Scotland's Rural College

Review of evidence on Integrated Pest Management

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Executive Summary

Background

IPM is an integrated multi-layered approach which includes a number of tangible measures as well as attitudinal and husbandry behaviours, which in combination can form an effective approach to crop protection. Integrated Pest Management (IPM) is an important part of the Government's future vision of crop protection and currently part of important policy documents, including the 25 Year Environmental Plan, and legislation, transposed from the European Union Sustainable Use Directive. ADAS and SRUC have been commissioned by Defra to conduct a research study to:

- Enhance Defra's understanding of what works in IPM through a comprehensive review of recent evidence; and
- Collect best practice examples that can inform communication with growers

Methodology

To meet these objectives twenty-one stakeholder interviews were conducting to inform a Rapid Evidence Assessment (REA). The interviews were semi-structured and with stakeholders in organisations from; farmer or grower member organisations, research institutes, Non-Governmental Organisations, the Ag-Chem industry and agronomists. Information from the interviews helped refine the methodology for the REA as well as provide key evidence from the stakeholders. Eight key research questions were developed as part of the REA protocol which set out a systematic way of searching, reviewing and synthesising the available evidence.

Research question 1: Are IPM approaches effective at reducing pesticide use?

The evidence was mostly consistent in showing a decrease in chemical pesticide use where an IPM approach had been taken. This was consistent across different countries, sectors and crops. Specific measures which reported a reduction in chemical pesticide use included; natural predators, the use of pest thresholds, crop rotation and later drilling amongst others. For some evidence the impact of IPM approaches on chemical pesticide use was not measured and instead seen as common knowledge which did not need to be proven. It highlighted that IPM provides a systematic approach which can help farmers and growers take a holistic approach to their pest control and highlight areas they may not have previously considered. Evidence gaps were identified including understanding the impact of new measures and combination of measures on chemical pesticide use.

Research question 2: What combination of IPM measures are most effective at reducing pests?

Key IPM measures and approaches were categorised within the framework of the eight IPM principles; prevention and suppression, monitoring, informed decision making, non-chemical methods, pesticide selection, reduced pesticide use, anti-resistance management and evaluation. Prevention and suppression measures are often most popular with farmers and growers as they are perceived as requiring fewer resources than other measures. A number of these measures were explored including, crop rotation, cover crops, pest resistant crop and plant varieties, soil cultivation and irrigation. Non-chemical methods focused on biopesticides, beneficial organisms, physical barriers and mechanical weeding. For monitoring using local and regional pest forecast data, crop walking and evidence on thresholds was explored. Thresholds were considered as useful for some crops, but not all depending on the crop type and pest characteristics.

Various sources of information are available to crop protection decision makers, including agronomy advice, online decision support systems, levy bodies and personal networks. In some countries there is evidence which identified that support networks have been found to be successful at helping farmers make informed decision on pest management. A holistic approach to IPM requires the incorporation of all eight principles across the farm and over multiple seasons, to create a sustainable and productive cropping environment.

Research question 3: What are the impacts of IPM on the wider environment?

The majority of the evidence identified positive impacts on the wider environment from the adoption of IPM. Much of the focus was on the positive impact of decreasing chemical pesticide use on the wider environment. The evidence focusses on benefits to the wider environment, including resilience of yield, soil quality and soil organic carbon (SOC), and biodiversity. To a lesser extent benefits were related to climate change. Additionally, it highlights a small amount of evidence which focuses on the positive public perception of IPM. The evidence gaps for this research question focus on the impacts of the IPM measure on the wider environment and not just the impacts of the reduction of chemical pesticide use.

Research question 4: What are the socio-economic impacts of IPM on the farming industry?

The main socio-economic impacts identified within the evidence focussed on the reduction of costs for the farmer through decreasing the use of chemical pesticides. IPM adoption was also associated with building networks and sharing knowledge within the farming industry. However, the evidence also raised the farmer and growers perception of the potential to reduction of yield or income if they decreased their chemical pesticide use. Beyond environmental benefits, IPM was viewed as being a systems-based approach, which can help farming become more economically and socially sustainable, partly due to the wide range of measures available as part of IPM. There is a lack of research identified on the social impacts of IPM uptake including information on human and social capital.

Research question 5 and 6: What are the barriers and enablers to uptake of IPM measures or approaches?

IPM is considered by farmers as high risk in terms of protecting yield and economic returns from the crop. Moreover, the evidence highlighted that benefits from IPM can take a longer time to realise than chemical pesticides. This is amplified by the supply chain and consumer preference. IPM measures can be costly in terms of time, due to the additional effort required to research and implement in comparison to chemical pesticides. There is very consistent evidence that the lack of farmer knowledge is a significant barrier to the uptake of IPM. IPM measures are often more complex and require a good understanding of the identification of pests, pest demography and ecology in order to work effectively. Additionally, farmers can receive unclear messages and information from too many organisations making it difficult for them to identify and assimilate the appropriate knowledge.

Policy mechanisms, knowledge exchange and pesticide resistance were all highlighted as enablers to IPM uptake. There are evidence gaps on effective policy interventions, particularly with newer approaches such as co-development and understanding what works for farmer initiatives in the UK. There is evidence of some early research looking into consumer willingness to pay for produce from IPM based operations.

Research question 7: What IPM initiatives are there?

Through interviews and the REA, initiatives were identified from many countries worldwide. Within the UK the evidence highlighted the Voluntary Initiative and LEAF as two key initiatives which have had a positive impact on the adoption of IPM. Furthermore, several European initiatives were identified which tended to be funded by European commission funding with more of a focus on IPM research and sharing this knowledge with practitioners. Ten case studies were produced as part of this research question, however, there was a limited amount of information evaluating the initiatives and highlight what works well and what works less well.

Research question 8: What is the extent of coverage of IPM in the UK?

There have been relatively few attempts to quantify the extent of coverage of IPM in the UK. It is widely assumed that some sectors (protected edible crops) are practicing much higher levels of IPM than other sectors (arable). Until very recently there has been little monitoring of IPM adoption in the arable sector and even less in the horticulture sector. Evidence suggests that all growers are practising IPM to some degree, but some have adopted significantly more IPM practices than others, therefore, universal metrics that encompass the vast majority of IPM practices are required to quantify levels of adoption. IPM adoption needs to be monitored so that schemes to promote IPM can be critically assessed and evaluated.

Contents

1 Acknowledgements

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2 Definitions and Acronyms

2.1 Table of key definitions

Several words are used within the industry with different definitions dependent on who and which context they are being used. The following table defines these terms for the purpose of this report.

Word or term	Definition
European Union Sustainable Use Directive (SUD) definition of IPM	Integrated pest management means careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment. 'Integrated pest management' emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms.
IPM Practices/ Measures	*Refers to the individual action that is taken by a farmer or grower, for example, crop rotation, cover crops, monitoring.*
IPM approach	*Refers to not only individual practices but also the mind-set of the farmer and grower, for example, an IPM approach covers a suite of IPM practices and a holistic view of pest management*
IPM Initiative	*Refers to an organised effort by government, industry or farmer organisation to promote IPM, for example, the LEAF marque. Excluded from this definition would be an individual agronomist who promotes IPM to their farmers.*
Pests	*Refers to pests, weeds and diseases. This review does not include vertebrates.*
Chemical Pesticides	*Refers to herbicides, pesticides and insecticides, this review excludes rodenticides.*
Growers	*Commercial farmers or growers who grow a commercial crop.*
Bioprotectants	*Collective term for biopesticides, biocontrol agents and semio chemicals.*
Cover crops	*A cover crop is a non-cash crop grown primarily for the purpose of 'protecting or improving' between periods of regular crop production (AHDB definition)*
Intercropping	*Growing different crops in the same field, for example through inter-row.*
Trap crop	*A crop that is planted to attract pests away from the cash crop.*
Micro-dosing	*Precision application of small amounts of pesticide.*

2.2 Table of acronyms

Acronym	
IPM	Integrated Pest Management
ICM	Integrated Crop Management
IWM	Integrated Weed Management
GHG	Greenhouse Gas
CO_2	Carbon Dioxide
N_2O	Nitrous Oxide
RQ	Research Question
VI	Voluntary Initiative
SUD	Sustainable Use Directive 2009/128/EC
PAN	Pesticide Action Network
LEAF	Linking Environment and Farming
FACTS	Fertiliser advisor's certification and training scheme
BASIS	British agrochemical standards inspection scheme
REA	Rapid Evidence Assessment

3 Introduction

3.1 Report objectives

This report is the final submission to Defra for project_27269 Review of evidence on Integrated Pest Management. ADAS and subcontractors SRUC have joined to deliver this project with the overall aims of:

- enhancing Defra's understanding of what works in IPM through a comprehensive review of recent evidence; and
- collecting best practice examples that can inform communication with growers.

This includes giving an overview of existing coverage of IPM, categorising the impact of IPM interventions, producing 10 best practice case studies, and assessing to what extent the current literature provides insights into the barriers and enablers to adopt IPM approaches. This project will help to inform Defra's communication with growers.

To meet these objectives, we have undertaken in-depth interviews with stakeholders (WP1), a Rapid Evidence Assessment (WP2) and reported the evidence (WP3).

This report includes:

- Background: Defining IPM and the importance of the evidence review.
- Project Approach: High-level overview of the project methodology.
- Results: Research questions, the synthesis of current evidence and key evidence gaps.
- Conclusions: Overall findings from the project and evidence gaps.

3.2 Background

3.2.1 Defining IPM

Integrated Pest Management (IPM) is at the heart of the Government's future vision of sustainable crop protection. The 25 Year Plan to Improve the Environment outlines a strategy with IPM contributing to "*protecting crops while reducing the environmental impact of pesticides*".

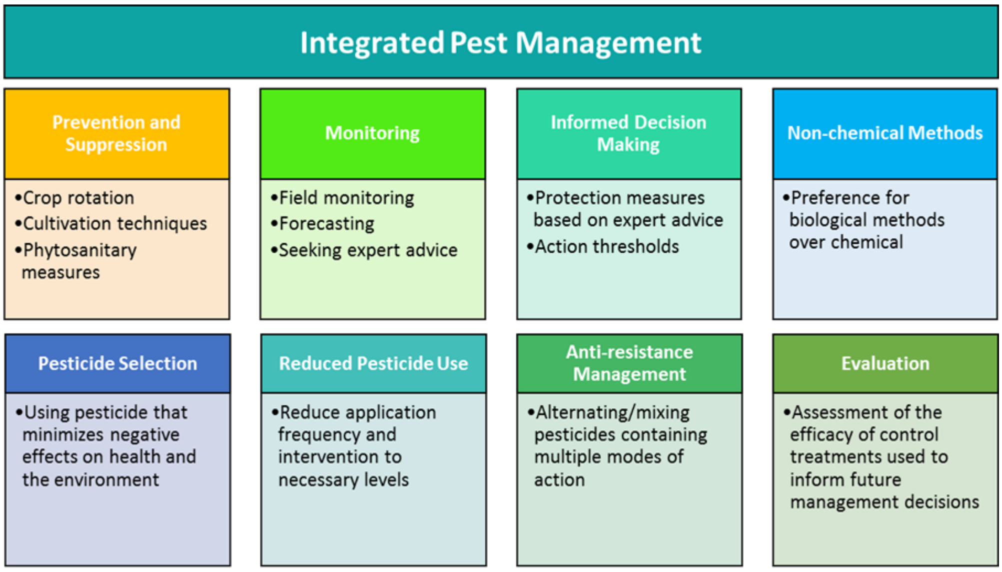
Additionally, the European Union Sustainable Use Directive (SUD) aims to achieve sustainable use of pesticides in the EU by reducing the risks and impacts of pesticide use on human health and the environment. Currently IPM is promoted through measures and mechanisms described in National Action Plans and, while this may not be the framework for IPM in the future, it provides the basis for understanding the context for this work. The SUD provides the following definition of IPM:

"Integrated pest management means careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment. 'Integrated pest

management' emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms."

