micro, meso and macro fauna: Ploughing has been shown to cause reductions in microbial activity, often linked to the loss of soil organic matter. This can be detrimental to overall soil health, especially if the abundance of arbuscular mycorrhizal fungi (AMF) or beneficial bacteria are reduced (Rodgers *et al*., 2021; van Groenigen *et al*., 2010). Although, one study by Shi *et al*. (2013) demonstrated that the effects of tillage on microbiota can change throughout the year, based on other environmental conditions. Non-inversion tillage did not result in a demonstrable gain in invertebrate numbers, but the author again suggests that this may be due to the type of animal monitored (Ogilvy, 2000).

Non-target plants: Brenchley and Warington (1933) observed that when land is cropped, cultivation affects the weed flora more variably than after fallowing. Where some species respond to cropping and fallowing in the same direction, i.e. being reduced by both methods, other species may show a divergent response.

After ploughing there were fewer species present and this reduced biodiversity within the fields, with weed seed banks also demonstrating reduced diversity (Feledyn-Szewczyk *et al*., 2020, Cardina *et al*., 1999). Plants with seeds that have greater viability at depth and can survive for multiple years, will be less negatively impacted than those whose seeds rapidly lose viability and die during the period of submersion (Mohler, 1993).

Protected species: No evidence of negative biodiversity effects found

Summary - cultivations

Cultivations are generally detrimental to biodiversity, the less soil that is moved to shallower depths the greater the benefits to biodiversity due to lower losses in soil organic matter (Table 1). The order of cultivations that offer the greatest benefits to biodiversity to those that offer the least are direct drill, no-till, shallow non-inversion tillage, deep non-inversion tillage and ploughing.

Table 2. Summary of the positive and negative impacts to increasing the intensity of cultivations on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	Reduction in food, nesting
Invertebrates as prey species	-	Reduced invertebrate abundance. Ploughing has a greater effect on epigeic collembola
Mammals	-	Reduction in food
Fish	-	Increase in sediment, eutrophication, death, habitat destruction
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increase in small carabids, epigeic earthworms	Decrease in bees, spiders, anecic earthworms, larval stages
Soil micro, meso and macro fauna	Increase in saprotrophic fungi , some bacteria	Reduces activity
Weeds	Reduced populations could help reduce herbicide use	-
Non-target plants	Non-inversion tillage and no till can increase the level of hard to control grass species, therefore increasing reliance on herbicides. Some uncommon species require ploughing	Ploughing can reduce abundance and diversity of species
Protected species	Skylarks found more regularly on non-inversion tillage compared to conventional tillage	-

Recommendations for future work - cultivations

- Studies are primarily centred around carabid beetle populations, with little focus given on other important arthropod taxa that may be more at risk from agricultural intensification.
- The focus in the literature is almost entirely on in-field weeds and did not assess biodiversity impacts of ploughing on plant species in general.

Crop rotation

Crop rotation is the practice of growing a series of different types of crops in the same area across a sequence of growing seasons. A good crop rotation includes a diverse range of crops over a three- or four-year period (or even longer); such as arable rotations including cereals (e.g., wheat, oats, and barley), legumes and an oilseed. Crops can be established both in the spring and the autumn. A good rotation, with the use of grass leys and/or cover crops, can help to reduce the build-up of pernicious grass weeds. For weeds, pests and diseases, rotating crops changes the selection pressure and reduces the likelihood of the same pests, weeds and diseases from establishing each year.

Benefits – crop rotations

Birds: A mosaic of different crops provides a diversity of habitats for wildlife, and certain species benefit from the shifting pattern of crops from year to year. Perennial fallows are a good option to support certain farmland birds in arable landscapes, it is recommended to optimise site selection, so they are not in shady locations and are structurally diverse to improve habitat quality (Meichtry-Stier *et al.*, 2018)

A six-year study looked at the response of bird populations and abundance to mixed cropping and low pesticide regimes within commercial crop rotations. (Henderson *et al.*, 2009). The results showed the carrying capacity of arable farmland can be increased significantly for birds with the use of crop mosaics to create habitats. Species of high conservation concern increased by 30%. Lapwing, yellow wagtail and tree sparrow began breeding on the site. Bird types had different associations: grey partridge was associated with set-aside; insectivores and granivores with oilseed rape, vining peas and zero pesticide stubbles; skylark with set-aside, spring wheat, vining peas and newly sown oilseed rape.

Ronnenberg *et al.*, 2016 showed that grey partridge was positively influenced by the presence of winter cereal crops and high crop diversity as provided by a crop rotation.

Results from the Colworth project (Unilever, 2005) showed that the mosaic created by inclusion of peas in the rotation helped to create breeding and foraging options for birds, especially grey partridge, skylark and yellow wagtail (Unilever, 2005). Henderson *et al.*, (2005) reported increased breeding of lapwings when peas or sugar beet were included in a rotation and these species were preferred over spring cereals.

Bird numbers were recorded for the Focus in Farming practice study between 1995-1997. Over the three years skylark numbers were significantly greater on winter beans, set-aside and grass and significantly lower in winter wheat. The same study found significantly more grey partridge and yellow hammers associated with break crops and set-aside than cereal crops

In a large-scale studying consisting of eight study sites in seven European countries it was shown that crop diversity had positive effects on total abundance of breeding birds and heterogeneous landscapes containing both arable and grassland supported the highest number species of farmland birds in winter (Geiger, 2011).

Invertebrates as prey species: Increased crop diversity may alter trophic level interaction by limiting pest populations' spread as distances between host crops is increased or by disrupting host locations (Rusch *et al.,* 2013). Extending crop rotation to include non-sensitive crops can reduce the build-up of pests such as wireworm (Furlan and Toffanin, 1996 cited by Elliot and Jarvis, 2016).

Mammals: A study from the Czech Republic of intensive arable areas showed that the European hare preferred winter grains, clover and lucerne, oilseed rape, stubbles and spring grains or catch crops in spring and autumn, respectively (Pavliska *et al.*, 2018). Hares have been shown previously to prefer cereal crops (Hansen, 1996; Smith *et al.*, 2005; Santilli *et al.*, 2014), particularly between October and May (Tapper and Barnes, 1986). Fallow was favoured because it provides food all year round (Tapper and Barnes, 1986).

Increasing crop numbers in a rotation had a positive effect on biodiversity in long term field experiments in France. However, some of the spring crops, such as sugar beet, because they induced a shorter duration of soil cover, which could be unfavourable to species needing soil cover for habitat (Deytieux *et al.,* 2012).

Fish: Rotated crop systems have the potential to improve some aspects of water quality which would influence the biodiversity of freshwater organisms (Hunt *et al.*, 2017).

Crop rotation was reported to reduce nitrogen and phosphorus runoff by up to 39% in the USA, with longer crop rotations including maize, soybean, oats, and alfalfa having the greatest impact on reducing runoff (Hunt *et al.*, 2019). Runoff adds sediment to watercourses which can starve fish eggs and juveniles of oxygen, as can eutrophication linked to phosphate, reducing fish numbers and some species, e.g. salmonids, are less tolerant than others. Crops should be analysed according to the location, Maize production in the UK is susceptible to runoff, with funding available in certain areas to establish grass clover mixes in the crop to reduce the problem (Wessex Water, 2022).

Amphibians: No evidence of positive biodiversity effects found

Reptile: No evidence of positive biodiversity effects found

Arthropods: Crop rotations can increase resources for beneficial species including bees. Rye and clover cover crops increase recruitment of natural enemies to help suppress pest populations (Iulian *et al.*, 2020). Phacelia in a cover crop mix is attractive to honey and bumblebees, whereas sunflower is attractive to solitary bees (Mallinger *et al.*, 2021). Crop rotation can be a positive tool to increase beneficial bee and arthropod populations, particularly when reduced tillage techniques are used alongside wheat and spring peas in the rotation (He *et al.*, 2019; Iuliano and Gratton, 2020; Legrand *et al.*, 2011). Inclusion of a flowering crop, such as oilseed rape, in the rotation will provide a source of nectar and pollen.

Soil micro, meso and macro fauna: In general, crop rotations were associated with an increased abundance of earthworms in the field, which can be amplified by reduced tillage and organic matter. Wozniak (2019) stated that wheat monocultures had 31% less earthworms than a pea-wheat-triticale rotation. A number of the studies demonstrated that it is specifically the inclusion of grass or legumes in the rotation which results in greater abundance and biomass of earthworms, improving soil quality (Hoeffner *et al.*, 2021; Hubbard *et al.*, 1999;). Crop residues also improve the soil moisture content, increase soil organic matter and stabilise soil temperatures which provides favourable conditions for earthworm populations (Hubbard *et al.*, 1999).

Crop rotations can enhance microbial activity in the soil, as continuous monoculture systems tend to reduce the biodiversity of soil microorganisms over time, especially arbuscular mycorrhizal fungi (AMF) (Douds and Millner, 1999). It should be noted however, that brassica species do not have associated AMF, so a snapshot taken in these crops could be misleading. One review calculated that crop diversification through rotation systems increased soil microbial richness by 15.1% on average, with leguminous crops enabling the greatest increase in microbial richness (Venter *et al.*, 2016).

When grassland is introduced into an arable cropping rotation it can have a positive effect on earthworm abundance, biomass and diversity (Hoeffner *et al*., 2021).

Non-target plants:

Rotations that involve a greater proportion of spring crops can change the balance of weed species to include a greater proportion of spring germinating species as shown in the TALISMAN experiment (Young *et al.*, 2001). Incorporation of spring crops into the rotation increased diversity and size of the weed seedbank, with a tendency for spring germinating species to occur in a higher frequency e.g. black bindweed (*Fallopia convolvulus)* and knotgrass (*Polygonum aviculare)* (Squire *et al.*, 2000). Plant species that are important food resources for arthropods occur at greater density and higher relative abundance in spring cereals than winter cereals (Hald, 1999). Higher weed populations can be attributed in part to decreasing diversity of cropping. In Canada, Doucet *et al*. (1999) reported that rotation only accounted for 5.5% of the variation in weed flora. Légère & Samson (1999) and Légère *et al*. (2005) reported that species abundance was regulated to a greater extent by weed management factors, but the difference between the actual flora and the seedbank was influenced more by rotation. Sosnoskie *et al*. (2006) also reported that weed seedbank diversity was greater with more diverse cropping sequences.

Overall, weeds are considered detrimental to crop production. However, they can be important food sources for insect and bird populations, therefore have the potential to increase farmland biodiversity. Certain weed species can have a high biodiversity value (e.g. seed source for birds and invertebrates). Increased diversity of weed species could provide greater food sources, however weed density would need to be low to minimise yield loss .

Protected species: See Henderson *et al.*, 2009, Unilever, 2005, Ronnenberg *et al* (2016) and the Focus on Farming study in the birds section for positive effects of crop rotations on lapwing, grey partridge, yellowhammer, tree sparrow and skylark populations.

See Pavliska *et al* (2018), Hansen (1996), Smith *et al* (2005), Santilli *et al (*2014) and Tapper and Barnes (1986) for the feeding preferences of hares in the mammals section.

The Biodiversity 2020 Terrestrial Biodiversity Group brought together a group of expert conservation ecologists (individuals and groups) to outline the work needed to enable the recovery of England's most threatened wildlife (the Section 41 (S41) species). The priority actions suggested in this work outline diverse land use as beneficial to many of the species listed (Natural England, 2013).

Negatives – crop rotations

Birds: Josefsson *et al.* (2017) found that crop structural diversity (i.e. the management and vegetation structure of crop) rather than crop diversity (rotation) positively affected species richness of non-crop-nesting birds but similar effects were not observed among field nesting birds (see Table S2 in Josefsson *et al* (2017) for detailed species lists).

Several workers have identified that increasing crop diversity alone is not enough to increase biodiversity, additional semi-natural cover is needed as well. Sirami *et al.* (2019) noted that the effect of crop diversity on vertebrate biodiversity is significantly mediated by the amount of semi-natural cover. Redlich *et al.* (2018) conclude that a possible reason they did not observe an effect of crop rotation on bird diversity was because the landscape surrounding the study sites had relatively high non-crop habitat cover. As a result, the birds were less reliant on crop resources compared to less diverse agroecosystems. Josefsson *et al.* (2017), observed that crop diversity was only positively associated with species richness and total abundance of non-crop-nesting birds in arable dominated landscapes, where birds are more likely to be reliant on crop resources.

Some farmers do not grow certain crops e.g. smaller areas of peas and vegetables where pigeons are too problematic or spring barley near rookeries or crow roosts. So, a farmer's rotation choices can be limited by some bird species.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: Hares may experience food shortages as crops mature where large blocks of arable land are in the same crop (Block cropping) (Frylestam, 1980; Tapper and Barnes, 1986).

Grasslands are generally less attractive for European hares (Frylestam, 1980; Vaughan *et al.*, 2003, Pavliska *et al.*, 2018), although grassland is preferred for feeding in late summer (Tapper and Barnes, 1986).

Fish: No evidence of negative biodiversity effects found. However maize production in the UK is susceptible to runoff and in areas with high manure inputs this can reduce water quality with negative consequences for fish. Funding is available in certain areas to establish grass clover mixes in the crop to reduce the problem (Wessex Water, 2022).

Amphibians: Conversion of pasture into arable fields, along with the consequent loss of cattle ponds has been shown to adversely affect the dispersal and population of toads and other amphibians (Piha *et al.* 2007; Janin *et al.* 2009; Curado *et al.* 2011).

Reptile: No evidence of negative biodiversity effects found.

Arthropods: Spring crops and potatoes were the least favourable crops for beetles and spiders (Ogilvy, 2000). Spring crops have a shorter duration of soil cover, which could be unfavourable to carabids, spiders, birds and small mammals needing soil cover for protection (Deytieux *et al.,* 2012).

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found

Non-target plants: No evidence of negative biodiversity effects found

Protected species: See Piha *et al.* 2007; Janin *et al.* 2009; Curado *et al.* 2011 cited in the amphibians section for potential adverse effects of toads and other amphibians if loss of ponds were to occur when converting pasture into arable fields.

See Frylestam (1980), (Tapper and Barnes (1986) cited in the mammals section for evidence of potential food shortages for hares in large blocks of arable land. See Frylestam (1980), Vaughan *et al.*, (2003), Pavliska *et al.* (2018) for feeding preferences of hares.

Summary– crop rotations

A varied rotation including spring and winter sown crops, grassland and fallow provides a wide range of habitats and food sources. Nevertheless, a varied rotation alone is not enough to support a wide range of biodiversity, additional non-crop areas such as margins, hedgerows and woodland are necessary to provide year-round opportunities for food and shelter. A comparison of arable and grass catchments showed phosphorus bound to soil particles was ten times higher in the arable catchment compared to the grass catchment. The sediment concentration in the highest yielding stream, for sediment load, was ten times higher than in streams running through wooded areas (Stoate, 2010), suggesting that water quality is more a result of land use and field operations than rotations being a panacea, for biodiversity.

Table 3. Summary of the positive and negative impacts of increased diversity of crops in arable crop rotations on biodiversity. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Breeding, food and foraging. Adding fallow and other habitat features to the rotation gives additional benefit to field nesting birds.	-
Invertebrates as prey species	Rotations can allow other species to find a niche so there is potential for increased activity, food and habitat whilst reducing invertebrate pest build up.	May need additional non-crop areas
Mammals	Food and habitat	. Hares prefer arable crops to grassland though large areas of arable can result in seasonal food shortages.
Fish	Reduces N and P runoff	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increased food and habitat	Spring crops and potatoes detrimental
Soil micro, meso and macro fauna	Increased activity, food, habitat	-
Non-target plants	Increased with spring crops	Decreases with less varied rotations although weeds tend to increase
Protected species	Beneficial to many species	Hares prefer arable crops to grassland though large areas of arable can result in seasonal food shortages

Recommendations for future work

- Research on rotations requires large areas of land over spans of typically three to six years. It is difficult to tease out the individual factors contributing to the whole picture as has been shown by the previous work done in the main IPM projects (Section 4 Further work on the effects of rotations on invertebrates as prey species would help to determine the level of pest reduction through crop diversity and suitable gaps between host crops, potentially helping reduce the need for insecticides.

Field margins and in-field strips

Arable field margins are non-cropped strips or blocks around arable fields that are managed specifically to provide benefits for wildlife. Pywell *et al* (2015) showed habitat creation in the lower yielding field edge areas can lead to increased yield in the cropped areas. Consequently, yields are maintained or even enhanced so no negative impact on yield or income over a 5 year crop rotation. Field margins are usually 2–12m wide on the edge of the arable field, although in-field strips are also used to break up the field and provide habitat and refuge. Margins can be sown to provide seed for wild birds, sown for wildflowers to provide pollen and nectar resources for invertebrates, sown with a permanent mix of different grass species, or cultivated low input margins to create habitat for annual arable plants.

Benefits - field margins and in-field strips

Birds: In SAFFIE, margin sward content in terms of a grass/flower mix, was best managed to encourage beetles (especially *Carabidae*) and spiders (*Arachnida*) as food sources for birds (Clarke *et al*., 2007). Bird densities and territories were consistently higher (1.3-2.8 times) in fields with margins (4% of field area) and two undrilled patches per hectare than in fields with a conventional crop. Factors that affected these increases in density and population size included: (a) in margins, the combined elements of higher numbers of beetles and spiders and more complex swards, and (b) in wheat crops, the presence of undrilled patches and bare ground.

Surveys of arable fields with wildflower strips had higher species richness and territory density of birds than arable fields without wildflower strips. Forb-rich vegetation (i.e. vegetation rich in herbaceous, non-graminoid, flowering plants) was the main driver for birds. Of the 15 farmland birds observed, six had significantly higher densities on wildflower strips compared to in fields with no wildflower strips. Ten species were only found on the wildflower strips. No species were higher on the control fields (Schmidt *et al.* 2022).

Birds were counted on 28 farms to assess how they were affected by the presence of uncropped land. Uncropped land had significant effect on the abundance of key bird species, with farms with >10% uncropped area having significantly higher densities of birds than farms with <3% un-cropped area (Henderson *et al*, 2012).

Invertebrates as prey species: Field margins containing wildflower/grass mixtures can help to reduce aphid densities in adjacent cereal crops (Powell *et al*., 2004).

Mammals: Broughton *et al.*, (2014) compared two levels of intervention,1% and 5% of cropped land taken out of production for the creation of field margins and habitat plots and a conventionally farmed control. The species richness and abundance of small mammals (voles *Cricetidae*, mice *Muridae* and shrews *Soricidae*) showed a significant increase on all treatments in spring and autumn and many increases were greater where margins had been created than in the conventionally farmed control.

Shore *et al.* (2005) compared 3m and 6m wide margins with conventionally managed field edges. They found that the margins supported a greater biomass of small mammals (voles *Cricetidae*, mice *Muridae* and shrews *Soricidae*), and higher abundance of bank voles (*Myodes glareolus)* and common shrews (*Sorex araneus)*, compared with conventional field edges.

Wood mice (*Apodemus sylvaticus*) prefer to live in weedy microhabitats within crops or grassy field margins, this could equate to in-field strips (Tew & Cox, 1993; Tattersall *et al.* 1999). This was in response to greater availability of food sources.

Fish: Margins are often used to provide buffer zones next to watercourses to prevent nutrient and sediment runoff/fertiliser or manure spreading losses and pesticide drift into water. So whilst not increasing biodiversity *per se* these may enable greater survival of organisms and opportunities for biodiversity. These organisms could include food species for fish (e.g. plants, diatoms, macrophytes, zooplankton, invertebrates and small/ young fish - as prey). The presence of margins could mean less chance of oxygen depletion from sediment which reduces fish egg survival or eutrophication which causes increased biological and chemical oxygen demand (reducing dissolved oxygen) and direct and indirect toxicity.

Amphibians: No evidence of positive biodiversity effects found.

Reptile: No evidence of positive biodiversity effects found.

Arthropods: Uncropped margins sown with mixtures containing nectar and pollen-producing plants were more effective in providing bumble bee forage than margins sown with a grass mix (Carvell *et al.*, 2007). Kells *et al.*, (2001) showed that significantly more bees visited naturally regenerated field margins than cropped field margins. Honeybees (*Apis mellifera*), and bumblebees (*Bombus terrestris*, and *Bombus lapidaries*) were the most commonly observed bee species.

Chaudron *et al* (2020) found mowing regimes on arable field margins affected insect communities differently depending on taxonomic group. One late mowing, with high mowing height and biomass removal could promote flower-visiting insects without increasing weed pressure in adjacent arable fields. The number of ground beetles within boundaries and arable fields were not affected by mowing regimes.