IPM is an integrated, multi-layered approach which consists of a number of themes outlined in the SUD including; prevention and suppression, monitoring, informed decision making, non-chemical methods, pesticide selection, reduced pesticides use, anti-resistance management and evaluation. Under each theme is a number of actions or husbandry behaviours that growers can use, which in combination, can form an effective and environmentally sensitive approach to crop protection (Figure 1).

Figure 1. SUDs IPM core Principles.



3.2.2 Quantifying IPM

IPM is a protocol or series of actions, with growers practising one or more elements, which can make it hard to quantify. Recently, a project team lead by SRUC devised a method for quantifying uptake of IPM practices on arable farms in the UK and Ireland (Creissen *et al.*, 2019). The 'IPM metric' showed that all farmers have adopted IPM to some extent but only 6% had adopted more than 85% of what is theoretically possible.

IPM uptake can also be estimated using a Treatment Frequency Index (TFI) (Lechenet *et al.,* 2017). This indicates the number of recommended doses applied to each unit of cropped area and can be averaged at a farm level to enable comparisons at regional and national levels. Using the TFI it is also possible to compare pesticide reliance at a crop level, or considering pesticide categories separately (herbicide TFI, fungicide TFI, insecticide TFI, TFI for other pesticides). Using this metric, the Dephy network has estimated that total pesticide use in France could be reduced by 42% without any negative effects on both productivity and profitability in 59% of farms. The TFI estimate has also been used in other countries, such as Denmark (Pedersen, 2016). It was believed that the TFI estimate has led to an average reduction of 37, 47 and 60% of herbicide, fungicide and insecticide use, respectively (Lechenet *et al.,* 2017). IPM is knowledge intensive and is often influenced by multiple information sources, particularly agronomists. Previous ADAS research (ADAS, 2002) has shown that growers can be undertaking IPM actions, such as crop monitoring, but be unaware that these practices are included within the definition of IPM.

IPM tools and techniques can be mechanical, biological or chemical and are usually dependent on the agricultural system (horticulture, grass, arable etc.) and the combination of pests, weeds or diseases targeted. The effectiveness of IPM actions is varied, with evidence available from different farming sectors (poultry, arable and horticulture). However, it must be noted that all best practice examples need to be tailored to individual farms with acknowledgement of local environments. This project will highlight current evidence available on quantifying the impact of IPM practices and barriers to understanding the quantification of IPM, including evidence gaps.

4 Methodology

4.1 Qualitative interviews

A semi-structured interview guide (Appendix 8.1) was developed to collect responses from stakeholders and comprised the following sections: the stakeholder, measuring IPM uptake, IPM practices, and IPM initiatives and our future research. Table 1 sets out the organisational groups that have been represented in stakeholder interviews. The distribution between groups was as intended and high-level stakeholders were selected to inform the Rapid Evidence Assessment (REA). A total of 24 stakeholders were interviewed across 21 interviews.

Table 1. Stakeholder organisation and interview format.

Type of organisation	Number of stakeholders interviewed
Farmer/ grower Organisations	8
Research	6
NGO	4
Industry	2
Agronomist	4
Total:	**24**

A team of experienced social science research staff conducted the stakeholder interviews, which were audio recorded. Interviews were transcribed verbatim and uploaded onto Dedoose, a web application for mixed methods research,[1] where they were qualitatively coded. The results were discussed with the ADAS technical team and an REA protocol was established and agreed upon with Defra. More detail on the interview methodology and findings of the qualitative interviews can be found in Appendix 8.1.

4.2 REA search methodology

4.2.1 Research questions

Key research questions were developed by the project team considering Defra's detailed objectives, clarifications from the inception meeting and the views of stakeholders interviewed (Table 2).

[1] www.dedoose.com

Table 2. Rapid Evidence Assessment research questions.

REA research questions	Defra Objectives: What works in IPM?	Best practice examples on IPM initiatives?	Provide an overview of the extent and coverage of IPM practice in the UK	IPM interventions by impact (positive, negative, no impact)
Are IPM approaches effective at reducing pesticide use?	x		x	x
What combination of IPM measures are most effective at reducing pests?				X
What are the impacts of IPM on the wider environment?	x			x
What are the socio-economic impacts of IPM on the farming industry?		x		x
What are the barriers to uptake of IPM measures or approaches?	x	x		x
What are the enablers to uptake of IPM measures or approaches?	x	x		x
What IPM initiatives are there?	x	x		
What is the extent of coverage of IPM in the UK?			x	

4.2.2 Search criteria

Search engines were tested to select which produced the most relevant publications. The search engines and resources used were: Science Direct, Google scholar, Google, Open Grey, and Defra science search, provding access to previous Defra science and research projects. Literautre was identified from interviews and by ADAS and SRUC research. Published and unpublished literature was included in the REA and collected both internally by ADAS and SRUC and through stakeholder interviews (where the participant permitted access). There was no exclusion criterion on the age of the publications suggested by stakeholder and suggested literature ranged from 1991-2020. The project team documented the date of each search, noting the number of hits and the top 100 titles and authors for each search engine.

The specificed project remit was to include evidence from countries where growing conditions could be replicable in the UK. These countries were: Ireland, and climatically or geographically similar areas, such as parts of the United States, New Zealand and North-West Europe.

Tables 3 and 4 detail the inclusion and exclusion criteria which are relevant across all research questions for the REA. The inclusion and exclusion criteria was applied by researchers after the top 100 titles were collated to ensure that evidence is appropriately screened and only relevant evidence is included in the REA.

Table 3. Inclusion criteria.

Inclusion	Rationale
Studies which focus mainly on IPM	IPM is the main focus of the REA
Countries – Belgium, Denmark, France, Germany, Hungary, Ireland, Lithuania, Netherlands, New Zealand, North America, Sweden, Switzerland	Countries most often suggested in stakeholder interviews with similar geography and climate to the UK
All farm commodities where PPPs are used for the purpose of pest control.	Farm commodities (crops) that are relevant to the countries outlined above.

Table 4. Exclusion criteria.

Exclusion	Rationale
Biocides and vertebrates	Agreed with Defra at inception meeting
Evidence not written in English	Research team English speakers and REA focussed on UK
Any pesticides/ chemicals not used for plant protection	Out of project scope
Publications before 2010	To highlight most relevant evidence. Evidence pre 2010 is included as part of the evidence collected from the stakeholders and project team.
Crops not grown in the UK	Out of project scope
Impacts related to Human Health	Out of project scope
Food Consumption	Out of project scope
Impacts on wider society	Out of project scope

4.2.3 Search Terms and evidence screening

Boolean search terms were used to develop searches that combine key words. After the hits were downloaded for each search term, the first phase screening ranked the publication title by 'clearly relevant', 'clearly not relevant' or 'uncertain'. Second phase screening involved reading the abstract or the first paragraph of the 'clearly relevant' and 'uncertain' publications. Evidence that is clearly relevant or was then obtained in full.

4.2.4 Data collection

This refined list of results was used in the evidence extraction. To ensure consistency between evidence reviewers, 10% of the searches were assessed by two reviewers. To assess the quality of evidence, information was collected on: type of evidence, research design, population studied and geographical context.

More information can be found on the REA protocol in Appendix 8.2.

5 Results

5.1 Overview of evidence found

5.1.1 Evidence base

In total 224 pieces of evidence were reviewed in full; this was more than expected and was due to more relevant evidence than expected. The evidence was spread across countries, with a significant number of pieces of evidence from the UK and the USA. Where the country is "other" often there was not a country explicitly identified (Table 5).

Table 5. Summary of evidence base

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Belgium	0	0	0	0	0
Denmark	1	0	0	0	0
France	3	1	1	0	0
Germany	4	0	0	0	0
Hungary	1	0	0	0	0
Ireland	5	0	0	1	1
Lithuania	1	0	0	0	0
Netherlands	2	0	0	1	1
New Zealand	5	0	0	0	0
North America	30	3	2	6	1
Sweden	3	0	0	0	0
Switzerland	0	0	0	0	0
UK	25	2	8	7	8
Other	59	10	6	22	4
Type of Pest					
Pathogen	10	1	2	0	2
Weed	28	3	1	3	2
Insect	48	3	8	5	2
Other	53	9	6	29	9
IPM SUD Principle					
Prevention and Suppression	16	3	0	0	0
Monitoring	5	0	0	0	0
Informed Decision Making	8	1	1	3	2
Non-Chemical Methods	22	1	1	2	3
Pesticide Selection	5	0	0	0	0
Reduced Pesticide Use	3	1	1	2	0
Anti-resistance management	7	0	0	1	1
Evaluation	16	2	2	1	0
Combination	57	8	12	28	9
Research Design Used					
Scientific Experiment - Quantitative	35	0	4	1	2
Scientific Experiment – Qualitative	2	0	0	0	0

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Review Paper	72	7	5	2	2
Social research – quantitative	4	0	0	0	1
Social research - qualitative	3	0	2	0	0
Case study	9	1	0	2	0
Other	14	8	6	32	10
Crop type					
Arable combinable	38	4	3	0	6
Arable non-combinable	5	0	1	0	0
Horticulture	21	3	4	1	2
Other	75	9	9	36	7

In total 224 pieces of evidence were reviewed in full; this was more than expected and was due to more relevant evidence than expected. The evidence was spread across countries, with a significant number of pieces of evidence from the UK and the USA. Where the country is “other” often there was not a country explicitly identified (Table 5).

Most of the evidence focussed on insects with fewer pieces of evidence on weeds and pathogens. However, those categorised in the “other” category included a mixture of pests. The evidence was also categorised in term of the IPM SUD principle it relates to. The majority of the pieces of evidence focussed on a combination of the principles, however there were fewer on the principles of pesticide selection, monitoring and reduced pesticide use (Table 6).

Table 6. Evidence sorted by SUD Principle

SUD Principle	Number of articles
Combination	114
Non-Chemical Methods	29
Evaluation	21
Prevention and Suppression	19
Informed Decision Making	15
Anti-resistance management	9
Reduced Pesticide Use	7
Monitoring	5
Pesticide Selection	5

The quality of evidence was relatively high, however those categorised as “other” scored more poorly. “Other” evidence included conference papers, presentations and manuals which tended to be shorter and therefore lacked sufficient information to be confident in the quality of the sources. The quality scoring criteria that was used by the research team can be found in Table 7.

Table 7. Scoring criteria to assess quality of evidence

	Strongly Disagree	Disagree	Nuetral	Agree	Strongly Agree	
Biased literature to serve interests of funding body	1	2	3	4	5	Full disclosure on data, theory and methodology which informs literature
Irrelevant to RQs	1	2	3	4	5	Fully relevant argument that is relevant to Research Qs
Ignorance of a factor or practice that distorts the coherence of the literature	1	2	3	4	5	Consideration of other practices, cultures and differences
Illogical article that does not provide a sound evidence base	1	2	3	4	5	Logically or factually sound conclusions reached from the primary or secondary evidence discussed
Unsubstantiated article	1	2	3	4	5	Provides consistent findings that are accurate and trustworthy
Vague and unclear, no clear argument	1	2	3	4	5	Clear, logical argument backed up with robust methodology

5.2 **Research question 1:** Are IPM approaches effective at reducing pesticide use?