The establishment of grass strips in organic arable ecosystems had a positive effect on carabids, although some effects are weak, with only a few species benefiting. Grass strips in organic arable fields assisted the dispersal of some carabid species. Grass strips impacted positively on carabid species richness in the arable field area and adjacent ecosystems Grass strips established for nine years were found to have a higher ecological value than young strips. (Ranjha *et al.*, 2013).

Species richness of ground beetles (Carabidae) was higher in short herbaceous boundaries (0.5m grassy with forbs) than in boundaries with tall herbaceous vegetation (1-1.5m tall grasses and forbs), or in hedge or woodland boundaries (Eyre *et al.,* 2013*)*.

The SAFFIE project showed a grass seed mix provided a good resource for those invertebrate species that are dependent on sward architectural complexity; however, it is a poor resource for phytophagous species, particularly where their host plants are wildflowers. Field margin outcomes from SAFFIE were:

- A seed mix of tussocky grasses and wildflowers provided an architecturally complex sward and host plants vital for many invertebrate species.
- For a variety of invertebrate taxa there was evidence that abundance and species richness will reach a maximum 2–3 years after margin establishment.
- Sowing a diverse seed mixture of perennial wildflowers was the most effective means of creating foraging habitat for bees and butterflies on arable field margins. Inclusion of forbs in the seed mixture resulted in increases in abundance and diversity of pollen and nectar resources, bumblebees and butterflies.
- Invertebrate species that required either an architecturally complex sward or dense grass responded poorly to scarification, e.g. planthoppers, spiders and sawfly, butterfly and moth larvae. In contrast, improved establishment of some wildflower species in response to scarification benefited some phytophagous invertebrates, e.g. weevils and leaf beetles.
- In scarified margins there were fewer species and lower abundance of woodlice than in other margins. Species assemblages in the scarified plots consisted of species commonly associated with cropped or exposed habitats.

Defra project IF01122 (Defra, 2015) showed that annual/biennial field margin mixtures containing a cereal, legume, and a brassica species support populations of the natural enemies of crop pests of the main arable rotation.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found

Non-target plants: In the SAFFIE project (Clarke *et al*., 2007) margins were sown with a seed mix of fine grasses and wildflowers and these had the greatest abundance of reproductive resources (buds, flowers, seed/fruit) compared to a grass seed mix. Plant species diversity in margins decreased over the five years, regardless of seed mix and treatment.

Walker *et al.* (2007) showed that uncropped cultivated margins had the highest species diversity compared to spring fallow and cropped conservation headlands.

Gaba *et al*., (2020) High weed diversity contributed to the regulation of pests by increasing weed seed and aphid predation rates. Fields with high weed diversity may shelter more pest natural enemies.

Protected species: Bees; See Carvell *et al,* Kells *et al* (2001) and the SAFFIE project in the arthropods section for the positive effects of crop margins for bumblebees (Bombus spp.)

Negatives - field margins and in-field strips

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptile: No evidence of negative biodiversity effects found.

Arthropods: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Whilst weeds and their seeds are biodiverse and act as food source, field margins can also act as a source of weeds and disease (e.g. Bayles *et al*., 2009).

Protected species: No evidence of negative biodiversity effects found.

Summary - field margins and in-field strips

The majority of fields have at least a 2m wide green cover margin as is required under cross compliance if claiming for the Basic Payment Scheme (BPS) (Good Agricultural and Environmental Condition (GAEC7a)) until 2027 when such rules are scheduled to no longer apply. Additional margins and in-field strips either funded through agri-environment schemes or as voluntary measures are used to provide other biodiversity benefits (Table 4). Field margins introduce a varied range of habitats and increasing food sources. They can be a reservoir of weed seeds and disease inoculum e.g. ergot, but overall the benefits outweigh the negatives.

Table 4. Summary of the positive and negative impacts of field margins and in-field strips on biodiversity in arable situations. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Increased numbers, food and habitat	-
Invertebrates as prey species	-	-
Mammals	Increased populations, food and habitat	Seed predation by mice
Fish	Reduced pesticide drift into watercourses	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increased food and habitat	-
Soil micro, meso and macro fauna	-	-
Non-target plants	Increased diversity, increased invertebrate number, food source (weed seed)	- reservoir of pernicious weed seeds and disease
Protected species	Positive for bumblebees	-

Recommendations for future work - field margins and in-field strips

- There is a wide range of research on field margins and the benefits are well reported.

Monitoring of crops, decision support systems (DSS), forecasting and pest thresholds

These methods have the potential to target pesticide applications according to need and thereby increase the effectiveness of control and/or reduce pesticide treatments. There are 200 such DSS in Europe and these have been reviewed as part of the IPM Decisions project and 40 are planned to be made available through this project - www.ipmdecisions.net.Benefits - monitoring of crops, decision support systems, forecasting and pest thresholds

DSS have been shown to increase the effectiveness of chemical control by incorporating monitoring data with up-to-date pest phenology. This allows for applications to be timed at a period of greatest risk to the crop. For example, Jakubowska *et al.,* (2020) applied these methods to the control of cutworms in sugar beet. This involved two forecasting models, one based on trapping adults in pheromone traps, and another based on cutworm development and information on migration and pest pressure. The DSS was able to identify times for effective insecticide application. Helps *et al*., (2021) evaluated DSS systems for root flies, cutworms and aphids. For both root flies and cutworms, the DSS performed considerably better than a calendar-based spray programme, although decision support for cabbage root fly saved less than the cost of a single insecticide spray.

DSS can also be applied, not in a combination with monitoring, but as a method to improve monitoring efforts. A project over four years looking at pollen beetle management in oilseed rape based on phenological and weather data was used to produce two risk management tools. A DSS that predicts pest migration and 'rule-based advice' that provides advice based on risk factors linked to the growth stage of the crop and a temperature threshold. This can help to prompt monitoring which will detect whether a treatment threshold has been reached. The DSS was more accurate at predicting migration times and predicted fewer monitoring days. Therefore, showing that the tool can effectively focus monitoring effort to times when it is most needed (Ferguson *et al.*, 2016).

Lutman (2005) concluded that correct product choice can deliver appropriate selective control. The author cited amidosulfuron not controlling chickweed (*Stellaria media)* and pendimethalin not controlling mayweed (*Matricaria recutia* and *Tripleurospermum inodorum*) and groundsel (*Senecio vulgaris)* as examples of herbicides controlling competitive weeds whilst not being active on non-target, potentially beneficial species. A further conclusion was that competitive crops can tolerate more weeds than farmers currently believe is the case.

Negatives - monitoring of crops, decision support systems, forecasting and pest thresholds

Negative effects could occur if the monitoring/DSS/forecasting methods lead to excessive false predictions, causing unnecessary pesticide treatments or missed applications where they are necessary for the crop, leading to mistrust of future recommendations. DSS require testing and regular updating to incorporate new research or changes to regulations or management strategies.

Summary - monitoring of crops, decision support systems, forecasting and pest thresholds

These methods do not provide a direct improvement or hindrance to biodiversity in farmlands, but could benefit biodiversity by reducing the amount of pesticides used. This can potentially benefit multiple taxa and trophic levels.

The actual benefit from reducing pesticide use depends on the particular pesticides involved. There is interest in the UK to use DSS to reduce use of pesticides that are more damaging for biodiversity. Such pesticides could, in principle, be identified by use of a pesticide risk indicator. In Denmark, the Pesticide Load (PL) consists of three sub-indicators for human health, ecotoxicology and environmental fate, respectively. For each of the three sub-indicators a pesticide load (PL) is calculated and expressed as the PL per unit of commercial product (kg, L or tablet). PL for human health (PLHH) is based on the risk phrases on the product label, while PL for ecotoxicology (PLECO) is calculated on basis of the LC/LD/EC50 values of the active ingredients for acute toxicity to mammals, birds, fish, daphnia, algae, aquatic plants, earthworms and bees and NOEC values for chronic toxicity to fish, daphnia and earthworms. PL for environmental fate (PLFATE) is calculated on basis of the half-life in soil (DT50), the bioaccumulation factor (BCF) and the SCI-GROW index. PL does not consider the actual exposure, i.e. it reflects the relative risks associated with the use of pesticides. Besides using PL for monitoring the yearly trend in pesticide use and load, it was also used for setting up a new pesticide tax scheme and for setting quantitative reduction targets (Kudsk *et al*., 2018). The Danish indicator aims to reflect the relative environmental pressure that occurs due to the differing hazardous nature of the pesticides and the variability in quantities applied. These sub-indicators are then (a) used to determine the level of taxation and (b) combined with national usage data to enable the monitoring of usage trends and environmental load over time. This system has been evaluated for the UK (Lewis *et al*., 2021) but various concerns were identified that may lead to modifications in how the indicator is calculated and what parameters are included to make it better able to support U.K. policy objectives.

The calculation of Total Applied Toxicity (TAT), as detailed by Bub *et al* (2022), could also be used for biodiversity means. TAT is based on amounts (masses) of pesticide and their toxicity for different species groups.

Non-chemical weed control - Mechanical weeding

Mechanical weeding kills weeds by burying, cutting or uprooting. Weeders can be mounted at the front or rear of a tractor and be powered, or ground driven. They can be steered from the tractor, have a second operator (vision guidance), or use GPS, or GIS. Weeding can take place both pre- and post-crop emergence. Weeds are best controlled as early as possible and early in a crop's life cycle when plants are smaller although multiple passes may be required to ensure adequate control.

Benefits – mechanical weeding

Birds: Navntoft *et al.,* (2007) concluded that a low weed cover is beneficial for insects and non-ground-nesting birds and harrowing twice in spring wheat could provide this low weed cover, provided it is performed before May 20, and it is not too intensive.

Steen *et al*. (2015) recognised the effects of mechanical weeders on nesting birds and developed an algorithm for use on a mechanical weeder.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptile: No evidence of positive biodiversity effects found.

Arthropods: Trials in Germany found mechanical weeding methods were less effective than herbicide applications. This led to a higher weed density that is advantageous to a range of epigeic arthropods, including staphylinids. Mechanical weeding is thought to produce a more favourable soil surface microclimate than herbicide application (Kroos and Schaefer, 1998).

Navntoft *et al.,* (2007) concluded that a low weed cover is beneficial for insects (see 'Birds' section above).

Kroos and Schaeffer (1998) citing Basedow (1991) and Lorenz (1994) found no negative response to different methods of mechanical weed control for spiders, ground beetles and rove beetles.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives – mechanical weeding

Birds: Weed harrowing in spring had a strong negative effect on the breeding of lapwings and oystercatchers and a modest number of skylark nests were damaged in trials in Denmark. Only 16% of the monitored skylark nests were exposed to harrowing as most of the harrow operations were performed before the peak of skylark nests. Of the 16% of the total skylark nests that came into contact with harrowing, 83% of these were destroyed. A total of 65% of skylark nests were successful in plots harrowed twice but only 28% were successful when harrowed four times. The trial concluded that harrowing no later than 35 days post-sowing of spring wheat and no later than May 20 would have only minor effects on the breeding success of skylarks in Denmark. Harrowing was the most frequent cause of nest failure for lapwings. Harrowing performed after May 1, or a few days after crop emergence has a negative effect on the breeding success of lapwings. Herbicide and insecticide use is also likely to be damaging to food supply for lapwing chicks (direct or indirectly) these results show the need for the creation of agri-environmental measures specifically for farmers with important lapwing colonies on their land. Low numbers of oystercatcher nests were present, but the data suggests weed harrowing is as damaging to this species as it is to lapwings. (Navntoft *et al.*, 2007).

The frequency of mechanical weeding had a marginally negative affect on the species richness and abundance of farmland birds in winter (Geigler, 2011).

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: In-crop mechanical weeding was considered harmful for most of the indicator organisms in a six-year field experiment comparing a range of different integrated weed management (IWM) systems with a standard weed management system (Deytieux *et al.,* 2012). The indicator organisms included birds, small mammals, amphibians, molluscs, spiders, carabids and wild bees.

Fish: No evidence of negative biodiversity effects found.

Amphibians: See mammals.

Reptile: No evidence of negative biodiversity effects found.

Arthropods: Weed harrowing killed spiders, reducing numbers by 37%. However, spiders recolonised fields within seven days of harrowing to levels equal to the original population. Therefore, the effects of mortality and recolonisation cancelled each other out. Weed harrowing caused substantial direct mortality on carabid beetles although this was not statistically significant (Thorbek and Bilde, 2004).

Harrowing was shown to have a significant negative effect on numbers of spiders (Linyphiidae) and rove beetles (Staphylinids, *Tachyporus* spp.) but no negative effects on the ground beetles (Carabids *Agonum* spp. and *Bembidion* spp.). Numbers of common arthropods were significantly higher in plots harrowed twice compared to those harrowed four times. However, the negative effects of harrowing could be partly explained by an indirect effect of lower weed biomass as a positive relationship between weed biomass and predator densities was found (Navntoft *et al.*, 2007).

Navntoft *et al* (2007) concluded that low dosage herbicides may be a better alternative to weed harrowing for beneficial arthropods residing on the soil surface.

Soil micro, meso and macro fauna: See mammals.

Non-target plants: Trials in Luxembourg showed mechanical weed control had a negative impact on weed diversity. Those species present in low numbers were most likely to disappear and a few species became more dominant (Richard *et al.*, 2020). However, this is also similar for many herbicide applications.

Protected species: See Navntoft *et al* (2007) in the birds section for negatives effects of mechanical weeding on skylarks and lapwings. Navntoft *et al* (2007 concluded that weed harrowing is a realistic alternative to pesticides but further work would be required to determine if low dosage herbicides are more beneficial for skylarks and arthropods than the most efficient weed harrowing. Similar work could also be done for selective herbicides that allow certain weed species to survive.

Summary – mechanical weeding

The mechanical action of the weeder disturbs the soil surface cutting weed roots or pulling them from the soil. Soil is often moved around the crop plants. Weeding generally occurs in the spring and summer when weeds are emerging, and soils are dry. Any creatures present in the field at the time of weeding are liable to be disturbed.

Table 5. Summary of the positive and negative impacts of non-chemical weed control on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	Destroys nests of ground nesting birds
Invertebrates as prey species	-	-
Mammals	-	Harmful, if present at time of weeding
Fish	-	-
Amphibians	-	Harmful, if present at time of weeding
Reptiles	-	-
Arthropods, annelids, molluscs	-	Direct mortality to surface dwelling arthropods
Soil micro, meso and macro fauna	-	Harmful
Non-target plants	-	Reduces diversity
Protected species	-	Harmful to nests

Recommendations for future work – mechanical weeding

- There is limited information on the general effects of mechanical weeding on biodiversity.

- Further work should be done to develop and implement algorithms that detect bird's nests for mechanical weeders

Sowing date

Sowing date can include the use of early or late drilling as an IPM strategy to aid in the reduction of key pest, diseases and weeds. The use of spring sowing is included in sowing date but also forms a large part of crop rotation and stubble management.

Winter wheat

Delayed drilling in winter wheat was shown to reduce black-grass populations by 31% (Lutman *et al.,* 2013). Studies have also shown pre-emergence herbicide applications to be more effective at later sowing dates (Moss *et al.,* 2016), This is likely attributed to the lower temperatures and increased soil moisture later in the year.

Later sowings (mid-October) are used to reduce the potential disease transfer from last season's crops and have been shown to reduce eyespot (Colbach *et al.*, 1997) and septoria severity in winter wheat (Morgan *et al.*, 2021), and take-all (Gutteridge *et al.*, 2003) and Barley Yellow Dwarf Virus (BYDV) in winter wheat and winter barley. However late sowings can be a risk where wet autumns prevent sowing or reduce seedbed quality and can result in a yield reduction. Late sowings can also increase yellow rust severity (Gladders *et al.*, 2007), powdery mildew (AHDB, 2021a) and fusarium incidence and severity (Gorczyca *et al.* 2017; Jurkovic *et al.*, 2006).

Early sowing can increase the tolerance to some pest damage such as slugs (Glen, 2000) and wheat bulb fly (Leybourne *et al.*,2022; Storer *et al.*, 2018) but can increase the risk of BYDV infection.

Oilseed rape

Delaying drilling in oilseed rape can be detrimental as it increases the number of barley volunteers resulting in a less competitive crop (Lutman, 1991) Oilseed rape plants require a higher base temperature for accumulating dry matter than volunteer cereals and chickweed (Lutman *et al.*, 2013; Cook *et al.*, 2013) so this puts rape at a disadvantage when sown later in the year. Delaying sowing can minimize the risk of cabbage root fly (Alford, 2003) turnip sawfly (Dewar *et al.*, 2013), turnip yellow mosaic virus (AHDB, 2021b) and cabbage stem flea beetle (CSFB) adult and larvae (White *et al.*, 2020). Later sowings can also reduce the transfer of light leaf spot spores from previous crop/nearby volunteers – which can offer the so-called 'green bridge' (Sutherland, 2001).

Early sowing can increase clubroot epidemics (Oxley, 2007), but can reduce the severity of phoma stem canker (Aubertot *et al.*, 2004) and limit pollen beetle damage (Scott *et al.*, 1973). Early sowing of oilseed rape can increase tolerance to slug damage (Dejoux *et al.*, 2003) and reduce leaf and cotyledon grazing damage from adult cabbage stem flea beetle (Barker, 1991). However, sowing early is likely to increase numbers of CSFB larvae as more eggs can be laid which hatch more quickly in the warmer weather so that the larvae invade plants earlier.

Sugar beet

The date for drilling sugar beet needs to consider soil temperature and soil moisture levels as well as varietal susceptibility to bolting. Establishing an even crop rapidly is the key driver so there is little flexibility to avoiding spring weed germination. Delaying drilling after mid-April will lead to severe yield loss.

Benefits – sowing date

Birds: Skylark surveys between 1994 and 1996 on downland turf, arable reversion grasslands, non-environmentally sensitive areas (ESA) grass and arable land found the highest densities of skylarks in undersown spring barley compared to winter barley, permanent grassland reversion and intensively managed non-ESA grass (Wakeham-Dawson *et al*., 1998).

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: Overwintered stubbles, which link to spring sowings, are thought to reduce run-off and erosion. This should benefit fish, in terms of helping egg survival, juveniles and aquatic invertebrates (fish prey) by reduced sedimentation (Turley *et* al., 2015; Turley *et al.,* 2016).

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods: No evidence of positive biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found

Non-target plants: The weed spectrum/plant community present in a crop is greatly influenced by its sowing date. Winter cropping will select for autumn germinating weeds and against spring germinating weeds.

The increase in autumn sowing of cereals has contributed to the decline in spring germinating species such as corn marigold (*Glebionis segetum*). The decline in this species has been linked to the decline in spring cropping in the past 20 years (Marshall *et al*., 2001).

Earlier harvesting of winter crops has led to declines in late autumn germinating species such as corn buttercup (*Ranununculus arvensis)* and shepherd's needle (*Scandix pecten-veneris*) (Robinson and Sutherland, 2002).

Hald *et al*., (1999) showed that a change in land use from spring to winter cereals involved an immediate reduction of more than 25% in the density of plants and species and a change and increased uncertainty in the composition of the weed flora.

Winter cropping selects for autumn germinating weed species and against spring germinating species such as the Polygonum (Chancellor, (1985) cited by Marshall *et al* (2001)). Lutman (2005) concluded that spring cropping increases the more environmentally beneficial spring emerging weed species whilst also providing benefit to birds in terms of winter stubbles.

Protected species: See Wakeham-Dawson *et al*., 1998 in the birds section for positive effects of spring barley on skylark populations.

Negatives – sowing date

Birds: Earlier sowing of cereal crops combined with earlier ripening varieties leads to earlier harvesting dates which means that more cultivations (including harvest) fall within bird breeding seasons. This causes greater destruction of eggs and chicks of field-nesting species, such as yellow wagtail (*Motacilla flava*) and corn bunting (*Emberiza calandra*) (Crick *et al*. 1994, Court *et al*. 2001).

Invertebrates as prey species: No evidence of negative biodiversity effects found

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: See Crick *et al*. 1994 and Court *et al*. 2001 in the birds section for evidence of earlier sowing of cereals alongside using early ripening varieties causing greater destruction of eggs and chicks for field-nesting species including corn bunting.

Summary – sowing date

Changing sowing date can mean a small delay of days or weeks as in the case delayed autumn drilling through to months where sowing is delayed until the spring. This delay can be effective in reducing weed, pest and disease levels or changing the species encountered.

Table 6. Summary of the positive and negative impacts of changing sowing date on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Increased densities in spring crops	Early harvest and early sowing could lead to nest and chick destruction
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	-	-
Soil micro, meso and macro fauna	-	-
Non-target plants	Spring and autumn sown crops in a rotation will increase plant population biodiversity. Delaying autumn sowing reduces weed populations, potentially reducing herbicide usage. Spring cropping increases environmentally beneficial spring germinating weed species	-
Protected species	Increased densities of skylarks in spring crops	Early harvest and early sowing could lead to nest and chick destruction

Recommendations for future work – sowing date

- Little is known about the wider effects of changing sowing date outside the effects on plants and disruption to birds. It is a wide area for research though nothing specific was identified for further research.

Precision application

Precision application is the mapping and analysing of field variation to enable the use of high accuracy variable rate or spot treatment application of fertilisers and pesticides, rather than a blanket application across the whole field.

Precision application helps to reduce agricultural inputs (pesticides and fertiliser) and therefore potentially reduce their environmental impact on non-target organisms particularly plants. Techniques include GPS, technological advancements in pesticide application (Brown *et al.,* 2007), plant identification technology (spot and spray), targeted area spraying (Blair *et al.,* 2002), weed wiping and fertiliser placement. For a wider list of precision application techniques, including integrated farm management (IFM) and integrated crop management (ICM) techniques see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/870307/fps-general-dataset-05mar20.ods

For this report's purpose, the search was limited to IPM techniques that control pests whilst reducing pesticide usage, such as spot and spray. The use of spot-spraying has shown reductions in herbicide use ranging from 60-66% (Power *et al., 2013* and Kömives *et al*., 2016).

Benefits - precision application

No direct evidence of beneficial effects of precision application on biodiversity was found. There is a reasonable inference that reduced pesticide use resulting from precision application should reduce direct and indirect effects on non-target organisms.

Negatives - precision application

No information on the negative aspects of precision application was found.

Summary - precision application

Restricting the area of pesticide application to a crop should, in theory, help preserve the number of non-target organisms but there is little evidence for this. Precision application is a rapidly evolving area and could be developed in line with biodiversity aspirations.

Table 7. Summary of the positive and negative impacts of precision application of pesticides on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Could be beneficial	-
Soil micro, meso and macro fauna	Could be beneficial	-
Non-target plants	Could target competitive plants only.	-
Protected species	Could be beneficial	-

Recommendations for future work – precision application

- Research into new precision application technology, such as spot spraying, has to date concentrated on the efficacy of detecting and controlling weeds alongside the amount of herbicide saved when applying the technology.

- Further work to determine the biodiversity implications of these technologies would give a deeper insight in to what species are affected from these types of precision applications. This information could inform priority areas where precision application techniques would bring the most benefit to biodiversity.

Bioprotectants

The term 'bioprotection' is used by the International Biocontrol Manufacturers Association (IBMA) as a collective term for all biological control technologies, including Invertebrate Biological Control Agents (IBCAs, macrobials), microbial biopesticides, semiochemicals and natural substances (IBMA, 2020). Invertebrate Biocontrol Agents or microbiological control agents provide control of pests through predation or parasitism. Microbial biopesticides are based on microorganisms such as bacteria, fungi, protozoans, viruses, viroids, mycoplasmas and any secondary metabolites, fermentation materials and cell fragments. IBMA (2020) state that bioprotectants have minimal environmental impact since biocontrol agents and microbials have existing ecosystem mechanisms to equilibrate their populations. Semiochemicals are volatile substances produced by organisms for intra or inter species communication with a target specific and non-toxic mode of action. Natural substances originate from nature, for example with components from plants, algae, animals, minerals or microorganisms, and these can be synthesised. According to the IBMA (2020) natural substances and semiochemicals have existing degradation pathways or are inert, and semiochemicals, biocontrol agents and microbials are usually specific to the target organism causing minimal effect on non-target species and any lasting effects are likely to be temporary, causing no persistent impact on biodiversity.

The release of IBCAs has been used for pest management for over 100 years and some exotic natural enemies have caused negative effects on biodiversity particularly from release of generalist predators including vertebrates for pest control and occasionally for weed control (Loomans, 2007). As a result, regulatory procedures are in place for the import and release of IBCAs in the UK to mitigate the risk to native biodiversity (Loomans, 2007). Hence the use of the active ingredient in neem oil (MAPP 18301), azadirachtin, is only on the Health & Safety Executive's list of approved substances for ornamental plant production (where the crop is under permanent protection with full enclosure).

Benefits - bioprotectants

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods: No evidence of positive biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives- bioprotectants

No evidence of negative biodiversity effects found in any category.

Summary- bioprotectants

The use of bioprotectants could help to reduce pesticide use, potentially benefitting a range of species. However, little information is available on the impacts on biodiversity.

Table 8. Summary of the positive and negative impacts of bioprotectants on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptile	-	-
Arthropods, annelids, molluscs	-	-
Soil micro, meso and macro fauna	-	-
Non-target plants	-	-
Protected species	-	-

Recommendations for future work - bioprotectants

- There is great potential for research in this area, but it will be prolonged (as there are many products) and detailed.

Selective and/or narrow spectrum pesticides

Selective pesticides (see http://sitem.herts.ac.uk/aeru/ppdb/en/ and https://agrobaseapp.com/united-kingdom) are those that are designed to target only the pest and ideally have a minimal impact on non-target organisms.

A comprehensive review of the non-target effects of herbicides on higher plant species and the subsequent indirect effects on fauna can be found in the impact of herbicides on weed abundance and biodiversity, Defra review PN0940[4]

Narrow spectrum pesticides only have a small target range and are designed to control a select group of organisms. These could be used to control competitive or undesirable

[4] https://www.yumpu.com/en/document/view/11412145/the-impact-of-herbicides-on-weed-abundance-and-biodiversity-

species whilst not controlling more desirable species that may contribute positively to biodiversity.

Benefits – Selective/narrow spectrum pesticides

Birds:

The approval of amidosulfuron has allowed selective control of cleavers, whilst not controlling desirable species. Amidosulfuron can be used early in spring before the main germination period of *Polygonum*, which are a source of food for 'chick-food' insects. It also suppresses competitive over wintered chickweed (*Stellaria media)* so it is less competitive and stays below the crop canopy (Boatman *et al.,* 1999 cited by Marshall *et al.*, 2001).

Natural England (personal communication) also have guidance that clodinafop-propargyl, fenoxaprop-P-ethyl, pinoxaden and tri-allate can be used for selective weed control in the countryside stewardship options whole crop cereals (AB7), unharvested cereal headland (AB10), and harvested low input cereals (AB14) Defra, 2022b).

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: In SAFFIE (Clarke *at al*., 2007) following single herbicide applications, arthropod abundance was generally highest where the selective herbicide amidosulfuron was applied in the spring. This benefitted nectar feeders, omnivores, Diptera and Heteroptera.

Pirimicarb is a selective carbamate insecticide used to control aphids on vegetable, cereal and orchard crops by inhibiting acetylcholinesterase activity but does not affect predators such as ladybirds and lacewing larvae that eat them. However, aphid control will also reduce the numbers of prey species available to the predatory insects.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: Herbicides were shown to be implicated in the decline of scarce weed species, though other factors were also said to have contributed to the decline (Cooke and Burn, 1995, Andreasen *et al.*, 1996). Moreby and Southway (1999) found significantly greater floral cover, weed species diversity and higher numbers of arthropod groups that are an important part of the diet of farmland birds in untreated plots compared to herbicide treated plots. This suggested that the use of selective pesticides may be an effective way of controlling only the competitive plants.

Spring applications of amidosulfuron in winter wheat allowed for a reasonable cover of desirable species whilst providing effective control of cleavers (*Galium aparine)*. Where other non-desirable species were present adequate control was not always achieved (Clarke *et al.*, 2007).

Lutman (2005) concluded that correct product choice can deliver appropriate selective control. The author cited amidosulfuron not controlling chickweed (*Stellaria media)* and pendimethalin not controlling mayweed (*Matricaria recutia* and *Tripleurospermum inodorum*) and groundsel (*Senecio vulgaris)* as examples of herbicides controlling competitive weeds whilst not being active on non-target, potentially beneficial species. A further conclusion was that competitive crops can tolerate more weeds than farmers currently believe is the case.

Specific graminicides can control target weeds, whilst leaving dicots unaffected. For example yarrow *(Achillea millefolium)*, black knapweed (*Centaurea nigra)*, lady's bedstraw (*Galium verum)*, ox-eye daisy (*Leucanthemum vulgare)*, bird's foot trefoil (*Lotus corniculatus)*, narrow leaf plantain (*Plantago lanceolata)*, sorrel (*Rumex acetosa)*, red campion (*Silene dioica)* and red clover (*Trifolium pratense)* were unaffected by the use of fusillade max (fluazifop-p-butyl) but grass species were controlled (Blake *et al*., 2012).

Protected species: No evidence of positive biodiversity effects found.

Negatives – selective/narrow spectrum pesticides

The use of selective/narrow spectrum herbicides may still negatively affect biodiversity when compared to untreated areas.

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Lutman (2005) concluded that low herbicide doses are unlikely to be an effective method to enhance selectivity of weed species controlled.

Protected species: No evidence of negative biodiversity effects found.

Summary- selective/narrow spectrum pesticides

Previous research has identified selective pesticide use to manipulate in-field weed populations. This has many beneficial effects on biodiversity but leads to 'dirty' crops which can have knock on effects for efficient harvest. Highly selective pesticides are rare in arable situations.

Table 9. Summary of the positive and negative impacts of application of selective/narrow spectrum pesticides on biodiversity in arable crops compared to the use of broad-spectrum pesticides. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Increases food availability	-
Invertebrates as prey species	Increased plant species could increase food availability	-
Mammals	-	-
Fish	-	Many pesticide labels contain warnings of toxicity to aquatic life. Care is needed in treatment, spraying, and disposal of containers of such actives
Amphibians	-	Many pesticide labels contain warnings of toxicity to aquatic life. Care is needed in treatment, spraying, and disposal of containers of such actives
Reptiles	-	-
Arthropods, annelids, molluscs	Increased food availability maintains beneficial predators.	-Control of aphids could reduce prey species for predatory insects
Soil micro, meso and macro fauna	-	-
Non-target plants	Can leave desirable species in place	Lower doses are unlikely to be effective.
Protected species	-	-

Recommendations for future work – selective/narrow spectrum pesticides

- Marshall *et al.*, (2001) concluded information on the susceptibility of weeds to existing herbicides is not easy to obtain, with only limited data on herbicide labels. They declared a need for easier access to existing information coupled with much more comprehensive dose-response data on weed species. Furthermore, they stated legislative and regulatory frameworks are required to encourage manufacturers to develop narrow-spectrum herbicides, targeted at competitive weed species, rather than broad spectrum control, and incentivise growers to use them. This is a key requirement in the training of agronomists that wish to practice Integrated Pest Management (appendix 1). It will also help farmers and spray operators to recognise the presence of desirable or uncompetitive ‘weed, pest and diseases' and relevant treatment thresholds so they can avoid applications that harm them.

- Managed herbicide use in competitive crops could lead to more opportunities for maintaining biodiversity.

Cover crops, companion cropping, intercropping, undersowing, trap crops, banker plants and floral strips

Cover crops are grown to improve and protect the soil between harvested crops. Cover crops can be grown on a short or long-term basis depending on the objective. Autumn sown cover crops can provide cover to reduce nutrient losses over winter and longer-term cover crops can help to improve soil structure. Cover crops can also be used to disrupt pest and disease cycles, suppress weeds and provide habitat for wildlife.

The term 'companion cropping' is defined as a system which involves two or more plant species growing together where part or all of their crop cycle overlaps temporally and/or spatially to provide potential benefits (Parker *et al.*, 2013; Brooker *et al.*, 2014; Howard, 2016).

Intercropping is two crops being sown together in which all plant species are harvested or systems in which one plant is harvested, and the other is 'sacrificial' (Finch and Collier, 2011). For a comprehensive review on companion cropping and intercropping see (Howard, 2016).

Most companion crop research has been conducted on its efficacy to control insect pests. Breitenmoser *et al.,* (2022) concluded that intercropping winter oilseed rape with frost-resistant companion plants, Faba bean (*Vicia faba*) and grass pea (*Lathyrus sativus*), showed a very high potential to reduce insect pest pressure from cabbage stem flea beetles (*Psylliodes chrysocephala*), cabbage stem weevil (*Ceutorhynchus napi*), and pollen beetle (*Brassicogethes aeneus*) and increase crop yield. But not all companion crops are frost sensitive and need specific herbicides to remove them from the crop. Hence, the use of companion crops for pest control may eventually reduce our reliance on insecticides but could increase herbicide use.

Undersowing is the sowing of a secondary crop underneath the primary cash crop to shade out weeds. The secondary crop is left as a mulch, cover crop or for grazing the following year. Living mulches are similar to undersown crops in their function but they remain under the crop for at least one year and can remain for several years. Allelopathic companion crops can be grown to be antagonistic to weeds. Allelopathy, first used by Hans Molisch (Olofsdotter *et al*., 2002), is the suppression of growth of a plant due to the release of toxic compounds (Lambers *et al*., 1998 as cited in Olofsdotter *et al*., 2002).

A ‘push-pull’ system involves using two companion crops alongside the cash crop. One species is planted with the cash crop to repel (push) pests away and the other is planted at the edge of the cash crop to attract (pull) pests to ‘sacrificial’ plants where they can be controlled with biological control agents or pesticides. A ‘trap’ or ‘catch’ crop refers to the ‘pull’ part of the system in which one sacrificial species, often planted on the border of the cash crop, is used as a sacrificial crop to attract immigrant pests and prevent migration to the cash crop.

Trap cropping is a method of crop pest suppression and distraction that relies upon habitat manipulation within the field. This involves the introduction of plant stands that are designed to attract invertebrate pests. This protects the crop, either by preventing it from being colonised by pests or by concentrating the pest population in areas where they can be targeted effectively with control agents (Hokkanen, 1991; Shelton and Badenes-Perez, 2006; Cook *et al*., 2007). Ideally the trap crops should not be competitive with the field crop and should be fast growing and provide a source of nitrogen. In winter sown arable crops, a frost sensitive companion crop would protect the field crop and then succumb to frost and no longer interfere with the field crop (Ortega-Ramos *et al.*, 2021). Trap crops are most common in horticulture in crops such as field vegetables. The few examples in temperate arable production are in oilseed rape for cabbage stem flea beetle management (Pickering *et al*., 2020) or maize for prevention of soil erosion (ADAS and Ricardo Energy & Environment, 2016) and improving arthropod diversity (Norris *et al*., 2018).

The banker plant system is another method of companion planting, which boosts numbers of predators and parasitoids by establishing them on a non-crop plant species, with or without an introduced pest species, which is not a risk to the cash crop.

Floral strips, beetle banks or pollinator margins can be planted along field edges, or through a field in strips. Cultivating attractant plants to encourage natural enemies is a form of companion cropping. The benefit from flowering strips is increased by a network of near natural habitat such as perennial, species-rich hedges and meadows (Messelink *et al*., 2014).

For information specific to horticultural crops see section 7.5.

Benefits – cover crops etc

Birds: A large-scale study consisting of eight sites in seven European countries found bird abundance in winter had a positive link to the area covered by green manure crops (Geigler, 2011).

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: Cover crops can reduce run-off volume by 10 to 98% and reduce sediment loss by 22-100%. Grass cover crops can help to reduce nitrate leaching up to 95% (Blanco-Canqui, 2018). High fine sediment from terrestrial sources resulting from anthropogenic activity are widely recognised to negatively impact freshwater fish and aquatic ecosystems (Kemp *et al,* 2011).

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: A greater occurrence of naturally occurring hymenopterous parasitoids (Buntin, 1998; Vinatier *et al.*, 2012), and an increase in the parasitism of cabbage seed weevil larvae by 60–80% was recorded in winter oilseed rape with a trap crop of an autumn sown spring variety of oilseed rape that flowers two to three weeks earlier than the winter crop (Buntin, 1998).

Soil micro, meso and macro fauna: Higher earthworm abundance was found in clover monocultures and grass-clover mixtures when compared to fallow in a one-year trial in the Netherlands, with epigeic earthworms positively correlated to the proportion of clover (Haas *et al.*, 2019). In a systematic literature review of cover crops Hao *et al* (2023) showed cover crops increased soil microbial biomass by up to 19.5%, The review cited studies by Puget and Drinkwater, 2001; Steenwerth and Belina, 2008a and Kallenbach *et al.*, 2016 showing cover crop root exudates increases microbial activity and biomass.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives – cover crops etc

A two year study at eight field sites showed cover crops can be used to suppress weed growth, however additional weed management measures are needed for reliable weed control (Dorn *et al.,* 2015).

Summary– cover crops etc

Adding species to the rotation has been shown to increase a limited number of taxa in the limited number of references found. The question is where to place these species? Placing them outside of crops is less problematic than placing them within crops. Benefits for pest and weed control have been shown but there are potential detrimental effects on crop yield.

Table 10. Summary of the positive and negative impacts of cover crops etc on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Winter bird abundance positively linked to the area covered by green manure crops.	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	Can reduce soil runoff and erosion benefiting fish and aquatic ecosystems.	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increase in parasitism. Increase in flowers and visiting arthropods.	-
Soil micro, meso and macro fauna	Higher earthworm and microbial abundance	-
Non-target plants	-	Can suppress weeds however additional measures needed so not clear of the impact on high biodiversity value weeds
Protected species	-	-

Recommendations for future work – cover crops etc

- More evidence is needed on the biodiversity effects of various cover crops etc. in a range of representative agronomic systems.

Varietal choice and mixtures

The use of resistant and tolerant varieties are an important part of non-chemical pest and disease control. Sources of information on disease resistance to the major pathogens in cereals, oilseed and potatoes are available in the recommended lists published by AHDB and by British Beet Research Organisation (BBRO) for sugar beet.

Varietal mixtures result from growing multiple varieties of the same crop species in one field. The increase in within-species genetic diversity (with respect to disease resistance genes) has the potential to reduce the threat from diseases. Research has shown varietal mixtures significantly increase yield and reduce *septoria tritici* blotch (STB) in winter wheat (Kristoffersen *et al.,* 2021). Four cultivar mixes with moderate to low fungicide input under high disease pressure showed the greatest benefits. The potential to reduce fungicide applications was identified in 67% of the cultivar mixtures.

Crops that are tolerant to specific herbicides have been developed, these are naturally bred. Examples include Clearfield® oilseed rape and Conviso® sugar beet. These varieties allow for control of weeds that are closely related to the crop such as brassicas in oilseed rape and weed beet and fat hen in sugar beet which are difficult to control with herbicides in standard varieties. Growers are advised to follow strict stewardship guidelines to prevent herbicide tolerant volunteers, and to bear in mind marketing of the end-crop, when choosing varietal mixtures.

Benefits - varietal choice and mixtures

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of positive biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives- varietal choice and mixtures

No evidence of negative biodiversity effects found in any category.

Summary- varietal choice and mixtures

There is limited information on the effects of varietal choice and mixtures on biodiversity Where competitive crops are grown, such as hybrid barley, an increase in canopy density could make it less suitable for birds which prefer open structured cereal crops for foraging and nesting.

Table 11. Summary of the positive and negative impacts of varietal choice and mixtures on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	-	-
Soil micro, meso and macro fauna	-	-
Non-target plants		May increase the likelihood of herbicide resistance Reduce plant density
Protected species	-	-

Recommendations for future work- varietal choice and mixtures

- The current lack of willingness of end-users and buyers coupled with marketing conservatism to accept varietal mixtures off-farm may need to be challenged.
- Initial work on varietal mixtures has concentrated on reduction in disease levels. Assessments could be expanded to look at the additional benefits.
- In work comparing hybrid, 2-row, 6-row barley and winter wheat there are large differences in canopy size and light penetration which is a major contributor to the effects on weed control. This has implications for biodiversity, and these could be quantified.
- See section 6.12 for additional comments on gene modification.

Genetic modification

Genetic modification (GM) and gene editing techniques, such as CRISPR, are likely to gain approval for food production in the UK in future. GM crops are widely grown in other parts of the world such as the US and India and the impact on biodiversity has been studied.

Not surprisingly, the effects on various groups of arthropods followed the effects on the abundance of their resources.

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: The effect of Bt crops on non-target above ground invertebrates has been studied in several reviews. Carpenter (2010) concluded that no significant adverse effects or landscape level effects have been recorded and abundance and activity of parasitoids and predators are similar in Bt and non Bt crops. A meta-analysis by Wolfenbarger *et al.* (2008) found that predators and specialist parasitoids of the target pest were less abundant in Bt cotton compared with unsprayed non-GM cotton, but numbers of other parasitoids were the same in both types of crop. This study also found that predators and herbivores were more abundant in Bt crops compared with sprayed non-Bt crops due to the use of different insecticides, whereas omnivores and detritivores were more abundant in sprayed non-Bt crops than the Bt-crops (Wolfenbarger *et al.*, 2008).

In a review by Areal *et al*., (2015) the authors stated that scientific evidence so far seems to indicate that there has been no environmental damage from growing GM crops. They may possibly even be beneficial to the environment as they result in less insecticides and herbicides being applied.