5.2.1 Research question 1: Headlines

The following headlines have been identified in the evidence in response to the first research question:

- Most of the evidence identified a decrease in chemical pesticide use with the introduction of IPM methods. This is across different sectors (arable and horticulture) and different crops.
- IPM provides a systematic approach which can highlight strengths and weaknesses in the farmer or grower’s pest control methods.

- Lower use of chemical pesticides has been linked to a number of economic and environmental benefits.

5.2.2 Research question 1: Overview of evidence

The evidence available from the REA was predominantly from North America and the UK, in the format of journals (**Table 8**). The main theme for RQ1 focuses on whether IPM approaches are effective at reducing the use of chemical pesticides (focussing on a reduction in terms of volume) (**Table 9**). Where the impacts have been measured, over 70% of evidence sources report a decrease in chemical pesticide use where IPM has been introduced. The quality of the evidence is 4.24.

Table 8. RQ1: Table of evidence.

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Germany	1				
New Zealand	2				
North America	6				
UK	5		1		1
Other	7				
Total	**21**		**1**		**1**

Table 9. RQ1: Main themes and supporting evidence.

RQ	IPM approaches are effective at reducing pesticide use?							
	Yes		No		No effect found		Not measured	
	Number[2]	Quality[3]	Number	Quality	Number	Quality	Number	Quality
Number of articles that answer the RQ	22	4.4	5	3.68	7	4.33	99	3.91

5.2.3 Research question 1: Content of evidence overview

5.2.3.1 *Impacts of IPM on pesticide use*

The majority of the literature indicated an overall decrease in pesticide use as a result of implementing a single or a combination of IPM measures. A detailed table of IPM measures and their effect on pesticide use can be found in appendix 8.4. The quality score indicates that evidence used to inform this question was considered high quality based on the scoring criteria in Table 7. Decreased herbicide, insecticide and fungicide use was reported across arable and horticulture sectors. Vegetable growers who were practicing IPM reported a 35% reduction in their overall pesticide use by using selective insecticides (Horrocks, Horne, and Davidson, 2018). An increase in the use of non-chemical pesticide reduction methods (for example hand weeding and mulching) has been shown to have a clear negative correlation to volume of pesticide use (Melander *et al*., 2013). Moreover, pesticide use had declined where growers were carrying out preventative measures to protect their crop (Bürger *et al*., 2012). The results of a six-year field trial in France (Pardo, Riravololona, and Munier-Jolain, 2010) indicated that integrated weed management led to a reduced reliance on pesticides and effective control of weeds. Incorporating the monitoring of insect numbers has been shown to lead to a lower volume of pesticides applied and an economic saving to farmers and growers (Waters, 2015).

Specific measures that have been reported to reduce pesticide use include understanding the role of natural predators (Tang, Tang, and Cheke, 2010; Horne, Paige, and Nicolson, 2008) and the use of pest thresholds to guide pesticide use (Nilsson *et al*., 2015; Muvea *et al.,* 2014). The more diverse crops in rotation were viewed as being more beneficial against weeds (Lamichane et al. 2017). Later drilling/planting and use of disease/pest resistant cultivars are strategies that can be implemented to lower pesticide inputs; however, the success of these strategies is dependent on the crop they are used on (Bürger *et al*., 2012). Decision support tools have been effective in increasing farmer confidence in reducing pesticide use. For example, the decision to use an insecticide for pollen beetle control is

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[2] Number of articles which provide evidence for that response to the RQ.

[3] Average quality score of the group of articles providing evidence to the RQ.

based on both the number of plants per m^2 and the number of beetles per plant (Cook *et al*., 2013). However, it must be acknowledged the success of IPM strategies to reduce pesticide use can vary between farms (Buitenhuis, 2014). Farmer networks that enabled information sharing were viewed as a contributing factor that lead to a reduction in pesticide use and the adoption of IPM (Mansfield *et al.,* 2019).

Articles that did not focus on a single or combination of measures leading to a reduction in pesticide use typically focussed at a higher level discussing IPM as a systematic approach to crop management. It was believed that following a systematic approach allows IPM to be a more robust approach to pest management than focussing on chemical pesticides as it allows for the identification of strengths and weaknesses across whole cropping systems.

Farmer networks (Mansfield *et al*., 2019) and the transfer of technical information (Toma, *et al*., 2018) have been noted as contributing factors that lead to a reduction in pesticide use and the adoption of IPM.

5.2.3.2 *Impacts of lower pesticide use*

Lower pesticide use was linked to:

- Increased efficacy of beneficial insects (Cuthbertson, Qiu and Murchie, 2014);
- Increased herbicide efficacy e.g. using measures such as cover cropping (Wallace, 2019);
- Financial savings that growers made compared to a standard cropping system (Pardo, Riravololona, and Munier-Jolain, 2010; Lechenet, *et al*., 2017);
- Environmental benefits (Chattopadhy, Banerjee, and Mukherjee, 2017);
- Yield safeguarding i.e. a decreased use of fungicide did not lead to lower yields in Scottish spring barley (Stetkiewicz, 2018); and
- The improvement of the productivity and quality of a crop through the adoption of an IPM strategy (He, Zhan, and Xie, 2016).

Research has indicated that there was no link between low pesticide use and high productivity and high profitability on 77% of farms in the Dephy network (Lechenet *et al.,* 2017). This echoes the findings that are reported in research question four, where reduced pesticide use by growers can have a positive economic impact on the farming industry. More detailed findings from the literature regarding the enablers to IPM uptake can be found in the response to research question six.

Five pieces of evidence report an increase in pesticide use when IPM measures are in place. This has been explained due to pest resistance (Benbrook, 2012) and the emergence of new pests (Haye *et al*., 2016). Herbicide resistant crop technology reportedly led to an increase in herbicide use in North America between 1996 and 2011 (Benbrook, 2012).

5.2.3.3 *Evidence gaps identified*

Evidence gaps were identified, particularly around the impact of new technologies and the potential impacts these would have on pesticide use. The new relative complexity of many IPM measures and the difficulty in quantifying the efficacy of these approaches within a wider strategy is an area that requires improved understanding (Bruce *et al*., 2017). This also highlights the need for effective communication with farmers, growers and their advisors on the reasoning behind IPM measures, the associated benefits and risks, and the tools available to assist them in making informed decisions (Barnes *et al*., 2016). Further evidence gaps were viewed as a lack of practical, demonstrable research that can inform farmers and growers to make decisions on farm.

5.3 Research question 2: What combination of IPM measures are most effective at reducing pests?

The evidence used to respond to the research question was predominantly from North America and in the format of scientific journals (**Table 10**).

Table 10. RQ2: Table of evidence used to respond to the research question.

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Ireland				1	
Netherlands	1				
New Zealand	1				
North America	7	1			
UK	2		1		4
Other	10	3	1	2	
Total	**21**	**4**	**2**	**3**	**4**

5.3.1 Research question 2: Overview of evidence

IPM measures featured in the literature are groups below corresponding to the eight principles outlined in the SUD. A table displaying all measures that were found in the literature search is included in Appendix 8.4.

5.3.1.1 *Prevention and Suppression*

Preventative measures are actions that contribute to the creation of a cropping system that is less likely to experience significant economic losses due to the presence of pests, while suppressive measures reduce the incidence of pests and the severity of their impact that pests can have on crops (Barzman *et al*., 2015). Preventative measures are often favoured by farmers and growers to manage pests (DAFM, 2020), as these require commitment of relatively fewer resources compared with other measures. The preventative measure of cleaning equipment between fields, for example, is viewed as a relatively easy and important preventative measure (Beckie and Harker, 2017; DAFM, 2020), while measures such as intercropping have numerous management implications (Lamichane *et al.,* 2017).

Crop rotation

Crop rotation is a widely implemented and effective agronomic alternative to synthetic pesticides (Barzman *et al*., 2015), and using a diverse crop rotation increases efficacy in controlling weeds (Jhala *et al.,* 2014). Crop rotation also performs a vital role in the prevention and suppression of invertebrate pests, which can build up in fields under continuous cropping. For example, the larvae of orange wheat blossom midge, *Sitodiplosis mosellana*, drop from wheat ears to the soil in early summer, where they overwinter and emerge in following years and migrate to new wheat crops (Jacquemin *et al.,* 2014). If the adults emerge directly into, or close to, a new wheat crop (i.e. where tight rotations are used) the pest population can rapidly build up, leading to subsequent increases in crop damage. Similar population increases under short crop rotations have been observed for other invertebrates e.g. potato cyst nematode (Minnis et al 2005) and clubroot in oilseed rape (McGrann et al., 2016). Cereal crop rotation is also viewed as an effective measure to help manage the weed *L. Avena fatua* (common wild oat) in arable crops (Beckie and Harker, 2017). Increasing the diversity of crops grown, both on an individual field over time and within the whole landscape in any given year, helps to limit the build up of pests over time. There are additional advantages to wider crop rotations, however diverse cropping requires access to a wider knowledge base and other resources for the farmers, growers and agronomists.

Delayed drilling

Adjusting the drilling date of crops impacts on the risk of pest injury to crops. For example, later drilling of winter wheat crops helps minimise exposure to aphid vectors of BYDV (Foster *et al*., 2004). Drilling wheat at the end of October rather than in September can also decrease weed plant densities by approximately 50% (Lutman et al, 2017). In North America, the delayed planting of sunflowers until late May or early June has reportedly led to a decrease in the sunflower stem weevil, *Cylindrocopturus adspersus* (Knodel, Charlet, and Gavloski, 2010). Delaying drilling can, however, reduce the yield potential of the crop (Lutman et al 2017). It can also increase the risk of other pests; wheat bulb fly, *Delia coarctata,* lay eggs in bare soil prior to crop emergence and extended periods of bare soil as a result of delayed drilling can increase egg laying and pest pressure during crop establishment. The risk of this can be reduced by ensuring cultivation takes place after egg laying and by using higher seed rates to compensate for losses. These measures have practical implications for the farmers due to the pressures to cultivate and drill fields without damaging soils as a result of travelling on wet land later into autumn.

Improved crop competition

Improving crop competition is an important cultural control option, particular for weed control. Improved competition requires increasing the ability of the crop to maintain high yields in the precence of weeds (tolerance) or its ability to reduce weed growth (suppression). Tolerance and suppression can be achieved by using crop varieties possessing a competitive advantage over weeds (e.g. fast germination, quick growth, high biomass and large leaf area) as well as manipulating the seed rate and direction of crop rows (Sardana *et al*., 2017). The density of blackgrass *Alopecurus myosuroides* in cereals, for example, can be reduced by up to 22% through the selection of more competitive cereal varieties (Lutman *et al*., 2017). As blackgrass mainly emerges in the autumn, crops such as spring barley are less affected and can be used to reduce weed infestations. Spring crops can, however, be more diffiuclt to establish on heavy soils, and tend to give poorer financial returns (Moss & Hull 2012). In winter oats, weeds can be supressed by the shading effect of crops with a high mid-season leaf area index (LAI) and high stem density, therefore good crop establishment can lead to early suppression of weeds (Fradgley *et al*., 2014). Inter-row hoeing can be effective in suppressing weeds, and has been shown to be viable alongside other techniques in vegetable crops such as onions (Melander and Hartvig, 1997) and organic spring cereals (Melander et al 2018). Depending on the crop, increasing plant density and/or biomass may increase the risk of lodging, the incidence of other pests or reduce the marketable quality of the crop (Sardana et al 2017).