Soil micro, meso and macro fauna: Plants influence biodiversity in the soil by nutrient cycling and release of root exudates. Studies have shown few or no toxic effects of Cry proteins from Bt crops on woodlice, collembola, mites, earthworms, nematodes, protozoa and soil enzymes (Carpenter, 2011).

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: GM crops have helped to increase yields in several countries, with the greatest yield increases in developing countries (Carpenter, 2010). An estimated 2.64 million hectares of land were not converted to agricultural use in the US, Romania, the Philippines and Canada due to yield increases from GM crops (Brookes *et al*., 2010). Not converting land into agricultural production might potentially enable conservation of habitat for protected species.

Negatives

Birds: The abundance of birds is related to the availability of food resources such as weed seeds and insects (Carpenter, 2011). More granivorous birds were found on non-GM sugar beet compared with herbicide tolerant sugar beet but there were no differences in a similar comparison in spring oilseed rape (Chamberlain *et al.*, 2007).

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: A quantitative review looked at 48 non-target species and found 21.2% of peer-reviewed papers analysed showed significant negative effects of GM plants on natural enemies compared to 4.8% showing significant positive responses to resistant crops (Lövei *et al., 2009)*). In another study negative effects were more common in laboratory studies than field studies and were associated with exposure to Bt proteins especially when non-target organisms were related to the target pest (Naranjo, 2009).

In 2015 genetically modified herbicide tolerant (GMHT) winter oilseed rape (WOSR) was compared to conventional varieties over a three-year period (Bohan *et al.*, 2005). Bees and butterflies that select and forage on dicot weeds were less abundant in GMHT WOSR management in July than in the conventionally managed crop. Year totals for collembola were greater under GMHT than conventional management. There were few other treatment effects on invertebrates, despite the marked effects of herbicide management on the weeds.

Limiting herbicide use to single modes of action on tolerant crops has implications for increased development of herbicide resistance in target and non-target plant species.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Genetically engineered herbicide tolerant sugar beet and oilseed rape crops were associated with fewer weeds and weed seeds compared with conventional crops, whereas herbicide tolerant corn was associated with an increased number of dicotyledon weeds and weed seeds and subsequently higher numbers of weed seed-eating beetles (Carpenter, 2011).

There is concern that geneflow from GM crops to wild relatives could have a negative impact on biodiversity, however, any impact would depend on whether or not the additional genetic material confers any fitness advantage or disadvantage (Carpenter, 2011).

Protected species: See Bohan *et al* (2005) in the arthropods section citing reduced bees and butterflies in GMHT oilseed rape. Some species of bee and butterfly are on Section 41 of the NERC Act (2006) so could be affected.

Summary

The success of GM crops has led to increased conversion of land to agricultural use in some parts of the world, such as Brazil and Argentina (Carpenter, 2011). GM may enable cropping on poor quality or marginal land, which has traditionally been unsuitable for cropping and left for wildlife.

There is little information available on the impact of genetic modification on biodiversity apart from in Bt crops. Many studies have concluded that Bt crops are safe to biodiversity and may lead to the reduced use of insecticides. Other studies have found negative effects or contrasting effects on different species. In herbicide tolerant crops, increasing reliance on a single mode of action can lead to increases in herbicide resistance in naturally occurring plant species (Schütte *et al*., 2017).

Table 12. Summary of the positive and negative impacts of genetic modification on biodiversity. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	Reduced or static numbers.
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	No difference in GM crops, or increased herbivore and predator numbers.	Reduced omnivores and detritivores in GM crops. Non-target organisms closely related to target organisms can be affected. Lower abundance in GMHT crops.
Soil micro, meso and macro fauna	-	-
Non-target plants	Potential for increased crop diversity	Potential for gene flow to wild relatives if GM trait is beneficial
Protected species	More land available for conservation	Increased cropping of previously unsuitable land

Recommendations for future work

- Further work is needed on the impact of genetic modification and gene editing on biodiversity in the UK.

Stubble management

Stubble is defined as the above-ground plant residue left in the field after harvest, including stem, leaf and glume of cereals. Stubble can be mulched, cultivated, drilled into or retained over winter for habitat. Stubbles can provide food sources for invertebrates and birds by leaving weeds and seeds in the field. Stubbles can be used to take out volunteers from the previous crop, pernicious grassweeds and can help minimise the carryover of pests and many diseases by removing the 'green bridge' between cropping seasons.

Generally, there are three types of stubble created following harvest in the autumn (Potts 2003).

1. Cultivated early to provide a seedbed for autumn sown cereals, usually prior to October.

2. Ploughed to allow establishment of spring sown crops, usually prior to Christmas but could be delayed by poor weather.

3. Stubble that carries an undersown crop.

Sprayed stubbles and over-wintered stubbles for agri-environment schemes (AB2 and AB6) could be added as further categories.

Benefits - Stubble management

Birds: The retention of over-winter stubble under set-aside provided foraging habitat for some farmland birds, although plant species diversity is usually low (Firbank *et al.*, 2003). The SAFFIE project (Clarke *et al*., 2007) showed barley stubbles were much better than wheat for increasing beneficial plant species due to earlier harvesting. Retaining winter stubble led to increases in population growth rates across multiple granivorous species of birds (Baker *et al.*, 2012); hence current agri-environment options Overwintered stubble (OP1), Basic overwinter stubble (AB2) and Enhanced overwinter stubble (AB6) (Defra, 2022b). If spring cultivation follows, there is potential for spring-germinating annuals to establish further increasing biodiversity (Critchley *et al.*, 2004).

Hancock *et al.* (2016) found the abundance of cereal seed eating birds was higher in stubble fields after combine harvesting compared to arable silage or reaper binders, but this relationship was not found for weed seed eating birds such as finches. Whilst Moorcroft *et al.* (2002) found the abundance of seeds and bare ground in stubble fields was positively correlated with the abundance of seed-eating birds and negatively correlated with wood pigeons that graze on vegetation.

Crop seed numbers on stubble were highest after oilseed rape and lowest after winter wheat and numbers declined over the winter period. Germination of weeds within the stubble and seed set on these plants was shown to provide up to 30,000 seeds/m² (Vickery *et al.*, 2005). Bird numbers on stubbles could be low with most stubbles supporting no birds at all. Where birds were present, up to 80% of the variation in number of granivorous birds was explained by the density of Chenopodiaceae and Polygonaceae seeds and the number of chemicals used on the preceding crop (Vickery *et al.*, 2005). This study supported work by Moorcroft *et al.*, (2002) who showed a strong correlation between the distribution of linnet (*Carduelis cannabina*), grey partridge (*Perdix perdix)*, chaffinch (*Fringilla coelebs*), yellowhammer (*Emberiza citrinella*), corn bunting (*Miliaria calandra*) and reed bunting (*Emberiza schoeniclus*) and food resources. In this work they compared stubbles following conventionally grown wheat and barley with an undersown organic wheat. The undersown crop discouraged the use of the stubble by birds due to the greater ground cover; more open stubbles were favoured where seeds were more available.

Undersown leys are important to insectivorous birds as they are rich in invertebrates (Barker *et al.,* 1999), but are not as good for granivorous birds as the sown grass competes with weeds reducing growth and seed production. Access to the soil surface is also restricted (Moorcroft *et al.*, 2002).

Beet tops and crowns can provide a significant food source for birds such as pink-footed geese (*Anser brachyrhynchus*). They can graze on harvested sugar beet fields for up to 30 days after harvest (Gill *et al.*, 1996). Twenty five percent of the world population of this species spends much of the winter on the beet stubbles and other fields of northwest Norfolk together with other species such as Bewick (*Cygnis columbianus*) and whooper swans (*Cygnis cygnus*), skylarks (*Alauda arvensis*), golden plover (*Pluvialis apricaria*), lapwing (*Vanellus vanellus*), pied wagtail (*Motacilla albus*) and meadow pipit (*Anthus pratensis*).

A large scale study consisting of eight sites in seven European countries found bird abundance in winter had a positive link to the area covered by stubble (Geigler, 2011).

Invertebrates as prey species: As described in 6.1.1, leaving straw residue can increase slug populations, which are prey for birds and invertebrates (South, 1992; O'Hanlon *et al*., 2019).

Mammals: A study by Cybulska *et al.* (2020) found that increased areas of stubble reduced the stress levels of hares and improved food and cover for small mammals.

Fish: Retaining stubble can protect the soil and minimise the risk of runoff to water.

Amphibians: Retaining stubble can protect the soil and minimise the risk of runoff to water.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: Fields in which oilseed rape has not been grown recently or nearby are likely to have relatively low cabbage stem flea beetle pressure. The presence of cereal stubble/straw could make it harder for the pest to locate emerging oilseed rape, but robust trial data is sparse. It may also help to conserve soil moisture. Trials suggest that wheat straw may be better than barley straw. Spiders also use stubble to support their webs. It is possible that longer stubble offers greater benefits (AHDB, 2022d).

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: Lack of a pre-harvest desiccant improves the survival of in-crop plant species, where stubble is left uncultivated as they can complete their lifecycle and return seed to the seedbank.

Protected species: See Gill *et al.*, 1996, Vickery *et al.*, 2005 and Moorcroft *et al.*, (2002) in the birds section for the positive effects of stubble on skylark, lapwing, linnet, grey partridge, chaffinch, yellowhammer, corn bunting and reed bunting populations.

See Cybulska *et al* (2020) for the benefits of stubble for hares.

Negatives - Stubble management

Birds: Stubbles can often lack a diverse range of plants and this lack of biodiversity can negatively impact on feeding opportunities for birds in the autumn.

Invertebrates as prey species: The disappearance of undersown cereals to create a ley has been identified as a key factor in the decline of invertebrates (Avery and Moorcroft, 2003), especially sawflies (Barker *et al.*, 1999).

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: No evidence of negative biodiversity effects found.

Summary- Stubble management

Retaining a stubble after harvest is already part of environmental schemes. Its value as a source of food during the autumn and winter is well known. Stubble management is key to maximising its value and its value is reduced by the application of a pre-harvest desiccant and cultivation immediately after harvest. Retention of stubbles protects the soil from rain and minimises erosion. Stubbles can be very varied depending on the crop they follow and the pesticides that have been applied.

Table 13. Summary of the positive and negative impacts of stubble management on biodiversity in arable crops. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Can be managed to provide improved food source	Diversity of food sources can be low.
Invertebrates as prey species		
Mammals	Improves environment and food sources	-
Fish	Minimises erosion, improves water quality	-
Amphibians	Minimises erosion, improves water quality	-
Reptiles	-	-
Arthropods, annelids, molluscs	Improves populations	-
Soil micro, meso and macro fauna		-
Non-target plants	Increases seed return to replenish seedbank	-
Protected species	Stubble management can benefit skylark, lapwing, linnet, grey partridge, chaffinch, yellowhammer, corn bunting and reed bunting populations	-

Recommendations for future work- Stubble management

- Stubble management can be very variable, work in this area is difficult to plan as several factors can influence the type of stubble, its duration, the following crops and time of destruction.

Outdoor horticulture

This part of the review considers the impact on biodiversity of IPM techniques used in outdoor horticulture, with specific reference to brassicas (such as broccoli, cauliflower, cabbage, and Brussels sprouts), root crops (carrots, beetroot, and parsnips) and top fruit (apples, pears, cherries, and plums).

A review by Adamson *et al.*, (2020) found that there was limited data available to quantify the uptake of IPM in horticulture. In general, IPM use in horticulture is practiced by most growers to some extent but some sectors such as protected edibles and organic growers rely on IPM more extensively than other sectors, such as outdoor horticulture (Adamson *et al.*, 2020). The Maximum Residue Levels (MRLs) of pesticides permitted in horticultural produce are very low since the edible part of the plant is often directly exposed to pesticides (Adamson *et al.*, 2020). The number of effective pesticides available for use in horticulture has reduced due to regulation and resistance (Adamson *et al.*, 2020). These restrictions pose a barrier to use of pesticides by horticultural growers and have driven the uptake of IPM.

Adamson *et al.*, (2020) considered that the impact of IPM on biodiversity was positive because of a decrease in the use of conventional pesticides, however there was an evidence gap relating to understanding the direct environmental impacts of individual IPM techniques. This section of the review will focus on the impact on biodiversity of some specific IPM techniques used in outdoor horticulture. Many of these are used in a similar way in arable farming and have been covered in the arable section. Refer to section 6.1 for cultivations, section 6.2 for rotations, section 6.9 for selective pesticides and section 6.10 for cover cropping.

Crop Rotation

See section 6.2 on arable crop rotation for more information. Specific reference to horticultural systems is given below.

Benefits

Arthropods, annelids and molluscs: Numbers of carabids in vegetable crops following clover were lower than in vegetables crops following potatoes (Kromp, 1999). Most carabid species have a preference for a warm microclimate but some prefer different microclimates, influenced by the phenology of the crop (Kromp, 1999). Autumn breeding species such as rain beetle (*Pterostichus melanarius*) prefer potatoes, which start with a lot of bare soil in the spring and become more shaded and humid by autumn (Kromp, 1999). Spring breeding species such as the ground beetles *Poecilus cupreus* and *Platynus dorsalis* prefer crops that are already established in early spring (Kromp, 1999).

Summary

As with arable cropping a varied rotation will provide a wide range of habitats and food sources but a range of non-crop areas are needed to provide all year round opportunities.

Monitoring, decision support systems, pest thresholds and forecasting

For a full description of these techniques see section 6.4.

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: Researchers found that Northern Irish apple growers had been spraying pesticides to control the beneficial predatory whirligig mite *Anystis baccarum* having misidentified it as the fruit tree red spider mite, *Panonychus ulmi* (Cuthbertson and Murchie, 2010). Identification cards were distributed to apple growers in the region and several applications of pesticides were prevented, benefiting the population of *A. baccarum* (Cuthbertson and Murchie, 2010). Reducing pesticide applications will have benefitted many species as well as *A. baccarum*, which has been recorded predating pests such as aphids, tortricid larvae, fruit tree red spider mite and apple rust mite (Cuthbertson and Murchie, 2010).

Decision support systems can be used to increase the efficacy of pesticide applications and reduce the number of applications and any negative effects on biodiversity. The woolly apple aphid (*Eriosoma lanigerum*) is one of the most damaging pests in apple orchards (Bangels *et al*., 2021). A phenology prediction model for woolly apple aphid and its natural parasitoid *Aphelinus mali* was able to successfully predict the migration of *E. lanigerum* and the first- and second-generation flights of *A. mali*. This enabled growers to target the most vulnerable stage of the pest lifecycle and avoid spraying the very sensitive parasitoid (Bangels *et al*., 2021).

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: No evidence of negative biodiversity effects found.

Summary

No negative effects of decision support systems have been identified; benefits are still being recognised as use of the technology increases.

Table 14. Summary of the positive and negative impacts of monitoring, decision support systems, pest thresholds and forecasting on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increased numbers by avoiding unnecessary pesticide applications	-
Soil micro, meso and macro fauna	-	-
Non-target plants	-	-
Protected species	-	-

Recommendations for future work

- Further research is needed to assess the impact on biodiversity of specific DSS applications as they become available.

Non-chemical weed control (includes mechanical, thermal and mulches)

Manual techniques include hand weeding, pulling and hoeing. These methods are very expensive due to the labour required, but tractor mounted 'lie-on' machinery can make it more cost effective (Cook *et al.*, 2019). Mechanical weeding techniques are common in organic horticulture and increasingly common in conventional horticulture, particularly to remove tap rooted weeds such as docks or ragwort, which can proliferate from small pieces of root when cultivated (See section 6.5 for information on mechanical weeding in arable cropping).

Mechanical weeding

Mechanical weeding has been reported in section 6.5. Mechanical weeding kills weeds by burying, cutting or uprooting. Stale seed beds are used for field vegetables where possible using shallow cultivating machinery such as a power harrow or a bed former (Cook *et al.*, 2019). Harrow and tine weeders are typically used pre-emergence in field vegetables to uproot seedling weeds. Inter-row weeders are commonly used once field vegetables are established such as the brush weeder which uses nylon brushes to uproot surface weeds (Cook *et al.*, 2019). Finger weeders uproot small intra-row weeds in well-established crops and use rubber ‘fingers’ which protrude from rotating discs (Cook *et al.*, 2019). Camera- and GPS-guided hoes can be used for inter- and intra-row weeding as the cameras can distinguish weeds from the crop (Cook *et al.*, 2019). Mowing and cutting is commonly used in top fruit orchards to prevent weeds flowering and setting seed and to control the growth of the ground cover.

Thermal weeding

Thermal weeding techniques are an emerging branch of non-chemical weed control, but they are less common due to cost, energy consumption and safety concerns (Cook *et al.*, 2019). Techniques include flaming, infrared weeding, hot water, steaming and dry heating radiation, ultraviolet and lasers, electrical weeding and freezing (Cook *et al.*, 2019). Electric weeding has been around since the 1970’s (Diprose & Benson, 1984, Bond *et al*., 2003) but recent developments have made the technology[5] more accessible to the arable and horticultural sectors. The technology has been tried in blackcurrants (Tatnell *et al*., 2020) and for desiccation of potato crops[6]. Weed control by hot foam[7] is a recent introduction but is currently limited to amenity areas. Flame weeding is used quite often in organic field vegetable crops and orchards to provide a stale seed bed and can also be used post emergence between or within the rows.

Mulching

Mulches are used to physically block light from emerging weeds and reduce seedling germination. Mulches are typically made from plastic film or woven polypropylene textiles or biodegradable materials such as straw, woodchips or corn/potato starch products (Huckle *et al.*, 2011). Plastic film mulches are more commonly used for cucurbits than for brassicas or root crops and woven textiles tend to be used for protected edible or perennial crops due to the cost of the material. Biodegradable mulches are suitable for brassicas, root crops and orchards (Cook *et al*., 2019).

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[5] https://ubiqutek.com/

[6] https://nufarm.com/uk/nucrop-ideal-for-desiccation-in-potatoes/

[7] https://www.weedingtech.com/

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: Mechanical weed control techniques (mechanical hoe and brush weeder) did not affect carabid beetles either directly or indirectly through altered soil structure (Lorenz, 1995). Numbers of *Amara* and *Harpalus* spp. adults and *Amara* larvae were increased with use of mechanical weeding compared with use of herbicides due to increased weed coverage (Lorenz, 1995). Flame weeding in organic carrots and onions did not affect numbers of carabids as flaming was done on hot days at noon, when the beetles were sheltering in the soil since these crops do not provide much shade (Dierauer and Pfiffner, 1993).

Soil micro, meso and macro fauna: In a study comparing four different weed control techniques in onion (plastic mulch, hay mulch, critical period cultivation and cultivations every 10-days) the hay mulch had the greatest benefit on the number of earthworms and the critical period cultivation had the greatest benefit on the number of carabid beetles (Brown and Gallandt, 2018).

Black plastic mulches do not provide a good habitat for beetles and earthworms (Birkenshaw *et al.*, 2008; Cirujeda *et al.*, 2012). Whereas biodegradable mulches provide habitat for seed predators (Bond and Grundy, 2001).

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: Earwig females make nests in the soil in winter and early spring to lay their eggs and rear their nymphs (Lamb, 1976). Soil disturbance and compaction from mechanical weeding can negatively affect earwigs and other invertebrates.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Non-discriminatory implements can damage feeder roots from fruit trees and from surrounding trees, reducing their ability to absorb nutrients. This can have a knock-on effect by reducing the ability for trees to sustain a higher biodiversity (Hussain *et al*., 2018).

Protected species: No evidence of negative biodiversity effects found.

Summary

Evidence of effects on non-target species is restricted to data on a few species.

Non-chemical weed control on field crops in the form of mechanical weeding has been reported in section 6.5. Electric weeding has been around since the 1970's (Diprose & Benson, 1984, Bond *et al*., 2003) but recent developments have made the technology[8] more accessible to the arable and horticultural sectors. The technology has been tried in blackcurrants (Tatnell *et al*., 2020) and for desiccation of potato crops[9]. Weed control by hot foam[10] is a recent introduction but is currently limited to amenity areas.

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[8] https://ubiqutek.com/

[9] https://nufarm.com/uk/nucrop-ideal-for-desiccation-in-potatoes/

[10] https://www.weedingtech.com/

Table 15. Summary of the positive and negative impacts of non-chemical weed control on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Static or increased carabid numbers	Can reduce numbers through soil disturbance or direct death (flame)
Soil micro, meso and macro fauna	Biodegradable mulches provide habitats for some species	-
Non-target plants	-	Can damage roots of trees
Protected species	-	-

Recommendations for future work

- Thermal weeding techniques are a rapidly expanding area of research and work will be needed to establish the impact on biodiversity of these novel techniques.
- Further work is also needed on the effects on non-arthropod, soil organisms or plant species.