Crop competition and competitive cultivars

The choice of crop species can play a vital role in cultural control of weeds. Different species vary widely in their ability to compete with weeds and within each species cultivars will have different competitive abilitie. For example, barley and oats can be more competitive than wheat (AHDB 2019). In maize, narrow row spacing creates a closed canopy earlier than wide spacing, which helps to suppress weeds because very little light reaches the soil surface; this example of cultural control is effective because most control programmes in maize are dependent on post-emergence herbicide application (Jhala *et al*., 2014).

The majority of studies show that the most competitive species have vigorous growth that reduces the quality and quantity of light that penetrates the crop canopy (Buhler, 2002). The potential for competitive cereal cultivars was reviewed by Andrew *et al*. (2015) identifying three aspects to competitiveness of a cultivar for weed suppression:

1. Reducing the fitness of the weed species through competition for resources such as light and water (suppression)
2. Resisting yield loss (tolerance)
3. Producing chemical exudates that reduce growth (an allelopathic effect).

Crop diversity, including weed competitive species, varieties in growth cycles and maturities can help to reduce resistance problems by providing different harvesting dates and herbicide diversity (Beckie, 2017).

Cover crops

Cover crops were identified by several sources an effective IPM measure for reducing weeds (Wallace *et al*., 2019; Li *et al*., 2019; Jhala *et al*., 2014). For example, cover crops were shown to reduce Canadian fleabane, *Erigeron Canadensis,* abundance by between 56% and 82% (Wallace *et al*. 2019). Cover cropping can have other benefits, such as improving the quality of the soil, suppressing glyphosate resistant weeds and providing resources for naturally occurring predators and parasitoids of pests (Lenssen *et al*., 2013; Jhala *et al.,* 2014; Wallace *et al*., 2019), and have been associated with improved productivity (Birch *et al*., 2011). Intercropping is an effective measure but has practical limitations in both the equipment and knowledge required to manage them effectively, which is a barrier for some farmers and growers (Lamichane *et al.,* 2017; Lenssen *et al.,* 2013). Trap crops can effectively suppress pollen beetle populations and ensure that thresholds are not reached (Culjak, 2016; Cook, 2013).

Pest resistant crop and plant varieties

In addition to traits that improve the ability of a crop to out compete weeds (see improved crop competition), wild plants have evolved traits that help resist and/or tolerate pest damage, either through direct defences making the plants less detectable, attractive, edible or susceptible. Indirect defences, such as use of semiochemicals to attract beneficial species, are also used (Mitchell *et al.,* 2016). The selection of varieties with desired traits is a key preventative IPM measure contributing to reduced pesticide use. Selecting disease resistant varieties was frequently reported as a favoured IPM measure due to its practical ease and relative low cost (Stetkiewicz, 2018) and is a central part of disease resistance management in the UK (Barzman *et al.,* 2015). The AHDB's recommended List for cereals and oilseeds is published each year, providing an independent summary of yield and quality performance, agronomic features (including disease resistance rating with associated information on insect resistance as appropriate) and market options to assist with variety selection (AHDB website, 2020). The associated Variety Seletion tool supports farmers in identifying the most suitable varieties based on several factors including varieties tolerance/susceptibility to key invertebrate pests and diseases. For example, resistance of wheat to orange wheat blossom midge, *Sitodiplosis mosellana,* has been incorporated into several varieties (Thomas *et al.,* 2005).

Clubroot (*Plasmodiophora brassica*), a major disease of oilseed rape in the UK, and variety selection plays a key role in reducing the impact of infestations (McGrann *et al.,* 2016). Using resistant varieties could result in economic savings to farmers and growers, however, different varieties may have characteristics that require alternative management strategies. Varieties resistant to a specific invertebrate pest or disease may have lower yield capabilities or be more vulnerable to other pests. As the resistance mechanism for clubroot is considered to be the same in all varieties, sites where a clubroot resistant variety has been grown frequently in the rotation can result in resistance-breaking being selected for, leading to loss of control using variety resistance over time (McGrann *et al.,* 2016). In the case of whitefly control on tomatoes, it was noted that some varieties may need additional protection from pests in the first months after planting because they showed reduced susceptibility to pests rather than resistance (Arno, 2008). Plant resistance can cause a disruption in the natural enemy population, associated with changes in crops production of alarm pheromones used by natural enemies to identify plants under attack from pests (Thomas, 1999). Using varieties with a greater degree of resistance and/or tolerance to pests is crucial to the success of IPM strategies, however, its ongoing success requires farmers, growers and their advisors to understand the costs and benefits of the variety selected and adapt their management strategy accordingly (Ramsden et al 2017).

Soil cultivation

Soil cultivation techniques can be effective prevention and suppression measures as part of an IPM strategy. The sterile seed bed technique involves cultivating soil to allow weeds to emerge and then using a contact herbicide to destroy weed cover before sowing the desired crop (DAFM, 2020). Ploughing soil (turning of soil at a depth of about 15cm) can be effective at reducing pests by reducing moisture retention and so reducing the viability of disease causing spores or invertebrates (Leake, 2000) and burying weed seed deeper in the soil profile (Lutman et al 2017; DAFM, 2020). Reducing moisture retention is effective for controlling many invertebrate pests that are vulnerable to drying out, however it can also damage populations of beneficial invertebrates including earthworms and predatory ground beetles. There can be a lag period between the implementation of ploughing as an effective means of controlling black-grass populations in winter wheat and it has been shown, on average, to reduce populations by 69% when compared to non-inversion tillage (Lutman *et al*., 2013). Minimum tillage was most recommended for autumn-based cropping (DAFM, 2020) and can form part of an effective IPM strategy as weeds that are left on the top of the soil are less likely to germinate (Jhala, 2014), although occasional ploughing can make an important contribution). The pros and cons of all cultivation techniques on weed management are outlined in managing specific pests, particularly blackgrass (Lutman *et al.,* 2017) and also in a recent review (AHDB 2019). No tillage systems can lead to an increase in weeds and can contribute to herbicide resistance problems in weeds due to greater herbicide use (Beckie and Harker, 2017).

Improved irrigation

Improved irrigation scheduling was also highlighted as an effective preventative measure due to the improvements in crop health to ensure that the crop is less susceptible to crop pests (DAFM, 2020). Irrigation can also provide benefits in potato crops such as helping prevent common scab.

5.3.1.2 *Non-Chemical Methods*

Biopesticides

Biopesticides encompass mass-produced plant protection agents based on living organisms or their products (Bailey *et al.,* 2010). There are three types: microorganisms, botanicals and semiochemicals. Microorganisms, including bacteria, fungi, oomycetes and viruses can be highly effective biological control agents and several fungal based products are in use on protected crops. Botanicals, which are secondary metabolites produced by plants, often have insecticidal or fungicidal properties, and are commonly used in protected crops. These can include naturally derived substances such as pyethrins, spinosad and pelargonic acid. Semiochemicals are insect pheromones or plant volatiles (or derivatives) that can be used to manipulate pest behaviour. Sex pheromones have been the most widely applied, disrupting the mating behaviour of the target pests to help prevent the build-up of damaging populations (Witzgall *et al.,* 2010). To date, mating disruptors have been used predominately in enclosed environments and horticultural crops. Volatiles are also widely used in lures, for example in pheromone traps as part of regular monitoring.

Beneficial organisms

Biological control is a method of using biocontrol agents, such as entomopathogenic fungi or predatory invertebrates, to manage pest populations (DAFM, 2020). In protected crops the use of biocontrol agents is well developed, and initiatives such as ENDURE have improved the uptake and effectiveness of their use in this sector. This is well established in Europe and largely consists of the intentional release and management of selected species against targeted pests within the cropping environment, known as augmentative biological control (van Lenteren *et al*., 2018). While there are some examples of augmentative biological control in outdoor crops, conservation biological control is far more common. This involves the enhancement of naturally occurring beneficial species through the provision of additional resources in and around cropping systems (Pujari, Battacharyya and Das, 2013; Ramsden *et al.,* 2015).

The abundance of beneficial insects within agricultural landscapes can be limited by a lack of key resources such as the availability of additional alternative prey when pest abundance is low, suitable habitat in which to survive winter conditions, pollen for sexual development, and sugars (e.g. honeydew or floral and extra-floral nectar) for sustenance (Wäckers, 2004; Landis *et al*., 2000; Griffiths, 2008). Field margins can be an effective measure for providing these additional resources (Ramsden *et al.,* 2015). By increasing resource availability, the abundance and behaviour of natural enemies can be manipulated to increase predation on pests within crops, for example reduction in the population growth rate of cereal aphids in wheat during the spring (Ramsden *et al*., 2016; Fraser, Sharma and Bailey, 2011) and reducing pollen beetles in oilseed rape (Cook *et al*., 2013). Beetle banks are already part of national stewardship schemes and have been designed to provide winter habitats for ground dwelling predators, including ground beetles and rove beetles (Thomas et al., 1991). Studies have shown them to be effective in increasing numbers of targeted species in the adjacent field (Griffiths et al., 2008), and they have proved popular with farmers. Evidence does suggest, however, that the associated benefits to pest suppression diminish after 50-80 meters from the beetle bank, and there is limited direct evidence of benefit to flight capable species such as hoverflies and ladybirds (Pywell *et* al 2005; Holland et al., 2012).

Landscape scale investigations have identified a link between landscape complexity and natural enemy abundance, suggesting that increased diversity of crops and non-crop habitat within the landscape leads to greater natural enemy abundance. It is likely that this diversity increases the availability of resources for beneficial species, though other facts such as habitat disturbance and management intensity play a role. For wheat growers in the UK, it was found that the proportion of grassland in the surrounding landscape had a positive effect on predation, whereas woody landscapes had a negative effect (Holland *et al*., 2012). Limitations of the benefits of grassland were acknowledged, and the findings of this should be communicated with caution as the introduction of semi natural habitats alone would not provide sufficient levels of crop protection (Holland *et al*., 2012). For natural enemies to be effective there is a need for farmers or growers to understand how species interact (Buitenhuis, 2014), which can be a barrier to correct implementation. Field margins may have some benefit in the adjacent crop; however, they are most effective where they are managed at a landscape scale to support a sufficiently robust, diverse and abundant polyculture of natural enemies (Greenop *et al*., 2018). Natural enemies may be less susceptible to pesticides than the targeted pest species, however, there are often sub-lethal effects leading to reductions in the diversity and abundance of beneficial natural enemies (Gentz *et al*., 2010).

Physical barriers

Nets have been reported as being an effective measure in reducing codling moths in apples (Heijne *et al*., 2014) and reducing silverleaf whitefly (*Bemisia tabaci*) in greenhouses (Arno, 2008). Witkowska *et al.* (2018) found that the use of net covers was the most effective approach for reducing damage to radish crops by the cabbage root fly (*Delia radicum*), however, this was dependent on a sufficient period of time being left following the previous radish crop to minimise the risk of the adults emerging from pupae in the soil beneath the net cover. Cropping fleeces and net covers can in some cases lead to the creation of a micro-climate which can increase the risk of disease (DAFM, 2020).

Mechanical weeding

Mechanical weeding techniques have been effective on a range of crops and the development of new technologies that can use sensing and robotic intelligence are predicted to eliminate the need for hand-weeding in the future (Lamichane *et al*., 2017). Similarly, the benefits of technological advancement in agriculture could support plant health, ensure stable yields and provide a new approach to crop protection (Nawaz and Ahmad, 2015).

The use of propane burning of weeds was viewed as a non-chemical alternative but the environmental impacts associated with the burning of gas and soil damage that it can cause could have detrimental effects on other areas of the farm and the long term benefits are limited (DAFM, 2020).