Bioprotectants

Bioprotectants are described in section 6.8. Bioprotectants are widely used in protected horticulture and use in outdoor horticulture is increasing.

The most commonly used bioprotectants in outdoor horticulture include the microbial biopesticide *Bacillus thuringiensis* (Bt) for control of caterpillars, semiochemicals for monitoring moth populations and the release of biocontrol agents such as predatory mites and anthocorids.

Additional information on biopesticides can be found in Collier (2013) and O'Neill & Gwynn (2014).

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: If bioprotectants can help to reduce the number of applications of conventional pesticides, then this could reduce lethal and sub-lethal effects on spiders (Benamú *et al.* 2017). However, Rosos-Ramos *et al.* (2020) found that dominant spider families were unaffected by or even benefitted from application of pesticides when comparing conventional and organic management in a cherry orchard in Spain. In the same study some mite families, *Trombidiidae, Stigmaeidae* and *Phytoseiidae* were more prevalent under conventional management than organic management, which could be due to tolerance for pesticides in these groups (Rosos-Ramos *et al.*, 2020). In contrast, a greater diversity of bee species and other pollinators was found under organic management compared with conventional management as most pollinators are highly sensitive to pesticides, except for melyrid beetles which were more abundant under conventional management (Rosos-Ramos *et al.*, 2020).

<u>Biocontrol agents</u>

Release of biocontrol agents is expensive and predominantly used in protected cropping. Most exotic biocontrol agents are currently licensed for release under permanent protection only and licences state that any identified negative impacts should be reported to Defra (Defra, 2022a). Therefore, biocontrol agents used in field and orchard systems tend to be native species such as the predatory mite *Amblyseius andersoni* and the anthocorid *Anthocoris nemoralis*. Integrated pest management strategies increasingly focus on augmenting natural enemy populations for example the commercial refuge ‘Wignest’ is available to provide habitat for earwig nests in orchards and Nutrimite™, which is cattail (*Typha sp.*) pollen, is commercially available as a supplementary food source to boost populations of predatory mites, such as *A. andersoni* (Shaw *et al.*, 2021; Wedgwood *et al.*, 2020). Growers and researchers in the 1980s found that populations of the naturally occurring predatory mite *Typhlodromus pyri* had developed resistance to organophosphate and synthetic pyrethroid insecticides and could effectively control the equally resistant fruit tree red spider mite where these pesticides were necessary for control of other pests (Solomon *et al.*, 1993; J. Allen, personal communication, August 9, 2022). Growers would move foliage containing these mites to new orchards to improve biocontrol of the fruit tree red spider mite, resulting in a substantial reduction in the use of specific acaricides for this pest (Solomon *et al.*, 1993; J. Allen, personal communication, August 9, 2022).

<u>Microbial biopesticides and natural substances</u>

The *Cydia pomonella* granulovirus is a species of baculovirus used to control codling moth in top fruit. A review by Flexner *et al.* (1986) found no evidence of direct toxicity of baculoviruses to natural enemies and any indirect effects were associated with parasitoid mortality due to deterioration of the host.

<u>Semiochemicals</u>

Mating disruption was used to control codling moth in an Australian apple orchard. Three strategies were assessed:

I. mating disruption alone;
II. mating disruption plus azinphos-methyl;
III. mating disruption plus fenoxycarb.

In strategies i and iii populations of generalist predators including ladybirds, lacewings and earwigs increased and also provided incidental control of two-spotted spider mite (Nicholas *et al*, 1999).

White apple leafhopper, (*Typhlocyba pomeria*) has been developed to be used as an indicator-species for non-target insects and system stability within US orchards adopting new IPM practices such as mating disruption for control of codling moth (Beers and Jones, 2004). The white apple leafhopper is a useful indicator species because it reproduces rapidly if its egg parasitoid (*Anagrus epos)* or other generalist predators are disrupted by pesticide application (Beers and Jones, 2004).

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: All bat species in the UK eat insects and are protected by law. A review of the European Food Safety Authority (EFSA) bat statement found that there was limited information available on the risk of pesticide exposure to bats, but they can be exposed to pesticides via oral, dermal and inhalation routes (Brooks *et al.*, 2021). Bats can act as biological control agents and can be attracted to orchards by providing water and retaining standing dead wood in orchards trees or hedgerows or by putting up bat boxes to provide nesting sites (Good Fruit Grower, 2014; PTES, 2022; Macemon, 2011).

Negatives

Birds: Use of Bt sprays for control of Lepidoptera can indirectly affect bird species due to reduced prey availability (Höllrigi-Rosta & Wieck, 2013).

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs:

Microbial biopesticides

The use of entomopathogenic nematodes is not common in outdoor horticulture compared with protected horticulture. Release of native entomopathogenic nematodes can cause mortality of non-target arthropods but only part of the population will be affected, limited temporally and spatially (Bathon, 1996). A study by Bathon (1996) found that the impact of nematode application on non-target fauna was negligible.

The bacterium *Bacillus thuringiensis* (Bt) is commonly applied in outdoor horticulture for control of lepidopteran pests. When ingested the bacteria produce crystal proteins in the gut, which release a fatal toxin as they break down. Bt toxins can produce multiple toxins and therefore have a complex host profile (Sanahuja *et al.*, 2011). Generally, Bt *kurstaki* strains are specific to Lepidoptera, *irsraliensis* strains are specific to Diptera, and *morrisoni* strains are specific to Coleoptera (Sanahuja *et al.*, 2011). Bt var. *kurstaki* sprays used to control oak processionary moth in woodland have negatively affected populations of non-target Lepidoptera such as the green oak tortrix, *Aleimma loeflingiana*, *Zeiraphera isertana*, spring usher, and species of quaker moths (Parsons, 2015).

Semiochemicals

Pheromone lures are used to monitor the population of several pests. Pheromones are target specific and traps are designed to reduce by-catch of non-target organisms. The plum fruit moth trap tends to catch more non-target species than other moth traps; *Grapholita tenebrosana* is commonly caught and mistaken for the plum fruit moth (AHDB, 2018b).

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: No evidence of negative biodiversity effects found.

Summary

Use of bioprotectants can potentially help to replace pesticide use and benefit many different species, however some species have evolved resistance to some pesticides in conventional systems, making the effect of switching to IPM less clear.

Table 16. Summary of the positive and negative impacts of bioprotectants on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	Reduced prey can reduce numbers compared to not treating the pest
Invertebrates as prey species	-	-
Mammals	Bats can be encouraged as biocontrol agents	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increased numbers of native biocontrol agents.	Non-target lepidoptera impacted by Bt. Pheromone traps - can catch non-target species.
Soil micro, meso and macro fauna	No change	-
Non-target plants	-	-
Protected species	Benefits to bats if their presence is encouraged to provide biocontrol	-

Recommendations for future work

- Further work is needed to look into the impact on the ecological community of artificially increasing numbers of generalist predators.
- Further work is needed to look into the impact on non-target lepidoptera in outdoor horticulture systems as the diversity of non-target lepidopteran species in these environments is unknown.
- Further work is needed to look into the impacts of semiochemicals on non-target species.

Cover crops, companion cropping, intercropping, undersowing, trap crops, banker plants and floral strips

There are many different IPM techniques which can be considered companion cropping in a horticulture system, and these are used primarily for pest control or weed suppression. For a description of these techniques see section 6.10.

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: Sikorska *et al.* (2019) found that management of field margins affected the population of Phytoseiid predatory mites. The frequently tilled field margin covered with spontaneous annual plants was beneficial to the predatory mite *Amblyseius andersoni* which helps control Red Spider Mite, whereas the presence of trees benefitted the polyphagous predatory mite *Euseius finlandicus*. The non-native grass margin was associated with a low number of mite species. The study concluded that management of the field margins only affected the population of mites in the field margin and the field edge to a limited extent, but mite diversity in the main crop was not affected (Sikorska *et al.*, 2019).

<u>Pest control techniques</u>

Increasing the diversity of crop species with companion crops can increase arthropod biodiversity in productive landscapes without compromising productivity (Brandmeier and Scherber, 2021). Companion cropping systems are more structurally rich than monocultures and therefore interactions in the plant canopy and the rhizosphere promote coexistence of multiple species (Brandmeier and Scherber, 2021). Companion crops provide shelter and food resources for biodiversity when the main crop is harvested or treated with pesticides. Crop diversity is particularly important in maintaining arthropod diversity when the proportion of semi-natural cover in the landscape is very low (Thomine *et al.*, 2022). Field margins and set-aside fields sown with wildflowers were found to promote taxonomic diversity of spiders within an agricultural landscape in Germany (Plath *et al.*, 2021). Some catch and companion crops, such as buckwheat, sown in August and September can flower within weeks of sowing; provision of flowering plants benefits key pollinator species of bee. Flowers are vital sources of amino acids and carbohydrates which many species of beneficial insect require for egg production and energy such as, hoverflies, lacewings and some species of ladybirds. Nectar and pollen are also the sole energy resources for adult parasitic wasps (Rosenfield and Sumption, 2009). Perennial stinging nettle *Urtica dioica* can support over 100 species of insect if left uncut in field margins (Shaw *et al.*, 2021). Field margins provide alternative food sources for predatory mites, which allows them to recover more quickly from pesticide applications, reducing their mortality rate (Pozzebon *et al.*, 2014).

<u>Weed suppression</u>

Alleyway living mulches in apple orchards increased the number of predatory beetles, parasitoids, active hunting spiders and pollinators without increasing pest populations; reduced mowing frequency and increased mowing height further increased the number of beneficial species (Webber, 2017). A study compared grass ground cover with six selected herb species areas in two wide belts along the tree rows in an apple orchard with herbicide-controlled areas. The study found that the diversity of heteropteran species (true bugs) was always higher on planted plots, six predatory species and 24 phytophagous species were found only on planted plots (Kinkorova and Kocourek, 2000).

<u>Intercropping</u>

Cabbage intercropped with white clover contained 32% more carabids than monocropped cabbage and cabbage undersown with clover had a greater diversity of carabid species compared with the control (Wiech and Wnuk, 1991; Booij *et al.*, 1997). Apple trees were interplanted with peaches bearing extrafloral nectaries, the peach trees were attractive to hymenoptera and hosted a greater abundance of hymenopteran parasitoids (Brown *et al.*, 2010).

Dense, year-round cover of clover vegetation provides adequate moisture and decaying organic matter to encourage earthworms, which help to improve soil structure (Burke *et al.*, 1998).

Soil micro, meso and macro fauna: Planting a companion crop of common vetch (*Vicia sativa* L.) between the rows of gala apples in Patagonia increased the population of bacterivore and herbivore soil nematodes from September to March compared with the control (Sanchez *et al.*, 2007). In this experiment the control treatment consisted of natural grass and legume vegetation with the soil disced twice in late winter, as is standard practice in Northern Patagonia (Sanchez *et al.*, 2007).

Allelopathic chemicals influence and are influenced by soil microorganisms as microbial degradation of allelochemicals requires specific microflora. In some cases, it is only the product of microbial degradation which is toxic to plants (Inderjit, 2005).

Non-target plants: Two living mulches of lady's mantle (*Alchemilla vulgaris)* and peppermint (*Mentha piperita)* were selected to suppress weeds and provide ground cover without competing with organic apple trees in Poland. Total weed coverage was significantly lower in the peppermint (26%) and Alchemilla (12%) plots compared to the control plots of mowed natural vegetation. The number of weed species present was 25% higher with the lady's mantle living mulch plots compared with control plots of mowed natural vegetation (Mia *et al.*, 2021).

Protected species: No evidence of positive biodiversity effects found.

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: Sikorska *et al.* (2019) found that management of field margins affected the population of Phytoseiid predatory mites The non-native grass margin was associated with a low number of mite species. The study concluded that management of the field margins only affected the population of mites in the field margin and the field edge to a limited extent, but mite diversity in the main crop was not affected (Sikorska *et al.*, 2019).

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: No evidence of negative biodiversity effects found.

Summary

Increasing the number of plant/crop species increases populations of beneficial and predatory species, due to a greater variation in food supplies. An increase in food sources generally results in an increase in predators. Plant biodiversity is also increased.

Table 17. Summary of the positive and negative impacts of cover crops etc. on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increases diversity, increases pollinators. Management of field margins can increase the number of predatory mites but only in the margin and field edge.	Less predatory mites in non-native grass margins.
Soil micro, meso and macro fauna	Increased numbers	-
Non-target plants	Increased biodiversity	-
Protected species	-	-

Recommendations for future work

- Research has shown that methods of companion cropping can benefit biodiversity. Further work should focus on optimising companion cropping practices with suitable species for enhancing biodiversity without also benefiting pest species. This will enable growers to have the confidence to adopt these practices.

- Further work is also needed on the effects on non-arthropods, soil organisms and plant species.

Soil amendments

Soil amendments such as green waste and mushroom compost, anaerobic digestate, biosolids, biochar and chitin are materials added to the soil to improve soil quality. Soil amendments can also include biological amendments such as mycorrhizal inoculation (Stockdale *et al.*, 2018).

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: Applications of cattle manure, cattle slurry and straw to brassica plots increased the number of carabid beetles including *Bembidion lampros* found in the current and following year, due to the increased availability of prey and subsequent breeding of beetles (Kromp, 1999).

Soil micro, meso and macro fauna: Compost amendments increased the population of bacteria in soil and caused a shift in the community to gram-positive bacteria and fungi and increased utilisation of complex substrates (Bernard *et al.*, 2012).

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Persistent herbicides such as picloram, clopyralid and aminopyralid have been found as residues in commercial compost and manure. Where contaminated straw or compost is applied these herbicide residues can have deleterious effects on non-target plants, including potential crops (WRAP, 2010).

Protected species: No evidence of negative biodiversity effects found.

Summary

Little research was found on the impact of soil amendments on biodiversity but there were benefits to beetles and bacterial communities and no observed negative effects except where amendments were contaminated with herbicides.

Table 18. Summary of the positive and negative impacts of soil amendments on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Increased carabids	-
Soil micro, meso and macro fauna	More diverse bacterial community	Slurry and manure application can lead to antibiotics in the soil that reduce diversity of microbial communities
Non-target plants	-	Possible presence of persistent herbicides
Protected species	-	-

Recommendations for future work

- More research is needed on the impact of both soil amendments and the potential impact of pollutants in soil amendments on biodiversity, particularly on non-arthropod or soil dwelling species.

Hygiene and pruning

Maintaining hygiene standards is an important aspect of cultural control in an IPM programme to limit spread of weeds, pests and diseases. In outdoor horticulture hygiene can be promoted by limiting the movement of infected or infested organic material. This can be achieved by visiting clean crops before afflicted crops and cleaning machinery or clothing to remove any contaminants. Removal of crop waste can help to prevent reoccurring infestations of pests such as carrots infested with carrot fly. Cultivations may be necessary to bury overwintered brassicas infested with aphids (see section 6.1 for the impact of cultivations on biodiversity).

In top fruit orchards pruning is a common practice. Removing excess growth particularly from the centre of the tree improves ventilation, sunlight penetration and access to predators, which in turn helps to suppress diseases, pests and improve ripening.

Benefits

Birds: Canopy thinning top fruit increases access for birds, to predate pest insects in the tree canopy such as aphids. Species of tits (*Paridae)* tend to feed on insects in apple and pear orchards (Shaw *et al.*, 2021).

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of positive biodiversity effects found.

Soil micro, meso and macro fauna: Rapid breakdown of fallen leaf litter is encouraged in apple orchards to reduce presence of apple scab and pear scab inoculum within leaves. Urea sprays can be applied in non-organic orchards to encourage microfloral degradation of leaf litter, which speeds up earthworm activity (Berrie and Cross, 2006).

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: No evidence of positive biodiversity effects found.

Negatives

Birds: Collecting unharvested fruit from the orchard floor helps to maintain crop hygiene and can reduce the population of codling moth in apples and pears. Bouvier *et al.*, (2020) found that the abundance of overwintering birds in south-eastern France, including 13 species of conservation concern was mainly driven by the quantity of unharvested fruit available. This suggests that disposing of unharvested fruit for pest control may negatively impact these birds. However, bird species diversity was primarily affected by the number of ivy bearing trees and seven species were significantly dependent on the number of ivy bearing trees; Blackcap (*Sylvia atricapilla)*, blue tit (*Parus caeruleus)*, Great tit (*Parus* *major)*, Robin (*Erithacus rubecula)*, Redwing (*Turdus iliacus)*, Blackbird (*Turdus merula)*, and Song thrush (*Turdus philomelos)* (Bouvier *et al.*, 2020).

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: No evidence of negative biodiversity effects found.

Summary

Maintaining hygiene standards is an important aspect of cultural control in an IPM programme to limit spread of weeds, pests and diseases. Little research was found on the impact of hygiene and pruning on biodiversity, but there were some positive and negative impacts reported on birds.

Table 19. Summary of the positive and negative impacts of hygiene and pruning on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Better access to prey species.	Reduced availability of unharvested fruit.
Invertebrates as prey species	-	-
Mammals	-	Reduced availability of unharvested fruit.
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	-	Reduced availability of unharvested fruit.
Soil micro, meso and macro fauna	Increased worm activity	Reduced availability of unharvested fruit.
Non-target plants	-	-
Protected species	-	-

Recommendations for future work

- Further work is needed to research the impact of hygiene and pruning practices on the biodiversity in orchards.

Physical protection of crops (crop covers, artificial shelters, barriers)

There are many types of crop cover used in UK horticulture predominantly to manipulate the crop environment to improve yields, extend the season and improve crop quality. For example, the use of temporary Spanish tunnels has markedly increased cherry cultivation (Huckle *et al.*, 2011). Some crop covers are used as an IPM technique to protect crops from insects and birds, such as fine mesh netting and fleeces. Fleeces are used to advance the crop, improve yields, and protect from frost and pests. (Huckle *et al.*, 2011). Netting is widely used to protect brassica crops from cabbage root fly and to protect cherries from birds (Huckle *et al.*, 2011). Fences made of wire, wood or electric fences are used to keep out mammals such as rabbits, badgers and deer. Straw and polythene can be used to protect carrots stored over winter *in situ* in the field.

There are many commercially available or home-made devices for encouraging natural enemies or deterring pests in an IPM programme, including paints applied to tree bark.

Fabric bands are tied around tree trunks in orchards to encourage populations of natural enemies particularly in young orchards, which lack developed bark and crevices (Shaw *et al.*, 2021). Bird scarers are often used in brassica crops to prevent birds from causing economic damage. They come in several forms. Some use a rotating disc or make a noise, such as a gas gun, to deter the birds.

Benefits

Birds: No evidence of positive biodiversity effects found.

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: Vertebrate pests such as rabbits, badgers, deer, rats, mice and voles can cause considerable damage to horticultural crops. Methods of control such as gassing, ferreting and shooting of rabbits can be replaced with fencing, although this is not fully effective (Hardy, 1990). Voles can be a major agricultural pest in Europe and one study in Switzerland found that a combination of fences and traps encouraged natural predators to patrol the traps and increased levels of predation (Fuelling *et al*., 2010). Water voles are protected in the UK under the Wildlife and Countryside Act 1981 and listed in Schedule 41 (NERC Act 2006), but fence and trap systems could be used for other rodents. A suitable cage-trap and baiting system has been developed to enable the safe release of non-target species (Hardy, 1990).

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: Artificial refuges are used in top fruit orchards to benefit populations of earwigs, the species most commonly found in orchards is *Forficula auricularia* which is a generalist predator of several orchard pests (Fountain and Brian, 2014). These devices provide daytime shelter and nesting sites for local populations of earwigs, which unusually for insects, care for their eggs and nymphs in nests (Staerkle and Kölliker, 2008). Provision of artificial earwig refuges can also provide habitat and improve overwintering survival of other invertebrates including anthocorids, coccinellids, and spiders from families such as *Araneidae, Clubionidae, Linyphiidae, Salticidae, Theridiidae*, and *Thomisidae* (Fountain *et al.,* 2020; Solomon *et al*., 1999).

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: No evidence of positive biodiversity effects found.

Protected species: Badgers and their setts are protected under the Protection of Badgers Act 1992 in England and Wales, unfortunately they can cause significant crop damage in field vegetables and orchards. Fences can be erected to exclude large mammals such as deer and badgers from at risk cropping areas, unelectrified fences offer minimal protection as a physical deterrent whereas electric fences alter the animal's behaviour (Poole *et al*., 2004).

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: No evidence of negative biodiversity effects found.

Summary

There are many types of crop cover used in UK horticulture predominantly to manipulate the crop environment to improve yields and extend the season and improve crop quality. No negative effects on biodiversity were found. Some positive effects for invertebrate were found. In other cases, physical exclusion of vertebrate pests can reduce the need for lethal control methods.