5.3.1.3 Monitoring

Local and regional pest occurrence and forecast data can be integrated into IPM decision support systems (Giles *et al.,* 2017). In combination with knowledge of the ability of a crop to tolerate damage and frequent crop walking by farmers, growers and their agronomists, it is possible to make informed decisions about the need to take further action, such as pesticide application (Ramsden *et al.,* 2017). Monitoring can also support the evaluation of the effectiveness of IPM measures (Beckie and Harker, 2017). In addition to crop walking, thresholds form an important part of informed decision-making during monitoring. The applicability of thresholds differs between crop types and pests, and most thresholds for arable invertebrate pests are not based on published evidence (Ramsden *et al.,* 2017). It was found that spray thresholds required revising for apple orcharards in Northern Ireland (Cuthbertson and Murchie, 2006). Reduced tillage combined with the use of control thresholds was shown to lead to a decrease in insecticide use and associated production costs, such as labour cost (Nilsson *et al*., 2015). For some diseases, thresholds are less useful, such as in late blight (*Phytophthora infestans*) in potato, downy mildew in field beans (*Perenospora viciae*) and septoria leaf blotch (*Mycosphaerella graminicola*) in wheat (DAFM, 2020). In oilseed rape, delaying treatment until pest thresholds are breached was viewed as positive (Nilsson *et al*., 2013) and forecasting systems were reported as being able to help farmers and growers make the decision of when to spray (DAFM, 2020). In the case of the pea moth *Cydia nigricana F.* (Lepidopptera: Tortricidae) the larvae feed directly on peas inside the pod, making direct monitoring difficult. For this, and many other pests, yield loss per larvae can be estimated and related to the abundance of an alternative life stage, such as monitored adults using pheromone traps (Huusela-Veistola and Jauhiainen, 2006). Where pest damage has an indirect impact on yield (i.e. reducing crop vigour rather than direct damage to seeds), losses are more difficult to quantify and are often only possible at a population level rather by monitoring local abundance of pests (e.g. cereal aphids, (Larsson, 2005). Sticky traps can be an effective monitoring tool, though, as they are indiscriminate in the insects caught, they have the potential to impact on non-target species. In French beans, sticky traps have been used effectively to monitor thrips, with little negative impact on their natural enemies (Muvea *et al*., 2014).

5.3.1.4 *Informed Decision Making*

Various sources of information are available to crop protection decision makers, including agronomy services, online decisions support systems, levy bodies and personal or public knowledge sharing networks. Farmers and growers can be risk averse, applying a more intensive application programme than is required. Often to avoid large losses in years where severe epidemics or large pest populations develop. In New Zealand, strong knowledge support networks were found to help farmers and growers make informed decisions on pest management. They found that farmers and growers often underestimate the potential impact of pests on their farm until they have experienced a significant event which led to economic loss (Mansfield *et al*., 2019). Following such an experience, or based on the experience of others, excessively high levels of protection may be implemented (such as insurance sprays) irrespective of the actual risk of the target pest occurring. Through networks it is possible to equip farmers and growers with the information on the costs and benefits of IPM and to provide the appropriate advice to implement effective IPM measures (Mouden *et al*., 2017). Evidence based recommendations of IPM measures are most effective when evidence is gathered on farm with support from influential network members (Nilsson *et al*. 2015). Provision of training for more challenging IPM measures, such as the use of bioprotectants, is highly effective in increasing their use and efficacy (Chattopadhyay, Banerjee and Mukherjee, 2017).

Access to technology improves the ability of farmers and growers to make effective decisions on pest control (Barzman *et al*., 2015, Toma *et al*., 2018). Decision support systems (DSS) cover a diverse range of tools including pest monitoring and treatment thresholds, forecasting pest density and damage and systems for comparing treatment options. DSS have been developed to assist all aspects of the eight principles of IPM and frequently combine a large amount of information on pests and crop growth resulting in different outputs depending on the needs of the end user. For example, they may focus on determining the risk in a specific region or provide information on crop inputs based on the susceptibility of a variety to a particular pest. The uptake of DSS can vary by country. For example, it is estimated that recommendations based on decision support systems for the control of late blight (*Phytophthora infestans*) are used on 8% of the UK potato area whereas in Nordic countries this is much higher at around 40% (Ritchie *et al*., 2018). New technologies that allow the latent detection of pathogens were viewed as being a positive effective future development that would help potato farmers and growers to make informed decisions on pest management (Barzman *et al*., 2015).

5.3.1.5 *Anti-resistance management*

Anti-resistance management is a key part of IPM and will help to ensure that chemical products remain effective. Three key groups are responsible for informing the industry in the UK; the fungicide resistance action group (FRAG), the weed resistance action group (WRAG) and the insecticide resistance action group (IRAG). When considering anti-resistance management strategies for all pests, it is necessary to:

- Measure and test the potential for resistance to develop
- Develop anti-resistance management strategies specific to target pests

- Consider the implications of using these strategies on ‘non-target’ pests
- Produce clear and practical guidelines to implement anti-resistant management strategies.

The aim of resistance management is to slow selection for resistance, whether for an insect, disease or weed species, thereby providing ongoing control and prolonging the effective life of pesticides. Several resistance management strategies have been proposed, including alternation of modes of action (MoA), mixtures of multiple MoA, and adjusting pesticide dose. Guidance on optimal strategies differs depending on whether the resistance concerned relates to fungicides, herbicides or insecticides (described in more detail below). However, a review of antibiotic, insecticide, herbicide and fungicide resistance research concluded that mixtures in which each component was used at its full label dose (the registered maximum dose per application, specified on the label) was the optimal resistance management strategy (Bourguet *et al*., 2013). Clearly, further research is needed to determine whether such mixtures are the optimal strategy regardless of the organism, or whether anti-resistance management strategies required for weeds, pests and diseases all differ.

Weed control is challenging as the availability of herbicides is declining, through withdrawal of active ingredients or resistance, and there have been no new MoA coming to the market. Currently, weed management strategies recommend considering weed control across the whole rotation: keeping weed populations low through both cultural control and maximising the performance of herbicides being used (AHDB, 2017). Tactics include limiting the number of applications in a single season, mixing different herbicide modes of action and using the appropriate dose to minimise survivors. This would also be considered good practice for anti-resistance management, however, in many instances populations are already resistant when such strategies are considered and, once resistance has developed, it does not go away (WRAG, 2012). For blackgrass control, the current ‘IPM’ approach has been highlighted as being used ‘out of necessity’ rather than an active step to reduce pesticide use (Moss, 2017). The annual cost of blackgrass resistance in the UK is estimated to be £0.4 billion with loss of total herbicide control estimated to be £1 billion (Varah *et al*., 2019). Resistance in broad leaved weeds occurs but is less common, with populations of poppy, chickweed and mayweed reported (Tatnell *et al*., 2016). Another example is glyphosate resistance where, although there are no known cases in the UK, an over-reliance globally has resulted in resistance development (WRAG, 2018). Research is underway in the UK to develop guidelines to reduce the risk of resistance development using four key anti-resistance management principles: prevent survivors, maximise efficacy, use alternatives and monitor success (AHDB, 2015).

The aim of fungicide resistance management is to slow selection for fungicide resistant strains. A peer-reviewed worldwide analysis of evidence on the effectiveness of fungicide resistance management strategies identified ‘governing principles’ which could be used to determine whether particular changes to fungicide programmes would increase or decrease selection for fungicide resistance (van den Bosch et al., 2014). There was strong evidence from field experiments for many pathogens across a range of crops that reducing the exposure time of a pathogen to a fungicide reduces selection. This supports the use of mixtures of two fungicide groups with contrasting modes of action, lowering the dose of specific fungicides used as well as using products with contrasting modes of action in alternation throughout the fungicide programmes. The use of fungicides has also been demonstrated, in modelling studies, to decrease the selection for virulent strains of *Phytophthora infestans*, which causes potato late blight (Carolan *et al*., 2017). The importance of cultivar/variety resistance has been stated previously as a key strategy for IPM therefore the appropriate use of fungicides may not only decrease the risk of fungicide resistance development, it may also reduce selection for virulence and help to prolong genetic resistance, however, this requires field-based experimental evidence to confirm.

For invertebrate pests, multiple new cases of insecticide resistance in economically important pests have been detected in the last decade in the UK. These include grain aphid (*Sitobion avenae*) in cereals (Foster *et al*., 2013), cabbage stem flea beetle (CSFB, *Psylliodes chrysocephala*) in oilseed rape (Højland *et al.*, 2015) and willow-carrot aphid (*Cavariella aegopodii*) in carrots (Fera, 2018). The majority of new cases of insecticide resistance in the UK is to pyrethroids, which is likely to due to our long-term over reliance on this class of insecticides, e.g. >90% of all insecticides applied to arable crops in 2018 were pyrethroids (Garthwaite, 2019). In some cases, resistance has meant that growers have no effective chemical options available, resulting in huge crop losses and widespread changes in crop cultivation. For example, losses of oilseed rape to CSFB in recent years [e.g. 9% of the national crop lost in 2016/17 (Wynn *et al*., 2017) with losses in 2019/20 likely to be considerably higher] has resulted in rapid reductions in oilseed rape cultivation in the UK (Harris, 2019). Monitoring of UK insecticide resistance has occurred annually for several years (e.g. AHDB, 2017b), and is central to understanding the status of current resistance cases and identifying new ones. Current guidance advises that alternating different MoA is the best insecticide resistance management strategy (IRAC, 2012; IRAG, 2019), while mixtures and reduced doses have not been advocated as strategies (IRAC, 2012; IRAG, 2019). However, a recent modelling study found that mixtures and lowering dose may be more effective, however, experimental validation is needed before guidance can be updated (White *et al.*, 2017).

Developing anti-resistance management strategies for key pests is necessary, however, their impact on 'non-target' species are also important and needs to be determined. We need to understand the distribution of insects, disease and pests nationally so the scale of a particular problem can be measured. This is likely to be particularly pertinent for weeds as understanding where they are in the country could result in better guidance and site specific implementation of measures to reduce their spread e.g. on machinery. This should be coupled with robust herbicide resistance testing to identify the location of resistant and sensitive populations and the associated long term risks to yield from resistance. For insecticides and fungicides, the effectiveness of anti-resistance management strategies need to be determined for specific pathogen/crop systems as there will be different requirements for fungicide inputs as well as access to modes of action for implementation. The contribution of other non-chemical control measures, such as biopesticides, is another aspect likely to require more investigation in future, particularly in arable crops where their use is histirocially lower.

For all pests, developing and implementing anti-resistance management strategies prior to resistance developing and a more targeted approach to the use of pesticides will be key to prolonging the effective life of an ever reducing chemical tool box and decreasing the environmental impact. Taking a proactive rather than reactive approach to anti-resistance management will mean that chemicals will be be used in a more sustainable way and help to prolong their availability.

5.3.1.6 *Pesticide selection, reduced pesticide use and evaluation*

Better understanding of the effectiveness and specificity of pesticides as well as the appropriate doses required to maintain effective control are all key components of an IPM strategy and prolonging the duration of time that they are available for use. Pesticide selection, reduced pesticide use and the evaluation of pesticides are therefore considered together as the three themes will be interlinked in practice. The effect that IPM measures had on pesticide use was explored in research question one where measures that led to a reduction in pesticide use are reported. Overall, reduced pesticide use was an important component of IPM in order to delay pesticide resistance (Waters et al 2012), (Wallace, 2019), (Lamichane et al. 2017). Biopesticides were viewed as being an environmentally beneficial alternative to chemical pesticide use (Chattopadhyay, Banerjee and Mukherjee 2017). Scheduled spraying, that was based on predicitions made by a decision support tool, was a method that was reported as reducing pesticide use because the farmer or grower was able to make an informed decision about the risk of a pest to the crop (Nilsson et al. 2015). The Voluntary Initiative's Crop Protection Management Plans were viewed as an initiative that helped to encourage farmers and growers to consider the type of pesticides to apply to their crops (Fraser, Sharma and Bailey, 2011). More detail about the Crop Protection Management Plans can be found as a case study in appendix 8.39.