Table 20. Summary of the positive and negative impacts of physical protection on biodiversity in outdoor horticulture. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	-	-
Invertebrates as prey species	-	-
Mammals	Physical exclusion avoids the need for lethal control of vertebrate pests.	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Potential to increase earwig, spider, anthocorid, and coccinellid numbers.	-
Soil micro, meso and macro fauna	-	-
Non-target plants	-	-
Protected species	Badgers excluded from crops.	-

Recommendations for future work

- Further work could take a more detailed look into the effects of protecting horticulture crops.

GRASSLAND

In England in 2022 there was estimated to be over 9 million hectares of agricultural land in England of which 8.94 million hectares of utilised agricultural area. This includes an estimated 398,000 hectares of common rough grazing land, the vast majority being eligible for grazing but isn't necessarily grazed. There is an estimated 3.64 million hectares of permanent grassland in agricultural use and 785,529 hectares of temporary grass sown in the last five years (Defra, 2023a). Alongside management, soil type, geology and climate are key factors in influencing the species composition of both flora and fauna. Management such as cutting frequency, drainage regime, stocking rate, intensity of grazing and defoliation height, lime and fertiliser application can all result in changes to species diversity. In most cases, intensive grass production from semi-natural grasslands is incompatible with maintaining a high level of biodiversity (Plantureux *et al.*, 2005). UK grasslands have over 200 grass species within them and many more forbs – they are highly diverse – but have been classified as an example see https://nora.nerc.ac.uk/id/eprint/5980/1/13.pdf page 37 and the 2007 GIS dataset can be downloaded from CEH.

A recent survey (2017) on the uptake of IPM measures in grass and fodder crops was done in Scotland (Monie *et al*., 2017). IPM data was collected from 119 farmers, collectively growing 18,711 ha of crops (17,408 ha grass, 1,302 ha fodder). This sample represents eight per cent of Scotland's 2017 fodder crop area (15,965 ha) and 0.4 per cent of the grass area (4,453,540 ha). The survey showed that the majority of farmers (95%) did not have an IPM plan. An IPM plan is voluntary but helps growers assess their approach to IPM. The survey was split into three parts, risk management, pest monitoring and control.

The majority of growers (97%) implemented at least one risk management activity (Table 21). Soil testing was done by 84% of respondents, soils were tested for nutrients (76%) pH and lime requirement (19%) with less than 10% testing for pests (nematodes, leatherjackets and wheat bulb fly) or disease (clubroot). The majority of growers used the seedbed to improve crop performance and reduce pest risk through increasing organic matter (60%) or by changing their cultivations using rotational ploughing (20%), direct drilling (10%) or non-inversion tillage (6%) to control weeds, slugs and leatherjackets. A stale seedbed technique to reduce weed pressure was used by 6% of farmers.

Table 21. A summary of the positive responses to IPM risk management in grassland and fodder crops (taken from Monie *et al*, 2017).

Risk management strategy	Positive responses (%)
Crop rotation	65
Soil testing	84
Seedbed cultivations	82
Cultivations at sowing	48
Varietal or seed choice	51
Catch and cover cropping	9
Protection or enhancement of beneficial organisms	57

Ninety three percent of respondents implemented at least one pest monitoring measure (Table 22) with the majority monitoring and identifying pests, using a BASIS qualified agronomist (76%) and/or by themselves (45%).

For the control of pests, the majority of growers used non-chemical control either in combination with chemical control or alone (87%, Table 23). The most commonly used non-chemical control method was mowing or topping (76%) to control grass weeds, thistles, rushes, ragwort, nettles and docks. A further 10 per cent of grassland farmers used intensive grazing to control weeds. The uptake of mechanical control of insects was much lower, 2% rolling to control leatherjackets. Control of slugs and leather jackets in the seedbed is reported above.

Fifty-one per cent of the growers targeted their applications to reduce pesticide use. The most common methods reported were spot treatments (44%) predominantly for weed control, weed wiping, (14%) and reduction of dose rate or frequency of application (10%). Minimising pesticide use was also cited as part of a strategy to reduce the development of resistance.

A key part of IPM is monitoring of success and this was done by 82% of growers surveyed using reviews with their agronomist, self-inspection and monitoring of yield.

This survey indicates that some IPM measures are widely used in grassland or in rotations containing grassland.

Table 22. A summary of the positive responses to IPM pest monitoring in grassland and fodder crops (Taken from Monie *et al.*, 2017).

Pest monitoring activity	Positive responses (%)
Monitor and identify pests	93
Regular monitoring of crop growth stage	81
Setting action thresholds for crops	18
Use of specialist diagnostics	17

Table 23. A summary of positive responses to IPM pest control in grassland and fodder crops (taken from Monie *et al.*, 2017).

Pest control activity	Positive responses (%)
Non-chemical control used in partnership or instead of chemical control	87
Targeted pesticide application	51
Follow anti-resistance strategies	39
Monitor success of crop protection measures	82

Studies from Italy (Marini *et al.*, (2009) report that high fertilisation and cutting frequency created tall, species-poor plant communities. If a grassland is being managed for bird populations it may become a less favourable habitat for pollinators (Tanis *et al.*, 2020) and therefore a rotational cutting regime may be required to increase species diversity.

Cultivations

Newly sown leys (direct sown and undersown crops) and grassland less than five years old constitutes 16% of the total area of grassland in England (Defra, 2023a).

Reseeding is used to maintain productive swards and is done primarily because sward production falls due to the presence of weeds. An AHDB reseeding survey reported that the top five problematic weed species before reseeding were thistles (*Cirsium* spp., 36%), docks (*Rumex* spp.,26%), buttercups (*Ranunculus* spp.,15%), chickweed (*Stellaria media.*11%), and nettles (*Urtica* spp.,9%) (AHDB, 2016). Additionally, the mechanical action of cultivations can be used to reduce soil populations of leatherjackets (Blackshaw, 1988), chafers and wireworms. The pests are brought to the surface and eaten by birds. Cultivations also reduce soil moisture and thus reduce pest mobility and reproduction. The levels of disease inoculum of leaf blotch, mildew, crown rust and *Drecheslera* can also be reduced by ploughing. Rolling soils post drilling can minimise damage from leatherjackets and slugs.

For establishment, cultivation choice would depend on the previous crop or land use but is likely to include ploughing to ensure weed seeds and trash, and any applied organic manures are buried. For re-seeding cultivation choices could include direct drilling after spraying off the old sward with glyphosate, a minimal cultivation (one-pass cultivation) or ploughing with the aim of creating a good level seedbed to allow a consistent seed depth (AHDB, 2022b).

The benefits and negative effects of cultivations have been discussed in the arable section and are applicable to cultivations for grassland management (see section 6.1).

Crop rotation

Permanent grassland comprised 40% of the utilised agricultural area in England with common rough grazing 4% and temporary grassland 9% (Defra, 2023a). This indicates that the majority of UK grassland does not form part of a rotation, due to factors such as topography, altitude, soil/geology, and climate.

Studies by Lemaire *et al.,* (2015) showed that integrated crop and livestock systems are a positive strategy to enhance diversity. The specific management of each system will vary and bring their own environmental impacts but using rotation as an IPM technique favours species diversity. Robinson *et al*., (2001) discussed the negative impact of having homogeneous landscapes on certain bird species and that the inclusion of 'pockets' of arable land within a grassland landscape and vice versa would positively benefit bird populations.

For additional information see section 6.2. Information specific to grassland is reported below.

Benefits

Birds: A mixed farming system consisting of both grassland and arable crops brings more habitat diversity and favours bird populations (Boatman *et al*., 2007). Studies have shown the benefit of having arable crops within any type of grassland landscape for bird species such as the skylark (*A. arvensis*), corn bunting (*M. calandra*) and grey partridge (*P. perdix*), which are subject to local decline if suitable habitats are not present (Robinson *et al*., 2001). The decline in the numbers of seed-eating birds in the western areas of the UK which occurred during the 1980's and 90's, may have been influenced by loss in habitat diversity and a decline in the amount of arable cultivation (Robinson *et al*., 2001). Agri-environment schemes from the late 1990's have helped to address this issue and encourage habitat diversity to support these species. For example, the importance of over-winter stubbles has been clearly demonstrated for the cirl bunting (*E. cirlus*), the UK population of which had fallen to 118 pairs in 1989, largely concentrated in south-west England. Provision of weedy stubble habitat through agri-environment schemes increased cirl bunting numbers to about 500 pairs in less than 10 years (Aebischer, Green & Evans 2000) but by 2016 had reached over 1000 pairs - https://www.rspb.org.uk/birds-and-wildlife/wildlife-guides/bird-a-z/cirl-bunting/.

Invertebrates as prey species: Grassland is a natural habitat for a wide range of invertebrates and they are the main diversity of animal life in grassland (Barnett *et al.*, 2016). Grassland systems are generally viewed as less detrimental ecologically than arable systems and the lack of disturbance compared to arable systems will increase invertebrate species of many species from frit fly, wireworms and leatherjackets.

Redhead *et al* (2020) modelled responses of insect groups to different agricultural land cover in Great Britain. This showed the restoration of grassland was generally beneficial for pollinators and natural enemies, with individual hectads having up to 22% increase in pollinators and 10% increase in natural enemies.

Mammals: In a review of 77 papers from 12 European countries, areas with large tracts of grassland were shown to be negatively associated with hares compared to arable areas (Smith *et al.*, 2005). The likelihood of seeing hares improved on pastural farms if improved grassland, woodland or in some cases arable land was present (Vaughan *et al.*, 2003).

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: A six-year study by Hoeffner *et al*., (2021) compared a rotation of three-years grassland, then three further years of arable crops to six years of fertilised grassland. Overall, they concluded that a three-year grass ley has a positive effect on earthworm abundance, biomass and diversity and is more productive in terms of forage than a six-year fertilised grassland ley.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: Introduction of a herbal ley into an all grassland rotation can be an opportunity to incorporate perennial forbs and legumes into pasture swards, including chicory (*Cichorium intybus*), bird's foot trefoils (*L. corniculatus* and L*otus pedunculatus*), lucerne (*Medicago sativa*), plantain (*P. lanceolata*), sainfoin (*Onobrychis viciifolia*), sulla (*Hedysarum coronarium*) and yarrow (*A. millefolium*) with the aim of benefiting from certain properties of these species for both the livestock and increased biodiversity (Jordon *et al*., 2022).

The decline of an arable seedbank under a grass-sward was monitored over a period of twenty years by Chancellor (1986). He concluded that planting a weedy arable field to grass for twenty years was insufficient to eradicate the seeds of even the most rapidly declining species.

Protected species: See Robinson *et al*., 2001 and Aebischer, Green & Evans (2000) in the birds section for the use of agri-environment schemes and integrating arable fields within grassland landscapes for benefitting skylark, corn bunting, cirl bunting, and grey partridge populations.

See Smith *et al* (2005) and Vaughan *et al* (2003) for evidence of positive impacts of crop rotation on hares.

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: Conversion of pasture into arable fields, if associated with loss of cattle ponds has been shown to adversely affect the dispersal and population of amphibians (Piha *et al.*, 2007; Janin *et al.* 2009; Curado *et al.* 2011).

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: No evidence of negative biodiversity effects found.

Protected species: See Piha *et al.* 2007; Janin *et al.* 2009; Curado *et al.* 2011 cited in the amphibians section for potential adverse effects of toads and other amphibians if loss of ponds were to occur when converting pasture into arable fields.

Summary

A varied rotation provides a wide range of habitats and food sources but is only appropriate for temporary grassland. Permanent pasture, by definition, is unlikely to be included in a rotation. A varied rotation alone is not enough to support a wide range of biodiversity, additional non-crop areas such as margins, hedgerows and woodland are necessary to provide year-round opportunities for food and shelter. Care must be taken to carefully select sites when introducing arable crops into predominantly grassland areas due to potential loss of habitats. The value of herbal leys has been shown to introduce a greater range of perennial forbs and legumes to the rotation. Establishment of a grass sward that is maintained as a monoculture will lead to a reduction in forb diversity.

Table 24. Summary of the positive and negative impacts of crop rotation on biodiversity in grassland. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Mixed farming systems increase habitat diversity therefore favouring bird populations.	-
Invertebrates as prey species	-Grassland with its lesser disturbance is less detrimental than arable.	-
Mammals	Rotations Increase habitat diversity	-
Fish	-	-
Amphibians	-	Amphibian dispersal and populations can be negatively affected where pasture is converted to arable if associated with loss of ponds.
Reptiles	-	-
Arthropods, annelids, molluscs	Leys are beneficial to earthworm population and diversity as long as good soil structure is maintained	-
Soil micro, meso and macro fauna	-	-
Non-target plants	Offers opportunities to introduce more species into the mix. Arable weed seed abundance declines under grassland but wouldn't eradicate even rapidly declining species	-
Protected species	Mixed farming systems increase habitat diversity therefore favouring bird populations	Amphibian dispersal and populations can be negatively affected where pasture is converted to arable due to loss of ponds

Recommendations for future work

Research on rotations requires large areas of land over spans of many years. It is difficult to tease out the individual factors contributing to the whole picture as has been shown by the previous work done in the main IPM projects (Section 4).

Monitoring of crops, DSS, forecasting and pest thresholds

A full description of these techniques is available in arable section 6.4.

A literature review uncovered no current DSS used specifically against insect pests or disease in grasslands. Blackshaw (2009) showed the potential benefits of simulation modelling for leatherjacket populations (*Tipula* spp.) but this was not developed further.

The IPM decisions project (IPM decisions, 2020) identified one DSS for grassland for the control of wild-oat, broad-leaved weeds, docks, thistle and barren brome, this is available as the Corteva forage app (Corteva, 2022). A DSS for calculating the effect of mowing and grazing regimes on biodiversity for agri-environment schemes (DSS-Ecopay[11]) was developed (Sturm *et al*., 2018). This system captured ecological and economic input data and used an ecological model for calculating the effect of mowing regimes, grazing regimes and combinations of mowing and grazing regimes on endangered birds, butterflies and habitat types.

Monitoring in grasslands, as in arable cropping, is a robust tool for identifying management successes and areas where management practices are having a detrimental impact on biodiversity. Research using monitoring can identify the value of landscape elements for biodiversity in agricultural systems. This can be used to identify management strategies that may be detrimental and adjust accordingly. For example, the monitoring of orthoptera (grasshoppers, leafhoppers and crickets) in Sweden identified areas that were previously believed to be of low value to these insects and highlighted the value of maintaining their presence as part of the landscape (Riggi & Berggren, 2020). It is good practise to determine pest levels before deciding on whether control measures are necessary, so monitoring is very important (Petroskii *et al*., 2014). Examples of pest monitoring exclusively in grasslands could not be found, more often monitoring is used to assess the effects of management on beneficial organisms and wider biodiversity (McCravy, 2018.; Berg *et al*., 2019).

The benefits and negative effects have been discussed in the arable section and some are applicable to grassland management (see section 6.4).

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[11] http://www.inf.fu-berlin.de/DSS-Ecopay/kontakt_eng.html

Precision application

Precision application has been defined in arable section 6.7. The main research evaluates the efficacy of the technology in detecting weeds. Spot-spraying has been shown to reduce herbicide usage by 60-66% (Power *et al.,* 2013; Kömives *et al*., 2016) and the use of other precision application techniques would reduce pesticide usage compared to standard application techniques.

Trial work in grassland showed automated spot-spraying had fewer negative effects on non-target organisms than traditional application techniques. The majority of blanket and manual application techniques reduced non-target plant diversity compared to the untreated control. The automated spot-spraying treatments (glyphosate, aminopyralid + fluroxypyr, triclopyr + fluroxypyr) did not reduce plant diversity or richness with the exception of the triclopyr + fluroxypyr treatment (Power *et al*., 2013).

Weed wiping is commonly used to target weeds in grassland. It can be useful where reseeding is difficult due to soil type, topography or where the field is in an environmentally sensitive area. For safe application, weeds should be a minimum of 10 cm above the height of the crop. Weeds not touched by the herbicide will not be controlled, and two passes in opposite directions may be needed where weeds are dense. Weed-wipers can manage rushes more efficiently than conventional boom sprayers using less chemical with a dramatic reduction in spray drift and minimal runoff to watercourses (AHDB, 2013). Currently only glyphosate is authorised for use for weed-wiping in the UK, but in New Zealand and Canada metsulfuron, clopyralid, triclopyr and picloram have been trialled (Harrington & Ghanizadeh, 2017). Weed wipers are also used for controlling bracken, either on ATV or tractor mounted rotating pressurised systems (Natural England, 1999 and 2008). There are examples of several water companies, including Welsh water (2018) and Northern Ireland Water (2018), offering to hire weed wipers to farmers for free to reduce the amount of pesticides reaching water and their impact in sensitive areas.

Some of the biodiversity impacts outlined in the arable section would also apply to precision application techniques in grassland.

Summary

Most research evaluates the efficacy of detection technologies and the reduction of pesticide usage rather than the effect this would have on biodiversity.

Recommendations for future work

Precision application is a rapidly developing area and could be developed in line with biodiversity aspirations. Research from work on the wider implications of reduced pesticide usage could be used to determine the impact of these developing technologies on biodiversity. Increasing the range of herbicides that could be put through a weed wiper would increase the versatility of this tool.

Varietal choice and diverse seed mixtures

Woodcock *et al.* (2012,2013 and 2014) found plant species-rich swards had a higher diversity of phytophagous and predatory beetles, spiders, bees, butterflies and hoverflies than species-poor grassland. The addition of forbs helped to maintain biodiversity as the legumes declined rapidly. The use of diverse species herbal leys comprising grasses, legumes and other forbs can, depending on management technique, increase resources for pollinators and therefore improve biodiversity of birds and insects as outlined in Sections 6.3 and 6.10. Adding plant species to grassland can increase yield as well as biodiversity in low intensity grasslands (Bullock., 2020). A long-term study on non-fertilised restored grasslands found grassland with 11 grasses and 28 forbs had 43% higher hay yield on average than grassland with just seven grass species (Bullock *et al*, 2007).

Benefits

Birds: Diverse seed mixtures are beneficial compared to dense, uniform, more homogenous grass swards, where fewer bird numbers and a smaller range of bird species can nest and forage (Wilson *et al* 2005).

Invertebrates as prey species: No evidence of positive biodiversity effects found.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: The presence of legume species increased the total density of springtails (*Collembola, Symphypleona, Neelipleona* and *Isotomidae*) in experimental grassland studies in Switzerland. The results indicated that microbivorous soil invertebrates are controlled by food quality not food quantity (Salamon *et al*., 2004).

Woodcock *et al* (2012, 2013 and 2014) found plant species-rich swards had a higher diversity of phytophagous and predatory beetles, spiders, bees, butterflies and hoverflies than species-poor grassland. The addition of forbs - yarrow (*A. millefolium)*, black knapweed (*C. nigra)*, chicory (*Cichorium intybus),* oxeye daisy *(L. vulgare),* sorrel *(R. acetosa) and* salad burnet *(Sanguisorba minor)* helped to maintain biodiversity as the legumes; bird's foot trefoil (*L. corniculatus),* clovers *(trifolium dubium, T. hybridium, T. pratense and T. repens*) declined rapidly once sown under a cutting regime.

Different field margin management strategies were tested with the aim of putting bumblebee and butterfly biodiversity back into intensive grasslands. Seven grass-based treatments; conventional silage management, unfertilized, raised mowing height, no aftermath grazing, single early cut, single late cut, no summer disturbance, and two sown mixtures; undersown spring cereal with grass and legumes and a diverse conservation mix with kale, mixed cereals, linseed and legumes were tested. Bumblebees were most abundant, species-rich and diverse in the sown treatments and virtually absent from the grass-based treatments. The diverse conservation mix treatment supported larger and more diverse bumblebee assemblages than the cereal, grass and legume mix treatment. The sown treatments, and the most extensively managed grass-based treatments, had the highest abundance, species richness and diversity of adult butterflies, whereas butterfly larvae were only found in the grass-based treatments (Potts *et al.*, 2009). The authors noted that extensification of conventional grass management by stopping fertilisation, reducing cutting frequency and not grazing, benefits butterflies. However, to enhance bumblebees requires a more interventionist approach in the form of sowing flower-rich habitat (Potts *et al.*, 2009).

Newly established grasslands with diverse seed mixtures were found to be more attractive to bees, bumblebees and hoverflies than legume-grass mixtures in comparisons in Austria (Brandl *et al.,* 2022).

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: A comparison of low diversity and high diversity seed mixtures, sown on ex-arable land, has indicated that higher plant diversity gave higher productivity and better weed suppression (Van der Putten *et al*., 2000), although this result was dependent on individual species within the grass and herb mixtures.

There is also experimental evidence that more diverse grassland is less susceptible to invasion by invasive weeds, although this effect is often obscured by extrinsic factors (Naeem *et al*., 2000).

The sowing of yellow rattle (*Rhinanthus minor*), a hemiparasite on grass, to restore traditional hay meadows helps reduce the competition from grass, enhancing the effectiveness of increasing plant diversity (Pywell *et al*., 2004; Bullock and Pywell, 2005)

Protected species: See Potts *et al.,* (2009) and Brandl *et al., (*2022) in the arthropods section for the positive effects of diverse seed mixtures and flower rich habitats for bumblebee populations.

Negatives

Birds: No evidence of negative biodiversity effects found.

Invertebrates as prey species: No evidence of negative biodiversity effects found.

Mammals: No evidence of negative biodiversity effects found.

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of negative biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Field experiments involving four grassland species; perennial ryegrass (*Lolium perenne), cocksfoot (*Dactylis glomerata), *red clover (*Trifolium pratense) and white clover (*Trifolium repens)* were grown in both monocultures and mixtures. The invasion of unsown species was reduced by the diverse species mix compared to the monocultures. However, species identity was important. Cocksfoot and white clover suppressed unsown species whilst red clover was the least suppressive variety (Frankow-Lindberg *et al*. 2009).

Protected species: No evidence of negative biodiversity effects found.

Summary

Species rich swards can help to suppress weeds and increase invertebrates and bird diversity by diversifying sward structure. The addition of non-leguminous flowering plants in mixtures will help to increase population numbers and species diversity of bumblebees.

Table 25. Summary of the positive and negative impacts of varietal choice and diverse species mixtures on biodiversity in grassland. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Fewer bird numbers and species can nest and forage in more homogenous grass swards	-
Invertebrates as prey species	-	-
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	The presence of legume species increase microbivorous soil invertebrates. Species-rich swards have higher diversity of invertebrates.	-

Category	Positive	Negative
	Bumblebees and butterflies favour flower rich and diverse species mixtures.	
Soil micro, meso and macro fauna	-	-
Non-target plants	Yellow rattle can help to enhance plant diversity when restoring traditional hay meadows	Vigorous species can reduce plant diversity
Protected species	Bumblebees favour diverse and flower rich seed mixtures	-

Recommendations for future work

There is plenty of available research work documenting the positive impacts of diverse species mixtures in grassland, as an integrated crop management practice. Evidence of efficacy as an integrated pest management practice is limited. No information was found on the effects of the increased root structure and variety of species rich swards on soil biodiversity.

Mowing and topping

Mowing and topping are key IPM methods for managing weeds in grassland. For semi-natural hay meadows maintenance of their conservation value is dependant, in part, in cutting for hay (Natural England, 1999). The timing of the cutting maintains the grassland communities of flora and fauna, limits the establishment of undesirable species and prevents the establishment of shrubs and trees.

The conservation benefits of mowing and cutting are different to grazing and can be used as an alternative management method of plant species (Natural England, 1999).

Weed surfer methods could be used for all taller weed species. Topping before plants can flower and set seed helps control thistles, docks, buttercups, bracken and nettles.

Cutting would need to be incorporated into an integrated weed management (IWM) system to achieve the best overall weed control. However, it is effective for reducing the energy stored within tubers and rhizomes and limiting the spread by seed, which could increase the success of other alternative methods of weed control e.g. electrical and manual removal, especially where non-chemical options are required.

Benefits

Birds: Manipulating sward height can favour different species. Boatman *et al.*, (2007) reported that sward height favours different bird species, where taller swards encourage higher numbers of cranefly larvae as a food source, but shorter swards favour aerial hunters such as kestrels (*Falco tinnunculus*).

Invertebrates as prey species: Studies by Humbert *et al.*, (2012) showed that by delaying the spring (May-June) cutting until summer (July-September) increased invertebrate diversity, but not always abundance. If it is not possible to delay cutting on a field scale it was shown that even the creation of smaller areas (mosaics) of different cutting regimes favoured a wider range of species.

Mammals: No evidence of positive biodiversity effects found.

Fish: No evidence of positive biodiversity effects found.

Amphibians: No evidence of positive biodiversity effects found.

Reptiles: No evidence of positive biodiversity effects found.

Arthropods, annelids and molluscs: No evidence of positive biodiversity effects found.

Soil micro, meso and macro fauna: No evidence of positive biodiversity effects found.

Non-target plants: Plant species diversity increases by delaying the first grass cut until summer instead of cutting in the spring (Humbert *et al.*, 2012).

Timing cuts in hay meadows can be used to increase populations of desirable plant species such as yellow rattle (*Rhinanthus minor*). Meadows are cut after the seeds have ripened. (Natural England, 1999).

A long-term experiment investigating the long term effects of cutting chalk grassland showed uncut plots had significantly fewer plant species compared to the cut plots after seven years. No significant differences were seen in the number of species in plots cut once, twice or three times a year (Terry *et al.,* 1993).

Two years of scrub clearance and hay mowing doubled the floristic species richness on grassy verges (Gardiner and Vaughan, 2009). Plants that benefitted from this management included black knapweed (*Centaurea nigra), hairy St. John's wort (Hypericum hirsutum*) and primrose (*Primula vulgaris*).

Management of semi-natural grasslands requires the maintenance of a low supply of specific soil nutrients, such as phosphate and potassium. Low soil phosphorus availability seems to be a key factor in maintaining high species richness in grasslands (Tallowin, 1997). Mowing and the removal of cuttings can remove biomass from dominant species, reducing soil nutrients to increase species diversity (Crawley, 1983 and Bakker, 1989 cited in Simpson *and* Jefferson. 1996).

Protected species: Some butterfly species require very specific habitats and plants to lay eggs successfully. This includes the Duke of Burgundy butterfly (*Hamearis lucina*) which requires primrose species (*Primula spp.)* in chalk grassland to survive. A study over a 14-year period by Hayes *et al.*, (2021) concluded that the grassland must be maintained by cutting and keeping scrub clear to ensure the correct habitat for both *Primula* and butterfly.

Negatives

Birds: Increase cutting frequency and timing can result in a loss of food source for birds, such as cranefly larvae (Tipulidae) (Boatman *et al*., 2007).

Singing skylark density was lower after mowing in May-June (Wakeham-Dawson *et al*., 1998).

Cutting prior to hatching of chicks can reduce populations of waders and wildfowl (Natural England, 1999).

Field bird populations such as curlew, black-tailed godwit, lapwing or harrier are the victims of significant losses due to mowers and tractor wheels (CIC, 2011).

Invertebrates as prey species: The cutting of grass can result in species-specific effects tending to cause more death and emigration of generalist arthropod predators such as spiders (Thorbek and Bilde (2004). The timing of cutting and whether the grass is then removed will result in different levels of species decline.

Mammals: Following mowing of grassland, the home-range size for common voles was reported to decrease by up to 74% (Jacob and Hempel, 2003) this was thought to be due to a reduction in cover which exposes small mammals to increased predation risk (Sheffield *et al.* 2001).

Mowing or topping grass may be detrimental for leverets or hares depending on the timing of cutting (Boatman *et al*., 2007). When making a cut for silage the best advice it to cut a field from the centre outwards to allow the hares to escape the machinery into neighbouring field or not cut marginal areas (GWCT Factsheet 2022a).

Leverets, fawns and various field birds, small mammals, amphibians and insects fall victim to the practice of early and more frequent mowing. (CIC, 2011).

Fish: No evidence of negative biodiversity effects found.

Amphibians: No evidence of negative biodiversity effects found.

Reptiles: No evidence of negative biodiversity effects found**.**

Arthropods, annelids and molluscs: Cutting grass is generally considered undesirable for arthropods, however these effects can be mitigated by the creation and management of refuge areas within and adjacent to fields (Thorbek and Bilde (2004).

High fertilisation and cutting frequency created tall, species-poor plant communities resulting in reduced orthopteran (grasshoppers & crickets) diversity by providing an unsuitable sward structure, and reduced butterfly diversity by creating disturbed plant communities with low species richness and abundance of flowering forbs and host plants. (Marini *et al.*, (2009).

Mowing of grasses shortens the plant and removes the flower head, leading to a reduced abundance of beetles (*Coleoptera*) and hoverflies (*Syrphidae*) that are sensitive to vegetation height. However, there are arthropod species (e.g., long-legged flies (*Dolichopodidae)* that are less sensitive to changes in vegetation height or other disturbances caused by harvest. This indicates that when mowing grasses, the height of harvest can impact some arthropods but not all (Lee *et al.*, 2018). Maintenance of similar cutting or grazing regimes (height, timing) prior to designation is critical on many nature reserves to aid the desired forbs and/or invertebrates.

Bee species richness and abundance decreased with increasing number of mechanical operations such as cutting (Luscher *et al.*, 2015).

Four lowland farms with a predominance of improved grasslands that were classified as species-poor perennial ryegrass (*Lolium perenne*) were used to test a range of field margin management techniques (Blake *et al.*, 2011). The experimental plots also contained common bent (*Agrostis capillaris*), Yorkshire fog (*Holcus lanatus*), white clover (*Trifolium repens*) and creeping buttercup (*Ranunculus repens*). Conventional management practices (inorganic fertiliser, cutting frequency and height, and aftermath grazing) were manipulated to create seven treatments along a gradient of decreasing management intensity and increasing sward architectural complexity. Leaf hopper and plant hopper (*Auchenorrhyncha*) abundance and species richness was highest in the most extensively managed treatments, either unmanaged, a single silage cut in May or a hay cut in July. Abundance was lowest with frequent grass cutting, while species richness was lowest where cattle grazing occurred.

Arthropods (insects and spiders) were sampled on 142 grassland plots in three regions in Germany, which were managed with different ways (mowing, fertilisation and/or grazing) and intensities of land use. Increasing fertilisation and grazing intensity increased the decay rate of all taxa, while increasing mowing frequency significantly affected the decay rate only in interaction with fertilisation (Simons *et al*., 2015). The authors concluded that increased land use intensity favoured the dominance of the most abundant species. Dominance generally increased with increasing fertilisation and rarity decreased with increasing grazing or mowing intensity.

Soil micro, meso and macro fauna: No evidence of negative biodiversity effects found.

Non-target plants: Rare plant species richness decreased with mechanical operations (Luscher *et al.*, 2015). However, some species persist under mowing and in semi natural hay meadows. See (Gardiner and Vaughan, 2009) in the positive effects section.

Protected species: See Wakeham-Dawson *et al*., 1998 in the birds section for the negative effects of mowing on skylark density and CIC (2011) for the effects of mowing on lapwing and curlew populations.

See Boatman *et al.,* (2007) and GWCT Factsheet (2022a) for best practise advice and the effects of cutting time on hare populations.

Summary

Generally mowing and topping tends to be detrimental to biodiversity. Reducing cutting frequency and timing cuts can be used to manipulate plant communities, from an IPM and conservation management perspective. Geographic location and local species must be considered in conservation management plans to achieve the best balance to improve biodiversity.

Table 26. Summary of the positive and negative impacts of mowing and topping on biodiversity in grassland. Note: some cells have been deliberately left blank.

Category	Positive	Negative
Birds	Low swards can favour aerial hunting birds.	Increased and / or early cutting can result in reduced food source. Early cutting can impact nesting waders and wildfowl.
Invertebrates as prey species	Delaying cutting can improve diversity but not abundance. Creating small areas of different cutting regimes favour a wider range of species.	Cutting can result in decline and emigration of generalist arthropod predators such as spiders.
Mammals	-	Reduces cover for small mammals increasing the risk of predation. Cutting from the centre of the field outwards gives hares the best chance of escaping machinery.
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Grass cutting, especially below 12.5cm, is generally undesirable for arthropods. Creation of refuge areas in and adjacent to fields and cutting later will reduce the impact.	Cutting reduces, bee, beetle and hoverfly numbers but some arthropod species are less sensitive to a change in vegetation height. Tall swards can reduce orthopteran and butterfly diversity.
Soil micro, meso and macro fauna	-	-
Non-target plants	Managing the timing of cuts can be used to manipulate species diversity	Diversity of rare plant species can decrease with mechanical operations, however some species persist under mowing and in semi natural hay meadows
Protected species	Can be specifically managed for protected species	Cutting from the centre of the field outwards gives hares the best chance of escaping machinery

Recommendations for future work

There is a wide range of research information on cutting operations and timings.

Grazing management

Grazing can be used to manage weeds in an IPM system whilst providing habitat for dung beetles and other invertebrates. Animals grazing pasture can influence weeds either directly, by eating or damaging them, or indirectly, by 'conditioning' the pasture and making it more competitive and resistant to subsequent weed invasion. The effect on the grassland is influenced by the type of animal and plant species present for example, horses and cattle are selective grazers, avoiding certain weed species, sheep graze more evenly (Popay & Field, 1996). Choice of animal species can be combined with timing to manage weeds particularly during the establishment of grass leys. Grazing with young cattle which are not selective feeders soon after establishment can reduce the first flush of weeds AHDB (2015). Grazing pastures before winter will reduce winter kill and reduce the number of bare patches. But pastures can be overgrazed, reducing competitiveness of grasses and causing poaching allowing undesirable species such as docks, ragwort or thistles to establish; although having some bare soil is beneficial to some invertebrates, including some dung beetle species.

Grazing has value for conservation management and increased biodiversity through creation of gaps to allow recruitment of new individuals, selective control of more palatable species and creates patchiness and structure of vegetation amongst other benefits (Natural England, 1999). Weiss *et al* (2013) suggest that grazing is more suitable for maintaining a high biodiversity in calcareous grassland than mowing.

The use of rare native breeds such as Exmoor, Dartmoor, Fell, Highland and Eriskay ponies or the Polish Konik Pony is a well-established method of conservation grazing for rewilding purposes with increased benefits to biodiversity (Wildlife and Countryside Link, 2020). Equines are selective grazers, creating vegetation mosaics with shortly grazed patches interspersed with areas of undisturbed vegetation, and they can be useful for slowing down scrub encroachment through browsing.

The increased presence of ponies in the vicinity of the salt blocks increased the percentage occurrence of bare ground, reduced sward surface height, reduced percentage occurrence of purple moor grass (*Molina*) and increased the germination of heather (*Calluna vulgaris*) seedlings. Through grazing and trampling, ponies can reduce the dominance of Molinia, leading to an increase in the germination and establishment of heather seedlings (Lunt *et al*., 2021).

Mob grazing with cattle using electric fencing can be used as a technique for bracken management.

Fencing off watercourses is usually done for water quality benefit by preventing livestock access. From an IPM perspective fencing can also allow a managed amount of ragwort to grow providing biodiversity benefit while the grazed or conserved part of the field is, ideally, hand rogued to comply with ragwort legislation and to ensure livestock health is not adversely impacted.

There are a wide variety of different types of grassland, divided into upland and lowland. Both upland and lowland grassland can be calcareous, acidic or neutral and can be classified as:

- Improved grassland –High input, intensively managed for high yielding grass. Typically, fewer plant species present
- Semi-improved grassland – Grassland modified through previous agricultural management. Less intense use of inputs and wider range of species present
- Unimproved grassland – Never improved for agricultural production. Most species rich grasslands are in this category

Management techniques will vary depending on the type of grassland and the species present. The evidence in this section is grouped into broad management techniques. This gives a brief overview of a wide-ranging topic.

Reduced grazing intensity

Birds: Singing skylarks were six times more abundant and non-singing skylarks twice as abundant in long-grazed (15-25cm) fields than short-grazed fields (10cm). Fields were surveyed during the skylark breeding season in experiments carried out over 12 fields (5ha each) between 1995-96 **(**Wakeham-Dawson *et al* (1998).

Arthropods, annelids and molluscs: Different frequency and height of grazing were found to change spider numbers and species (Gibson *et al.*, 1992). Over grazing of heavily grazed areas favoured *Linyphiidae*. Large web-spinner spiders preferred the rigid grasses of less disturbed areas.

The number of taxa and total number of chick-food invertebrates were about twice as large in long-grazed fields than in short-grazed fields in experiments carried out over 12 fields (5ha each) between 1995-96. Ungrazed areas (swards up to 40cm tall) had over five times the number of invertebrates and over three times the number of invertebrate taxa as grazed areas (sward <2cm tall). **(**Wakeham-Dawson *et al* (1998).

Studies of different sheep grazing intensities on semi-natural calcareous grassland in Belgium and the Netherlands found nest volume and caterpillar survival of the Glanville fritillary (*Melitaea cinxia)* were 50% lower on the high intensity grazed treatments compared to the ungrazed and low intensity grazed treatments (Van Noordwiijk *et al.*, 2012). The study concluded that grazing intensity will likely have similar effects on other invertebrates and the impact of grazing depends on the timing in relation to the lifecycle of individual species.

Improved high input grassland

In a study in thirteen areas of upland Britain between 1968-80 and 2000, improved grassland either reseeded or receiving regular annual applications of fertiliser to promote a dense, uniform monoculture of ryegrass were associated with increase of wood pigeon (*Columba palumbus*), pied wagtail (*Motacilla alba*), carrion crow (*Corvus coreone*), jackdaw (*C. monedula*) and goldfinch (*Carduelis carduelis*) probably due to their less specialised habitat requirements (Henderson *et al*., 2004).

A three-year study in Norway found no difference in population growth rates between different grazing intensities in field scabious (*Knautia arvensis)* populations in semi-natural grassland (Johansen *et al*., 2016).

In a study in thirteen areas of upland Britain between 1968-80 and 2000, improved grassland either reseeded or receiving regular annual applications of fertiliser to promote a dense, uniform monoculture of ryegrass were attributed to the decline of grey partridge (*P. perdix*), snipe (*Gallinago gallinago*), redshank (*Tringa totanus*), skylark (*A. arvensis*), meadow pipit (*Anthus pratensis*) yellow wagtail (*Motacillus flava*), dipper (*Cinclus cinclus*), whinchat (*Saxicola rubetra*), wheatear (*Oenanthe oenanthe*), ring ouzel (*Turdus torquatus*), goldfinch (*Carduelis cannabina*), reed bunting (*E. schoeniclus*) and yellowhammer (*E. citrinella*) by over 67% (Henderson *et al*., 2004).

An experiment on Tadham/Talham Moors in Somerset demonstrated the use of inorganic fertiliser inputs caused the loss of botanical diversity on hay meadows. Once botanical loss from fertiliser use has occurred the diversity does not recover, even if fertiliser inputs stop and traditional management is reinstated (Natural England, 1993a)

Grazing intensity

High intensity grazing in this section implies long duration intense grazing with short grass recovery periods keeping sward heights low.

Baines (1996) reported that black grouse (*Tetrao tetrix*) numbers had declined due to increased stocking densities which reduce the sward height and diversity of plant populations. Newton (2004) also reported that the kestrel and barn owl (*Tyto alba*) had declined in numbers due to overgrazing of rough grassland which supports their principal prey species the field vole

Arthropods (insects and spiders) were sampled in 142 grassland plots in three regions in Germany, which were managed with different modes (mowing, fertilization and/or grazing) and intensities of land use. Increasing grazing intensity increased the decay rate of all taxa (Simons *et al*., 2015).

High intensity grazing results in a lower number of grasshoppers and butterflies, compared to low intensity grazing (Wallis De Vries *et al.*, 2007).

Intensive grazing reduces botanical diversity and favours a select few competitive species that can tolerate grazing such as perennial ryegrass (*Lolium perenne),* Rough stalk meadow grass *(Poa trivialis)* and white clover (*Trifolium repens)* as well as plants avoided by grazing animals such as thistles (*Cirsium spp)* (Vickery *et al*., 2001). Sheep and horses tend to avoid these species more than cattle (Natural England, 1993b).

Grazing timings

Goodenough and Sharp (2016) found autumn and winter grazing intensity are positively associated with primrose (*Primula spp.)* abundance on calcareous grassland. *Primula* is the sole larval host plant for The Duke of Burgundy butterfly (*Hamearis Lucina)*. From studies they recommend moderately high grazing intensity during autumn with a free roaming system, rather than rotational grazing, with reduced grazing intensity or grazing removal in winter. Other butterfly host plants such as bird's foot trefoil (*L. corniculatus)* also benefitted. This plant is the host for the dingy skipper (*Erynnis tages)*, green hairstreak (*Callophrys rubi*), chalkhill blue (*Polyommatus coridon*), common blue (*Polyommatus icarus*), and silver-studded blue (*Plebejus arguslarval*).

Heteroptera (true bugs) are reduced by spring grazing but increased by autumn grazing (Brown, Gibson and Sterling 1990 cited by Vickery *et al*., 2001).

Summary

Grazing can be used to manipulate weeds or undesirable species in grassland. Subtle changes can be made to grassland area through the choice of animal species used through selective feeding, timing of grazing in relation to developmental stage of the crop and weed and density of stocking. High intensity grazing and overgrazing reduce biodiversity in grassland. Timing of grazing in relation to a species lifecycle influences impacts either positively or negatively on a species. Types of regenerative grazing using a high stocking density, frequently moved with long resting periods between grazing, result in positive impacts on biodiversity.