The AHDB funded 'Fungicide Performance' project is an example of the provision of independent information on fungicide effectiveness at a range of doses, allowing growers and advisors to select the appropriate dose and product(s) for the control of key fungal diseases in wheat, barley and oilseed rape (AHDB, 2018). This allows the implementation of fungicide programmes that appropriate to local disease risk and at doses that will provide effective control. The project was also linked to the 'Fungicide Futures' initiative, which was a joint venture between AHDB and FRAG to put anti-resistance management at the heart of fungicide programmes. This meant that fungicide programmes are not only effective but there are in line with current best practice guidelines for fungicide resistance management.

It has been highlighted that the eventual solution to herbicide resistance will require a reduction in pesticide use (AHDB, 2019). Although there are environmental considerations, the evolution of herbicide resistance driven by the intensity of exposure to herbicides and correlated to the frequency of herbicide applications (Hicks *et al*., 2018). Herbicide doses need to be appropriately high to limit survivors, however, steps need to be taken to limit their use. Therefore, selecting the right herbicide at the appropriate dose to maximise control will be a key focus for research going forward. Moss (2019) highlights that there has been little reduction in herbicide use despite evidence to support the use of non-chemical alternatives. These alternatives can increase complexity and management time required to implement a weed management strategy. The recommendations are to encourage a longer-term approach to weed control, working to change attitudes towards using non-chemical strategies and the routine use of herbicides, re-evaluating research and knowledge transfer priorities. The introduction of IPM strategies, for example rotational ploughing, without an associated decrease in herbicide spend and use is unlikely to be of benefit with regards to costs and resistance management. Recently there has been an interest in introducing livestock into the arable rotation, which offers an opportunity to decresed pesticide inputs and decrease the black-grass seed bank (AHDB, 2018). There is a current project funded by AHDB Beef & Sheep sector 'Sustainable beef systems on arable units' (April 2016-March 2021) led by ADAS. The project is investigating the practical, economic, environmental and agronomic implications of integrating beef enterprises into arable system at two farms (in Cambridgeshire & Somerset).

Reduced pesticide application and the associated uptake of IPM measures will require farmers, growers and their advisors to adjust their behaviours and agronomic philosophy (Barzman *et al.,* 2015). Change will come with crop specific and farm-wide economic, technological and environmental challenges (Laminchane *et al.,* 2017). Similarly, some minor pests currently controlled as a result of conventional broad-spectrum pesticides being applied to control major pests may require closer attention in the future. Reduced pesticide use is likely to require more than just selecting an effective pesticide. The re-evalution of pollen beetle thresholds is a recent example which resulted in a substantial decrease in insecticide use on oilseed rape. Applications for pollen beetle control used to account for 34% of all insecticide usage in 2010 (Garthwaite *et al.*, 2011) and just 8% in 2018 (Garthwaite *et al.*, 2019). The area sprayed for pollen beetle in 2018 can be estimated at approx. 92,000 ha (Garthwaite *et al.*, 2019) compared to a high of approx. 398,000 ha in 2012 (Garthwaite *et al.*, 2013). This change is likely due both to the appearance of pyrethroid resistance in pollen beetle in 2007 (Richardson, 2008), which meant that increasingly growers would need to resort to more expensive alternatives to pyrethroids, and the revision of the yield impact of the pest, which meant that treatment thresholds could be raised (Ellis & Berry, 2012; Ellis *et al.*, 2017). The availability of wheat varieties resistant to orange wheat blossom midge (OWBM) also resulted in dramatic reductions in insecticide use. In 2006 (before resistant varieties were widely available), 32% of insecticides applied to wheat were for OWBM control (approx. 635,000 spray ha) (Garthwaite *et al.*, 2007), while in 2014 this had dropped to just 1% of insecticides (approx. 16,000 ha) (Garthwaite *et al.*, 2015).

Evaluation is an important element of an IPM approach. It is common for farmers, growers and agronomists to frequently scout fields, which can lead to an improvement or modification in their pest management strategy for the following year (Herbet and Flessner, 2016). Record keeping and monitoring the results of a pest management strategy was viewed as a continuous activity that enabled farmers and growers to evaluate the effectiveness of their IPM approach (Tuovinen, 2015). Additionally, by evaluating the success of IPM measures and strategies it could be possible to increase IPM uptake by being able to provide farmers and growers with quantitative data, giving an indication of the efficacy of an IPM strategy. This lack of quantification was viewed as an evidence gap in the literature that if appropriately addressed could help to build confidence in IPM, leading to an increase in uptake (Ehler, 2006).

5.3.1.7 Combining IPM Measures

A holistic approach to IPM requires the incorporation of preventative and suppressive measures, non-chemical control, monitoring, informed decision making and evaluation across the farm and over multiple seasons to create a sustainable and productive cropping environment. In some cases, IPM measures that are beneficial for controlling one pest may encourage another, or result in a yield penalty (e.g. delaying drilling date can reduce the risk of BYDV, but also reduces yield potential (Foster *et al.,* 2004). Within the Dephy network in France, the main management measures implemented by farmers with low pesticide use were the inclusion of temporary grassland within the rotation (for livestock), crop diversification (crop and sowing season), cultivar diversification, delayed drilling for cereals, reduced doses, reduced ploughing and moderate application of fertilisers (Lechenet *et al.,* 2017). These are all preventative and/or suppressive actions that would fit well with existing agronomic practices and are important components in resistance management strategies (Moss et al 2017). There is a need, however, for robust research and demonstration to support the implementation of such strategies on farm. Non-chemical measures are more difficult to implement, as they require bespoke management in order to be effective and are often most effective in combination with other measures (Beres *et al.,* 2011). Furthermore, many of the preventative and suppressive measures will impact on the way in which non-chemical measures should be implemented and the scale of impact of different measures makes quantitative comparison of measures extremely difficult.

5.4 Research question 3: What are the impacts of IPM on the wider environment?

5.4.1 Research question 3: Headlines

The following headlines have been identified from the evidence on environmental impacts of IPM:

- Most articles identify a positive impact on the wider environment from IPM, linked to a decrease in chemical pesticide use.
- A number of evidence sources highlight a public perception that chemical pesticides have a negative effect on human health and biodiversity.
- The evidence focusses on benefits to the wider environment, including resilience of yield, soil quality and soil organic carbon (SOC), and biodiversity. To a lesser extent benefits were related to climate change.

5.4.2 Research question 3: Overview of evidence

Evidence was spread across different countries, with most coming from scientific journals (Table 11). The following themes were identified:

- IPM improves biodiversity;
- IPM improves soil health;
- IPM helps suppress weeds and reduce overall use of chemical pesticides, which could reduce weed resistance to chemical herbicides; and
- IPM does not negatively affect yields (Table 12).

Table 11. RQ3: Table of evidence

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
France	1				
North America	1				
UK	1			1	
Other	6	1	1		
Total	**9**	**1**	**1**	**1**	

Table 12. RQ3: Main themes and supporting evidence

Theme	IPM approaches improve biodiversity.			
	Yes		No	
	Number[4]	Quality[5]	Number	Quality
Number of articles that answer the RQ	11	4	0	n/a
Theme	IPM approaches improve soil quality.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	6	4	2	5
Theme	IPM helps suppress weeds and helps reduce overall use of chemical pesticides which could lead to a decrease weed resistance to chemical herbicides.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	7	4	1	5
Theme	IPM does not negatively affect yields.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	6	4	1	5

5.4.3 Research question 3: Content of evidence overview

5.4.3.1 *What are the impacts of IPM on the wider environment?*

The evidence available covers several environmental impacts of IPM, often relating them to a decrease in continued volume of use of chemical pesticide. In many articles, the impacts of IPM and pesticides are not directly researched but rather discussed via a review or report. The majority of the evidence indicated that there are negative environmental impacts from chemical pesticides on air, soil and water quality, biodiversity and now a significant increase in chemical resistance due to the overuse of chemicals, especially for weed control. IPM was routinely reported as promoting healthy plants, sustainable bio-based pest management alternatives, reducing environmental risk from pollution, and protecting non-target species through reduced impact of pest management activities (County of Santa Clara, 2019; Heijne *et al*., 2015). Three of the top four findings indicate that IPM has environmental benefits and

[4] Number of articles which provide evidence for that response to the RQ.

[5] Average quality score of the group of articles providing evidence to the RQ (1 = low quality, 5 = high quality evidence).

this was represented in over three quarters of the evidence reviewed for this research question.

There were a few articles linking IPM uptake to an improvement in soil health and quality. These are focused on the measure ‘no-till’, which is sometimes considered an IPM measure as some weeds on the top of soil are less likely to develop, and no-till helps conserve soil water content. Additionally, those who practice IPM often practice other conservation farming methods, including no-till or min-till farming. Van der Meulen *et al*. (2015) and Duke (2011) draw attention to reduced tillage resulting in improved soil organic matter and reduced carbon dioxide (CO_2) emissions. Bahadur *et al*. (2015) describe how conservation or zero-tillage can positively impact soil carbon and organic matter, thus reducing nitrogen mineralisation and potential GHGs. However, Chauhan *et al*. (2012) links low tillage to an increased weed abundance, explaining how the lack of tillage can help weed germination and make weed management much more complicated in an IPM low tillage system. Additionally, low tillage is more suited to drier and stable structured soils, as sandy soils could experience compaction damage due to minimum tillage (SAC). However, low or no till systems commonly leave weeds on the surface of the soil that is controlled by herbicide application, which has been noted as a criticisim of this approach (Soil Association, 2018).

The Global Food Security report (2017) highlighted that reductions in pesticide use could lead to other methods of weed control, such as ploughing, which can reduce the ability of soil to store carbon, increasing emissions, and depleting micro-organisms in the soil. It is apparent that there is a trade-off between tillage and IPM which can impact the wider environment. There is potential for micro-dosing and the use of robots as weeding machines to help address this issue.

Although the evidence focuses mainly on the positive aspects of IPM on the wider environment, the issue is complex and it is likely that different measures in different places will have differential impact on the wider environment. Way and van Emden (1999) found IPM was good for game birds, using field corners for rough grassland and bird seed. However, they also state that the flowering buffer strips may promote viruses and bring disease to crops, especially wheat.

Vermue *et al.* (2013) found integrated weed management led to higher emissions of the GHG nitrous oxide (N_20) than conventional weed management strategies, which typically include a higher use of herbicides. However, this finding was thought to be due to soil condition within the trial rather than a finding which is applicable across the majority of IPM use. Additionally, Lenssen *et al*. (2013) recognised that cover crops can lead to a decreased soil water content for the following crop. This is beneficial in the UK where winters are often wet; however, in hotter countries, reduced soil moisture could be problematic. Lenssen *et al*. (2013) stated that, although there are many benefits to IPM, in their study, there was no difference in incidences of club root or weed infestation between conventional and diverse cropping fields. The report is not wholly negative about IPM but rather reports some issues found in their trial. Ultimately, the evidence finds that it is important to have the right IPM measure in the right place to secure the best environmental outcome.