Table 27. Summary of the impacts of grazing management on biodiversity in grassland. Note: some cells have been deliberately left blank.

Category	Reduced intensity grassland	Intensive grassland
Birds	Tall grass favour skylarks. Improved grassland favours species with less specialised habitat requirements. such as wood pigeon and carrion crow.	Increased stocking density and overgrazing reduce species such as grouse, kestrel and barn owl.
Invertebrates as prey species	Heavily grazed grassland can benefit certain species of spider	High intensity grazing results in a lower number of invertebrates.
Mammals	-	-
Fish	-	-
Amphibians	-	-
Reptiles	-	-
Arthropods, annelids, molluscs	Ungrazed grassland has higher invertebrate numbers and taxa. Invertebrates numbers are higher in long grass than in short grazed grass. .	High intensity grazing reduces invertebrate numbers.
Soil micro, meso and macro fauna	-	-
Non-target plants	Autumn and winter grazing intensity are positively associated with spring flowering plants	Intensive grazing reduces botanical diversity, favouring a few competitive species that can tolerate grazing or are avoided by grazing animals.
Protected species	Tall grass favours skylarks.	Intense grazing leads to dominance of abundant species risking loss of rare species.

Recommendations for future work

A comprehensive review of grazing management is necessary to identify its value in IPM systems.

Weed tolerant approach

Some grassland weeds are of important conservation value as a food source or habitat for many species of invertebrates, birds and mammals. Specific weed species and their benefits are shown below (Table 28) summarised by SRUC (2014). Surveys suggest that around 5% of UK grassland receives a weedkiller in any year and few farmers treat more than 10% of their pasture in a season (Voluntary initiative, n.d.). In areas of species rich grassland or organic systems good husbandry and physical and cultural controls can reduce the need for herbicides. Weeds are often linked to pH, Phosphorus or Potassium levels, or other factors such as over/under grazing, poor drainage, compaction or poaching and these factors should be considered, and problems rectified if weeds are a problem (AHDB, 2018a).

Table 28. Conservation value examples of specific weed species in grassland – not an exhaustive checklist. Note: some cells have been deliberately left blank.

Common name of weed	Value to invertebrates	Value to birds/ mammals
Annual meadow-grass	Three red data list species; various butterfly larvae	Grey partridge and chicks - seed and invertebrates
Bur chervil	Butterfly and moth caterpillars	-
Buttercups	-	Seeds eaten by small mammals, tree sparrow, turtle dove
Chickweed, common	26 species of insects including honeybees, small bees, aphids, moth larvae	Skylark, linnet, grey partridge adult and chicks
Couch-grass, common	Speckled wood, gatekeeper and ringlet butterfly caterpillars	-
Cow parsley	Some moth caterpillars	-
Daisy	Larvae of some moths, aphids and flies	-
Dandelion	Large red-tailed bumblebees	Finches eat seed
Dock, broad-leaved	80 species found	Small mammals and birds use seed
Dock, curled	Several aphis, beetles, and moths. Larvae of blood-vein moth	Small mammals and birds use seed
Fool’s parsley	Bees visit flowers. Parasitoids of wheat blossom midge feed on flowers.	-
Groundsel	Host and food for many insects	Number of birds eat seeds
Hawksbeard, smooth	Moth caterpillars	-
Knapweeds	Great yellow bumblebee and male shrill carder bee	-
Mouse-ear chickweed	Hosts flies and bugs	Various birds eat seed
Nettle, common	Small tortoiseshell caterpillars; peacock butterfly	Dunnock eat seed
Nettle, small	Various moths and aphids	Bullfinch, dunnock eat seed
Plantains	Plantain aphid	Various adult birds eat seed
Ragworts	Cinnabar moth caterpillar; long- and short-tailed bumblebees	-
Thistle, creeping	Short-haired and large red-tailed bumblebees	Goldfinches eat seed
Thistle, spear-	Short-haired and large red-tailed bumblebees; four species of moth larvae	Goldfinches eat seed

Common name of weed	Value to invertebrates	Value to birds/ mammals
Yarrow	-	Small mammals eat seed
Yorkshire-fog	Wall brown, speckled wood and small skipper caterpillars	-

For a more in depth look in to the conservation value of grassland plants for invertebrates, birds and other vertebrates please see: http://publications.naturalengland.org.uk/publication/87001

Summary

Weed species can provide benefits to biodiversity and can be tolerated at low levels with minimal effect on yield.

Recommendations for future work

Work to determine the desired weed population that would impact on yield and farm economics sufficiently to warrant control measures as well as the environmental and conservation impacts.

ELM options and Agri-environment schemes

The Defra policy paper (Defra, 2021a) states the scope to increase biodiversity in improved grassland by having areas of increased structural diversity, allowing for flowering and seed production. Linking these areas with woodlands, hedgerows and semi-natural areas will create wildlife corridors to increase habitat diversity and resources for wildlife bringing wider benefits to wildlife. The more efficient and targeted use of nutrients will help to reduce the impacts on the environment

Mills *et al*, 2007 and Wallis De Vries *et al*., 2007 summarise that Agri-environment schemes requirements should include individual sites more often than a blanket approach. Stocking density should not be prescribed as it varies depending on which species you have or trying to favour. For example, butterflies and grasshoppers require certain sward heights and these can be achieved in different ways. A set stocking density would not be useful although it is understood that schemes need some level of prescribed structure.

Kleijn *et al* (2006) evaluated the biodiversity effects of agri-environment schemes in five European countries, which included hay meadows in Switzerland and wet grassland in the Netherlands. Species density of vascular plants, birds, bees, grasshoppers, crickets and spider were compared on 202 paired fields. Results showed agri-environment schemes had marginal to moderately positive effects on biodiversity. However positive effects for uncommon species were only found in two of the countries and Red Data listed species seldom benefited from the schemes. They concluded that the schemes need to distinguish between biodiversity of common species that can be benefitted by simple changes or abundance of endangered species that require more complex measures. Norris has a Science and Evidence team that regularly publishes evidence and reports from Agri-environment work, examples include: [Landscape-scale species monitoring of agri-environment schemes (LandSpAES project)] and Natural England Access to Evidence http://publications.naturalengland.org.uk/publication/64014?category=47017

Agri-environment schemes (AES) are likely to increase biodiversity where there are larger resource areas, as opposed to the current practice of smaller, fragmented areas (Whittingham, 2007). Hedgerow trees were found to have a higher impact on the abundance and diversity of large moths than six-metre-wide grassy field margins. Where the amount of land in AES in one area was increased the presence of hedgerow trees gave a substantially higher abundance and diversity of moths (Merckx *et al*., 2009).

Improving understanding of the overwintering ecology of arthropod groups is needed to reverse biodiversity decline in agricultural landscapes. Arthropod diversity is important in many ecosystem services and these arthropods require shelter habitats for overwintering in agricultural landscapes, such as perennial agri-environment schemes e.g. flowering fields (Boetzl *et al*., 2022).

Comparisons of newly established grasslands with diverse seed mixtures compared to subsidised legume-grasslands for pollinators and old grasslands found bees, bumblebees and syrphids were significantly less attracted to the subsidised legume-grassland compared to the newly established diverse grasslands. Butterflies were most abundant in the old grasslands. The work urged policy makers to use high quality, regionally adapted seed species and mixtures to increase plant diversity whilst preserving permanent grasslands to support different sets of insect communities (Brandl *et al*., 2022).

The policy paper ‘Environmental Land Management (ELM) update: how government will pay for land-based environment and climate goods and services’ (Defra, 2023) sets out how government intends to work with farmers and land managers to 'improve the natural environment, alongside food production, with environmental goods and services playing a key role in all farm businesses.’ The policy paper sets out the range of environmental land management actions that farmers and land managers will be paid for through the Sustainable Farming Incentive (SFI) and Countryside Stewardship (CS). The SFI enables farmers to be paid for farming in a more environmentally sustainable and integrated pest management is one of six new standards to be introduced in 2023.

GAP analysis

This review is not exhaustive but gives a good indication on the information available on how IPM affects biodiversity. A total of 414 references have been quoted, most of the literature related to arable IPM techniques, followed by outdoor horticulture then grassland. Within the individual IPM techniques, the greatest amount of references were found for crop rotation and cultivations (Table 30). All references for bioprotectants were associated with horticultural crops only, but this is a technique of increasing interest in all crops.

There are several IPM techniques that were poorly supplied with references including physical protection, monitoring of crops (DSS, forecasting and pest thresholds), hygiene and pruning, soil amendments, precision application and a weed tolerant approach.

The techniques associated with the most negative references were cultivations and mowing.

Table 29. Number of references - positive, negative and total for each IPM technique

IPM Practices	Positive	Negative	Total
Crop rotation	64	31	95
Cultivations	31	42	73
Mowing and topping	10	22	32
Bioprotectants	15	15	30
Cover crops, companion cropping, intercropping, undersowing, trap crops, banker plants and floral strips	24	2	26
Non-chemical weed control	12	12	24
Stubble management	21	2	23
Field margins and in-field strips	20	1	21
Grazing management	8	9	17
Genetic modification	6	8	14
Sowing date	10	4	14
Varietal choice and diverse seed mixtures	13	1	14
Selective and/or narrow spectrum pesticides	10	1	11
Physical protection of crops (crop covers, artificial shelters, barriers)	8	0	8
Monitoring of crops, DSS, forecasting and pest thresholds	6	0	6
Hygiene and pruning	2	1	3
Soil amendments	2	1	3
Precision application	0	0	0
Weed tolerant approach	0	0	0

Within the biodiversity search terms the greatest percentage of references found covered arthropods, annelids and molluscs, followed by birds, non-target plants and protected species (Table 29). Looking at the summaries from the main IPM projects (Chapter 4) birds, mammals, plants, arthropods and annelids were the main species groups monitored, with general counts of species encountered being made. There were some instances of specific species being targeted such as skylarks in the SAFFIE project.

There was a lack of information found relating to other groups of organisms such as fish, amphibians and reptiles, possibly reflecting how difficult they are to monitor and ascribe relevant impacts, with commensurate research cost implications. Mammals were counted within the Boxworth project but not in the other IPM projects. Soil micro, meso and macro fauna have been monitored in many of the IPM projects, but there were generally few references found on these groups.

Table 30. Percentage of references to the listed subject area, made within the review (a total of both benefits and negatives).

Species	%
Arthropods, annelids, molluscs	30
Birds	18
Non-target plants	14
Protected species	13
Mammals	7
Soil micro, meso and macro fauna	7
Invertebrates as prey species	5
Fish	3
Amphibians	2
Reptile	0

Summary and conclusions

There was little published evidence found on the effect of IPM methods on biodiversity in its strict sense. The evidence reviewed was therefore almost exclusively from studies where changes in abundance of species were measured under different management regimes. Although abundance is relevant to biodiversity, it is not a measure of species diversity. Where an IPM method was found to result in increases in species abundance, or more increases in abundance than decreases, the review has categorised the method as being broadly positive for biodiversity. Caution is needed in the interpretation of the findings.

Thirteen IPM techniques were covered in the arable sector, nine in horticulture and ten in grassland. These were identified as priority techniques in the AHDB broadacre crops IPM review (Blake *et al*., 2021) and by Natural England. The biodiversity categories covered were birds, mammals, fish, amphibians, reptiles, arthropods, annelids, molluscs, soil micro, meso and macro fauna, non-target plants and protected species. Some of these categories were poorly represented in the evidence.

A summary is reported of seven IPM projects conducted between 1981 and 2005. The projects looked at the effects of reducing inputs on biodiversity but not all were designed with an IPM remit. These projects were complicated and most tried to look at a whole system approach to improving biodiversity whilst reducing pesticide use in crops. The reporting predominantly covered both the benefits and the negative effects to biodiversity. In general, the projects showed that an integrated approach to crop and pest management led to an increase in species abundance and can lead to an increase in species diversity. However, there are no fixed 'blueprint' for integrated systems. Methods need to be site specific, adapted to local circumstances with a diverse range of techniques used to benefit a wide range of species. In IPM there is much crossover between techniques and achieving a balance between positives and negatives for biodiversity groups can be difficult.

An assessment was made of both positive and negative impacts of the potential components of IPM systems. In general, the majority of techniques were positive towards biodiversity with crop rotation, field margins, cover crops and companion crops, stubble management, varietal choice and seed mixtures, and bioprotectants having the most positive references. The techniques that had the most negative impact on biodiversity were cultivations (arable) and mowing and topping (grassland). However, these techniques sometimes have positive benefits as well.

<u>Cultivations</u>

Cultivations were identified as being generally detrimental to biodiversity. The less soil is moved and/or the shallower the depth of cultivation the lower the negative benefits to biodiversity due to lower losses in soil organic matter and direct disruption of organisms. Ploughing was the most damaging cultivation followed by deep non-inversion tillage, shallow non-inversion tillage, no-till and direct drill.

<u>Crop rotations</u>

A varied rotation including spring and winter sown crops, grassland, herbal leys and fallow provides a wide range of habitats and food sources. A varied rotation even with a mosaic of land uses / crops alone are not enough to support a wide range of biodiversity, additional non-crop areas such as margins, hedgerows and woodland are necessary to provide year-round opportunities for survival and thriving – with sufficient food, water and shelter – for warmth, security and rest. Rotations were identified as being beneficial for biodiversity.

<u>Field margins and in-field strips</u>

The majority of UK cropped fields currently have at least a 2m wide green cover margin, sometimes with additional margins and in-field strips, either funded through agri-environment schemes or as voluntary measures to provide biodiversity benefits. Field margins introduce a varied range of habitats and increasing food sources and have been identified as being beneficial to biodiversity. They can be a reservoir of weed seeds and disease inoculum e.g. ergot, but overall, the benefits outweigh the negatives.

Field margins in grassland can be developed through differential seeding or management providing similar benefits to those in cropped situations.

Monitoring of crops, decision support systems, forecasting and pest thresholds

These are tools that can help growers better understand pest risk and how to target treatments according to need. Effective monitoring/DSS/thresholds may benefit biodiversity by reducing pesticide usage.

Mechanical weeding

The mechanical action of weeders disturbs the soil surface cutting weed roots or pulling them from the soil. Other methods include hand pulling and hoeing. Weeding generally occurs in the spring and summer when weeds are emerging and soils are dry. Any creatures present in the field at the time of weeding are liable to be disturbed. Overall, non-chemical weeding was identified as being slightly detrimental to biodiversity.

Sowing date

Changing sowing date can be a small delay of days or weeks, as in the case of delayed autumn drilling, or months where sowing is delayed until the spring. This delay can be effective in reducing weed, pest and disease levels or changing the species encountered. Effects on biodiversity are minimal, but spring crops generally have lower pesticide usage than winter sown crops.

Precision application

Restricting the area of pesticide application in a crop should reduce impacts on biodiversity.

Bioprotectants

The use of bioprotectants could help to reduce use of conventional chemical pesticides, potentially benefitting a range of species. However, limited information is available on the impacts on biodiversity.

Selective pesticides

Previous research has shown that use of selective pesticides can manipulate in-field weed populations. This has beneficial effects on biodiversity but can lead to 'dirty' crops which can have knock on effects for efficient harvest. Highly selective pesticides are rare in arable situations as currently there is a limited market for their use, but all pesticide actives have specificity.

Cover crops, companion cropping, intercropping, undersowing, trap crops, banker plants and floral strips

Adding species to an area has been shown to increase populations of beneficial and predatory species, due to a greater variation in food. An increase in food sources generally results in an increase in predators. The question is where to add these plant species? Placing species outside crops is less problematic than placing them within crops. Benefits for pest and weed control have been shown but there are potential detrimental effects on cost, complexity of management and crop yield and /or quality.

Overall, the introduction of cover crops was seen to be beneficial to biodiversity, but more work needs to be done to exploit them for maximum benefit.

Varietal choice and mixtures

The use of resistant and tolerant varieties are an important part of non-chemical pest and disease control and can reduce the need for pesticides which may benefit biodiversity.

Genetic modification is not currently available in the UK but in countries where it is it has been used it has been shown to be generally beneficial to biodiversity by reducing the use of pesticides. Other studies have found negative effects or contrasting effects of genetic modification on different species.

Naturally bred crops that are tolerant to specific herbicides are available in oilseed rape and sugar beet to control weeds that are closely related to the crop. Growing herbicide tolerant crops e.g. Clearfield® varieties of oilseed rape still requires herbicide use. Growing more competitive species, e.g. hybrid barley, can reduce herbicide use, but weed species which are less competitive and of biodiversity value will also be suppressed.

Interest in the use of varietal mixtures is increasing for disease control in arable crops particularly cereals. In grassland, species rich swards can help to increase invertebrates and bird diversity by diversifying sward structure.

Stubble management

Retaining a stubble after harvest is already part of environmental schemes, as it provides a source of food during the autumn and winter. Management is key to maximising the value of the stubble. The value is reduced by the application of a pre-harvest desiccant and cultivation immediately after harvest. Retaining stubbles generally has positive biodiversity benefits.

Soil amendments

Little research was found on the impact of soil amendments on biodiversity, with the exception of organic manures. There were some benefits to beetles and bacterial communities and no observed negative effects except where the amendment was contaminated with herbicides.

Hygiene and pruning

Maintaining hygiene standards is an important aspect of cultural control in an IPM programme to limit spread of weeds, pests and diseases. However, there has been little research on the impact of hygiene and pruning on biodiversity. There were some positive and negative impacts on birds.

Physical (crop covers, artificial shelters, barriers)

There are many types of crop cover used in horticulture, predominantly to manipulate the crop environment to improve yield and quality and extend the season. No negative effects on biodiversity were found and a number of positive effects were identified for a wide range of species including birds, mammals, arthropods and protected species. Some benefits relate to keeping non-target vertebrate species out of cropped areas to avoid the need for lethal methods of control.

Mowing and topping

Reducing cutting frequency and timing cuts can be used to manipulate plant communities, from an IPM and conservation management perspective. Generally, mowing and topping tends to be detrimental to biodiversity. Geographic location and local species must be considered in conservation management plans to minimise impacts on biodiversity.

Cutting at different timings or leaving smaller areas uncut for longer can favour a much wider range of species than having a monoculture of habitats.

Grazing management

Grazing can be used to manipulate weeds or undesirable species in grassland. Subtle changes can be made to grassland through the choice of grazing animal, timing of grazing in relation to developmental stage of the crop and weed and density of stocking. High intensity grazing and overgrazing reduce biodiversity in grassland. Timing of grazing in relation to a species' lifecycle will determine if grazing has a positive or negative impact. Types of regenerative grazing that use a high stocking density, frequently move the animals, and incorporate long resting periods, can have positive impacts on biodiversity.

Future work

There are many studies of the effects of IPM practices on species abundance. Studies of the effects on species diversity and biodiversity are required.

The effects on biodiversity and species abundance of the paid actions within the new SFI IPM Standard should be monitored. This would ensure the actions are delivering a key area of public good.

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Conservation Evidence is a free information resource summarising scientific literature, including non-peer reviewed and unpublished sources, on the effects of conservation actions. A conservation action or intervention is what is done to manage, protect, enhance or restore wildlife or ecosystems. A synopsis of the evidence for each action is provided and an assessment of the effectiveness of the action is provided by an expert panel. The Conservation Evidence team is based at the University of Cambridge with collaborators and advisers in all continents in the world. The resource is available at: https://www.conservationevidence.com/content/page/24 and see for many relevant Natural England publications on biodiversity http://publications.naturalengland.org.uk/category/47017 including IPM at http://publications.naturalengland.org.uk/publication/62023?category=47017

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Appendix 1. Farmer training

The opportunities for training in pesticide use for advisers has developed in recent years as conservation, enhancing the environment and biodiversity and sustainable farming practices have become key goals in the farming sector. BASIS have recently introduced a Certificate in Sustainable Land Management qualification which covers many aspects of environmental management, including Agri-environment schemes, habitat and species management, soil and water management, and IPM.

Those applying professional plant protection products under the Plant Protection Products (Sustainable Use) Regulations, 2012) must hold the mandatory unit for a LANTRA or City and Guilds (NPTC) Certificate of Competence such as the ‘Principles of Safe Handling and Application of Pesticides (PA1)’ with the relevant additional specialist modules that are available for the machinery to be operated - including mounted or trailed sprayers, boat mounted equipment, hand held sprayers, pellets or granules, pesticide plugs in tree stumps and pesticide injection equipment (http://www.nptc.org.uk/). Agricultural and horticultural spray operators after passing the relevant Certification exam should join the National Register of Sprayer Operators (NRoSO) which provides for continuing professional development (CPD). Amenity users should join the BASIS Amenity Training Register (BAR).

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