5.4.3.2 *Public perception of IPM*

Many of the articles comment on the public perception of pesticides and herbicides and that IPM is seen as favourable by the public as it is associated with a lower impact on the wider environment. Kevan (2011) states *"the general public is an influential stakeholder driving market changes in production agriculture politically and industrially"*. Public perception and a favourable view of IPM has been linked to the growth of agri-environment schemes and uptake of IPM methods though government funding (Holland *et al*., 2012; PAN UK, 2018). PAN UK[6] (2018) believe that the growth of IPM is dependent on further support from the government post-Brexit to ensure that the cost-benefits and potential initial losses of yield are acceptable. Non-governmental organisations promoted the reduction of pesticide use on behalf oft the public (Lundgren, 2018[7]) but there is a gap of quantitative evidence that provides an insight into the public's understanding of IPM.

Labussiere *et al*. (2010) state that practices such as biotechnologies, micro-dosing and the use of robots, are likely to help in reducing overall pesticide use and will likely be accepted by the public for their overall 'good'. They noted that even though some technologies may raise new environmental and health concerns, the overall reduction in use of chemical pesticides will be positive for the planet and people (Labussiere et al., 2010).

5.4.3.3 *Evidence gaps identified*

A range of evidence is available on the impacts of the uptake of IPM on the wider environment, but the majority focuses on the impacts of decreasing chemical pesticide use rather than informing the understanding of direct environmental impacts of the individual IPM measures. Evidence gaps that were identified are that there could be an increase in the availability and awareness of information on non-target effects of pesticides. Additionally, there has been little work completed on the role that IPM has in creating a more robust agricultural landscape. The impact of climate change could be partially or entirely mitigated through implementation of IPM measures. For example, creation of a more diverse crpping landscape as part of enhancing beneficial organisms will also benefit non-target species, that may be otherwise vulnerable to changes in climate.

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[6] PAN UK are a campaigning charity with the main aim of reducing chemical pest control.

[7] This paper was produced by Friends of the Earth who are an environmental campaigning organisation.

5.5 **Research question 4:** What are the socio-economic impacts of IPM on the farming industry?

5.5.1 Research question 4: Headline

The following headlines have been identified in the evidence in response to the third research question:

- The socio-economic impacts of IPM on the farming industry are mainly identified as those from decreasing chemical pesticide use, including the economic saving to the farmer/grower by following an IPM approach.One of the key social benefits outlined was increased confidence in IPM, which helps to build networks within the farming industry.
- Other topics discussed included the effect that the supply chain can have on IPM uptake, policy incentives that encourage farmers/growers to take up IPM and how an improved understanding of IPM can lead to positive impacts on the farming industry.

5.5.2 Research question 4: Overview of evidence

The evidence used to respond to the research question was from across the world and mostly in the format of scientific journals (Table 13). The following themes were identified from the evidence available to respond to the research question: What are the socio-economic impacts of IPM on the farming industry?

- The uptake of IPM has an economic benefit to growers,
- Growers are reluctant to take up IPM as they wish to protect yields,

Reliability of IPM intervention is important for growers (

- Table 14).

Table 13. RQ 4: Table of evidence.

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Germany	3				
Netherlands				1	
New Zealand	4				
North America	9	1		1	
UK	5	2			2
Other	21		5	2	
Total	**42**	**3**	**5**	**4**	**2**

Table 14. RQ4: Main themes and supporting evidence.

Theme	IPM uptake has an economic benefit to growers			
	Yes		No	
	Number[8]	Quality[9]	Number	Quality
Number of articles that answer the RQ	14	4.06	0	n/a
Theme	Growers are reluctant to uptake IPM because they want to protect yields			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	11	3.96	0	0
Theme	Reliability of IPM intervention is important to growers			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	16	3.8	0	0

5.5.3 Research question 4: Content of the evidence overview

5.5.3.1 *Economic impacts of IPM uptake*

The role of IPM in reducing the use of pesticides was viewed as having a positive financial benefit to growers. The literature clearly indicated that growers can increase profitability by adopting IPM techniques. In England, no till conservation agriculture, which is no inesntive soil manipulation (e.g. ploughing), was thought to be more economically advantageous than a high input system (Lundgren, 2018[10]). However, it is suggested that for North American growers to implement IPM practices an economic assessment of the potential impact that IPM could have on their business is needed. An economic assessment takes into account likely savings from reducing the amount of pesticides used but also the potential differences in produce prices if the farmer or grower entered alternative markets, such as wholesale, where there may be a difference in the price paid for unblemished fruit (Bradshaw and Hazelrigg, 2017). Communicating the financial gains that growers could make by increasing IPM

[8] Number of articles which provide evidence for that response to the RQ.

[9] Average quality score of the group of articles providing evidence to the RQ (1 = low quality, 5 = high quality evidence).

[10] This paper was produced by Friends of the Earth who are an environmental campaigning organisation.

measures was viewed as being important in increasing IPM uptake (Way and Emden, 1999). There has reportedly been a decrease in California's pesticide use since 1995, despite an increase in agricultural production (Farrar, Baur and Elliott, 2016). In North America pesticide-use has escalated through the introduction of herbicide resistant crops (Benbrook, 2012).

Biological control was viewed as increasing profit for growers (van Lenteren, 2012) and it was described as commonplace in the glasshouse sector (George *et al*., 2011). However, for some growers, IPM is viewed as too economically risky if it does not adequately protect their crops and more confidence is needed in IPM for uptake to be widespread (Horne, Page and Nicholson, 2008). Encouraging growers to account for risks and the length of time it takes for an integrated pest approach to be effective has been described as a key part of France's National Action Plan and importance has been placed on the role that socio-economics plays in IPM. Sharing knowledge between growers has been noted as a way of helping to build confidence in IPM (Bürger *et al.,* 2012). Public and private institutions could play a role in developing knowledge exchange amongst growers (Anderson *et al.,* 2019). Networks that provide an opportunity for discussion and knowledge exchange were also noted as being important in encouraging growers to take more risks and adopt IPM (Mansfield *et al.,* 2019).

5.5.3.2 *Growers are reluctant to take up IPM as they wish to protect yields*

The literature indicates that the focus that growers have on protecting yield has limited the levels of IPM that are practiced. Farmers and growers were reportedly willing to use a high volume of pesticides to protect yields, however, the savings that growers can make by using IPM measures can offset any losses to overall yield (Way and Emden, 1999) and IPM has been shown to sometimes improve yield (Heijne *et al*., 2015). The desire to protect yields is understandable and in the USA, it has been estimated that the agricultural industry loses US$470 billion dollars annually due to pests (Harvey, 2015), even with current pesticide usage. Growing crop mixtures has been suggested as a way of achieving high and stable yield, whilst reducing the cost of chemical inputs (Creissen, Jorgensen and Brown, 2016). Where growers have experienced negligible yield differences due to changing their practice to follow an IPM approach they have reportedly developed a keen interest in protecting their beneficial predators (Horrocks *et al*., 2010). This supports the wider benefits that are outlined above, such as encouraging knowledge exchange between growers (Bürger *et al*., 2012) and working towards increasing the reliability of IPM (Labussiere, Barzman and Ricci, 2010).

Pesticide resistance of crops was viewed as having a conflicting impact on pesticide use and yields. On the one hand it could be seen that poor management of herbicide resistant crops has led to increased resistance and in turn, increased pesticide use (Green and Owen, 2010). On the other hand, it may have also led to farmers trying alternatives to pesticides. Resistance was viewed as an inevitability (Matthews, 2014) and in Ohio potato growers were reported as being reliant on chemicals and contributing to resistance problems (Waller *et al*., 1998). The potato growers also believed that a cycle of insecticides would continue to be produced to replace chemicals that were no longer effective (Waller *et al*., 1998).

5.5.3.3 *Social impacts of IPM uptake*

Change in attitudes towards IPM was viewed as helping to increase the adoption of IPM but only if accompanied by more effective and economical biopesticides (Glare *et al*., 2012). The

Voluntary Initiative was viewed as helping to encourage best practice pesticide use in industry and research and has helped to quantify IPM uptake in England (Bailey et al. 2009). IPM uptake can be measured on a self reporting basis, where farmers, growers and agronomists complete their IPM plans, which were introduced in 2014 and are a requirement for crop assurance schemes, such as red tractor. The number of Voluntary Initiative IPM plans that were completed for England in April 2016-March 2017 was 16085 (Pesticides forum, 2017). However, the lack of formalquantification for IPM uptake can been viewed as a gap in the literature (Ehler, 2006).

The literature outlined positive environmental impacts that IPM can have. Alternatives to conventional pesticide use, such as biopesticides, augmentative control, mechanical weeding, resistant cultivars and prophylactic methods were believed to lead to a reduction in chemical use but it was believed that they need to be more reliable for growers to use them (Labussiere, Barzman and Ricci, 2010).

Beyond environmental benefits, IPM was viewed as being a systems-based approach, which can help farming become more economically and socially sustainable, partly due to the wide range of measures available as part of IPM (Midmer, Drummond and Mitchell, 2016). Cherry producers in the USA were able to make informed decisions from monitoring and reduce chemical applications, which was able to provide a financial saving and an environmental benefit, whilst not lowering the quality of their products (USDA, 2020). However, the effectiveness of IPM measures and the ease of their implementation could differ between cherry growers and arable farming (USDA, 2020). In the Netherlands, economic savings made by using IPM measures were found to be an important incentive to encourage the adoption of IPM techniques by growers (van Eerdt *et al*., 2014).

Supermarkets, maltsters and distillers have been noted as being influential actors to encourage IPM in the supply chain (Barnes *et al*., 2016). In the US, the seed industry help encourage more sustainable weed and insect pest management systems (Benbrook, 2012). Public attitudes towards pesticides could also be a driver for IPM uptake, specifically lowering pesticide use, which has reportedly affected apple orchard growers in Northern Ireland (Cuthbertson, Qiu and Murchie, 2014). Pressures that the growers face include a demand to produce more food, both profitably and sustainably, whilst using fewer pesticides and keeping consumer prices low (Hillocks, 2011). Food production failure could potentially lead to higher prices, due to the need to rely on imports (Global Food Security, 2017).

5.5.3.4 *Evidence gaps identified*

The literature identified research gaps such as the socio-economic impact on the agricultural sector from a large reduction in pesticide use (Lechenet *et al.,* 2017). Quantification of IPM uptake has been noted as a research gap in America and Europe (Ehler, 2006) and there is also a need for more quantitative evidence on the costs and benefits of IPM (Lefebvre, 2017). Moreover, there is a lack of research identified on the social impacts of IPM uptake including information on human and social capital. Local demonstration of the efficacy of IPM measures could be viewed as a research gap that if addressed can help IPM be viewed as a normal process. There is a perceived lack of evidence on the frequency of damaging levels of pest infestations, the potential scale of yield loss, and the frequency of decision support systems giving false negatives. These are critical to the uptake of IPM, as without this evidence it is very difficult for farmers and growers to move away from often prophylactic pesticide use. The utilisation of large-scale UK IPM experiments and economic data could be a possible contributor to building this evidence base.

5.6 **Research questions 5:** What are the barriers to uptake of IPM measures or approaches?

5.6.1 Research question 5: Headlines

The following headlines have been identified in the evidence in response to the fifth research question:

- The literature identifies many barriers to the uptake of IPM measures, including economic risk, additional costs and perceived low economic returns.
- Barriers around knowledge have also been identified including a lack of research, expectations of farmer knowledge and time, narratives, lack of educational initiatives.
- Finally supply chain barriers and unintended consequences were highlighted.

5.6.2 Research question 5: Overview of evidence

The evidence used to respond to this research question was from North America and the UK and mostly in the format of scientific journals (**Error! Reference source not found.**). The quality of evidence available is all relatively high and the majority is consistent in their main findings. This is particularly true for the themes on knowledge exchange and the importance of the farmer and grower perception on the time to implement IPM approaches. The main themes include:

- IPM is perceived as high risk in comparison to chemical pesticides;
- IPM is perceived as high cost;
- knowledge gaps are a barrier to IPM uptake;
- IPM is perceived as taking more time from the farmer/ grower to implement and this is a key barrier to adoption; and
- A lack of research on IPM leads to unclear research messaging (Table 16).

Table 15. RQ 5: Table of evidence.

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Germany	1				
New Zealand	2				
North America	7			1	
UK	4		2		2
Other	8	1	1	2	
Total	**22**	**1**	**3**	**3**	**2**

Table 16. RQ5: Main themes and supporting evidence.

Theme	IPM is perceived as high risk in comparisons to chemical pesticides.			
	Yes		No	
	Number[11]	Quality[12]	Number	Quality
Number of articles that answer the RQ	27	4.6	1	4.4
Theme	IPM is perceived as high cost.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	36	4.8	7	4.4
Theme	There is a knowledge gap which is a barrier to IPM uptake.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	35	4.8	0	n/a
Theme	IPM is perceived as taking more time from the farmer/ grower to implement and this is a key barrier to adoption.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	18	4.8	0	n/a
Theme	A lack of research on IPM leads to unclear research messaging			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	27	4.6	2	5

5.6.3 Research question 5: Content of the evidence overview

5.6.3.1 *The perception of risk in the adoption of IPM approaches*

The perceived risk of adoption of a fully integrated IPM approach in comparison to traditional pesticide use is possibly the largest barrier to uptake, as farmers need assurance that the shift in management will not compromise crop yields (Brewer and Goodell, 2012; Hinz, et al., 2017; Duggan *et al.*, 2018; Lechenet, Dessaint, Py and Makowski, 2017; Barratt,

[11] Number of articles which provide evidence for that response to the RQ.

[12] Average quality score of the group of articles providing evidence to the RQ (1 = low quality, 5 = high quality evidence).

Moran, Bigler and Van Lenteren, 2018; Hillocks and Cooper, 2012; Goldberger, Lehrer and Brunner, 2013; Swiergiel *et al*., 2019; Owen, 2016; Doonan, 2017; Waller *et al*., 1998). There is consistent literature to support risk as a barrier. However, there is one piece of literature that contests this perception and headlines concerns about the risks from herbicide resistance, suggesting that IPM could be less risky than herbicides in circumstances where there is herbicide resistance (Benbrook, 2012). Many of the perceived risks are due to the fact that benefits from IPM are realised in the longer term, whereas benefits from pesticides can be seen immediately. For example, farmers must choose between low costs and short-term gains and higher initial costs with longer-term benefits for the farmer and the community (Brewer and Goodell, 2012). Hamer also describes this phenomenon in her interview with The Croptec show (2019), where she identifies a "*reluctance to commit to long-term strategies*" as they are seen as higher risk and may not offer shorter term benefits. Although many of these concerns about risk are perceived, some are demonstrated with scientific results. There can be an increase in actual risk of using IPM approaches over pesticides due to reliance on environmental conditions and unclear thresholds (Cook *et al*., 2013; Finch, Collier, 2000; The Croptec Show, 2019; Moss, 2018).

In parallel to concerns about risk, many farmers are also concerned about the cost or low economic returns from a shift to IPM. Most literature suggests that economic concerns are a barrier to IPM adoption, with a small minority suggestion otherwise. These concerns relate to one of two factors, costs and lower economic returns. In terms of cost, most of the literature argues that implementing IPM often involves expensive purchases of equipment or increased use of time and labour. Ramsden *et al*. (2016) advise that whilst the environmental cost of pesticide use is not internalised into the retail price, there will be no economic incentive to shift away from pyrethroid insecticides as they are currently convenient and low cost. There is some scepticism in the literature about economic viability and whether the economic returns from adopting an IPM approach are worthwhile (Glare *et al*., 2012; Khandelwal *et al*., 2016; Owen, 2016; Andert, Bürger, Stein and Gerowitt, 2016; Waller *et al*., 1998). This is a significant barrier, as pyrethroid insecticides are currently perceived as relatively cheap and represent the norm, so less effort is required for the farmer. However, resistance that is developing to a number of inexpensive synthetic pyrethroid insecticides could help to encourage alternative methods of pest control (Ramdsen, et al. 2016).

5.6.3.2 *Time cost of IPM uptake*

IPM measures can be costly in terms of time, due to the additional effort required to research and implement IPM in comparison to pesticides (Sappington, 2014; Hinz, Cock, Haye and Schaffer, 2017; Li, Gomez, Rickard and Skinner, 2013; Owen, 2016; Bradshaw and Hazelrigg, 2017; Hovmoller and Henriksen, 2008; Moss, 2018; Waller *et al*., 1998). This is particularly true in terms of time needed for monitoring thresholds. It was found that regular observations in commercial orchards can be limited by time and budgetary constraints (Bradshaw and Hazelrigg, 2017); this is concerning as thresholds are only useful when used correctly. Another example is the rare use of thresholds for whitefly nymph parasitism due to the workload and time needed to assess parasitism rates (Bockmann, Hommes and Meyhofer, 2014). To add to this time pressure, a portion of the literature highlights that some IPM measures have to be conducted at very strict times during growth cycles. Finch and Collier (2000) explain that on field vegetables unless a large workforce is available then it would be a very difficult task to sample and monitor all fields for pests within the timeframe before a decision has to be taken; this is especially true for larger enterprises. This increases the risk factor as time is limited to make decisions with imperfect information (Finch and Collier, 2000). Therefore, time constraints and the cost of time are significant barriers to uptake of IPM whilst routine pesticide spraying is cheaper more convenient.

5.6.3.3 *Knowledge and information as a barrier to IPM uptake*

There is very consistent evidence that the lack of farmer knowledge is a significant barrier to the uptake of IPM. IPM measures are often more complex and require a good understanding of pest demography and ecology in order to work effectively; farmers often lack this knowledge (Sappington, 2014; Prakash, Kalyana, Nagarju and Prathima, 2016; Beres *et al*., 2011; Mouden *et al.,* 2017; Cuthbertson, Qui and Murchie, 2014; Swiergiel *et al*., 2019; Lamichhane *et al*., 2018; Hill, 1989; Ehler, 2006; Hovmoller and Henriksen, 2008; Doonan,2017; Pertot *et al*., 2017). Effective results from IPM approaches are dependent on the correct treatment being given for the identified pest at the right time; this includes considering the pest's behaviour and lifecycle. Without accurate knowledge, IPM measures are not being used to their full potential and the results can discourage farmers from continuing to follow this approach. The risk of crop damage or yield loss increases with the farmer's lack of knowledge and flawed application of the IPM measure. This is a distinct disadvantage of IPM in comparison to pesticide use, as it is not seen as a 'silver bullet' and requires the farmer to adapt the methods to the individual situation and pest (Alyokhin *et al*., 2015). However, farmers and growers that make decisions in partnership with their agronomist will be able to mitigate against this risk.

Some of this shortfall in farmer knowledge is due to a lack of published research or research clarity. The literature describes how there is significant research into disease and pest preventative systems but a distinct lack of research into practical applications for effective pest management (Gent, Mahaffee, McRoberts and Pfender, 2013). Birch (2017) and Moss (2010) agree on this point and highlight the situation where research is rewarded for creation of papers within an academic setting, rather than providing practical solutions to real on-farm issues. This is a supply chain issue as there needs to be research to link up the scientific papers and actions taken on farm (applied research). There are also concerns about relevance, for example, the research that is available on tree fruit IPM was conducted in the 1980s and 1990s and does not account for modern technology such as social media or the internet (Bradshaw and Hazelrigg, 2017). Many innovative farmers who are using novel methods for disease management are not being studied and these methods cannot be utilised to their full potential across the sector (Bradshaw and Hazelrigg, 2017).

With regard to unclear messages from research, in a 2019 Voluntary Initiative survey, 22% of farmers said that they receive too much information from too many organizations regarding IPM (Johnswire, 2019). Therefore, in order to really promote IPM, there should be more coordinated and applied research conducted, that involves participants and looks to overcome many of the barriers mentioned in this section such as imperfect farmer knowledge.

Other barriers with less evidence include narratives, insufficient supply chain engagement and communication to share knowledge and unintended consequences. In terms of narratives, Hillocks (2012) indicates that "*farmers will only use IPM because it works better than their current practice, not because it conforms to an eco-fundamentalist belief system or simply because it reduces pesticide use*". Therefore, there is a need for IPM to be promoted as an economically sound business investment in order to persuade farmers to adopt IPM measures. This relates to the evidence gap identified throughout the literature that there is a need to be able to quantify the effectiveness of IPM and communicate this to farmers on a local level. This is similar to an argument by Hurley and Frisvold (2016), where they suggest that the shift to IPM measures to avoid the development of pesticide resistance can create a "tragedy of the commons" scenario where farmers act on individual interests rather than community interests such as health or environmental benefits and instead continue using pesticides.

5.6.3.4 *Unintended environmental consequences as a barrier to IPM uptake*

There are two pieces of literature that reference unintended consequences as barriers to IPM adoption. Hill (1989) promotes long term planning as a way of increasing the effectiveness of cultural control, as well as the timing of carrying out this control and the knowledge of crop and pest biology and ecology. An example that illustrated the importance of having enough local knowledge, was that a pest problem can be avoided by planting the crop in an area that is unfavourable to the pest but beneficial for the pest's natural enemies and the crop itself (Hill 1989). However, Hill (1989), writing in the US, noted that some cultural control measures could have a negative environmental impact if not performed at the correct time or in the correct conditions, such as cultivations and irrigations. Overall, the literature indicated that IPM provides a multitude of environmental benefits and any unintended environmental impacts are likely to be small. Additionally, farmers and growers tend to make decisions with their agronomists, which would lower the risk of environmental damage occurring due to implementing an IPM approach.

5.6.3.5 *Supply chain barriers to IPM uptake*

Three main barriers were identified in the evidence that relates to the pesticide supply chain; agronomist risk aversion, farm size and consumer preferences. In the US it was suggested that it is more difficult for smaller farms to adopt IPM measures than larger farms, due to reduced economic and labour flexibility (Owen, 2016). However, in the US it was reported that farm size continue to increase as farm household numbers decine, suggesting that fewer farmers are managing more land and time management problems associated with this, as well as herbicide resistant wed populations have made reactive strategies the only option for some farmers (Owen et al. 2015).

Some literature has highlighted barriers created by the supply chain. There is a pressure on agronomists to get their pest management right as the success of the crop (and their reputation) can depend on it; therefore, agronomists are likely to choose the most risk averse option and not offer potentially radical IPM approaches (Doonan, 2017). Independent agronomists were commonly reported in in depth interviews as being able to provide advice without a commercial link to chemical companies. The Association of Independent Crop Consultants view independent agronomists as being best placed to deliver agronomy advice and promote IPM because they do not have any commercial interest in selling chemicals (AICC, 2020). However, it is a legal requirement for agronomists to hold a BASIS certificate in Crop Protection IPM (BASIS Information Booklet, 2019).

Consumer preferences can also be a barrier to uptake of IPM (Newton, Creissen, Havis and Burnett, 2019). It is argued that consumers have the power to choose what type of produce they will accept, which limits what cultivars can be grown by farmers, and this in turn limits the selection of pest resistant cultivars (Newton, Creissen, Havis and Burnett, 2019). However, it is noted that this is only relevant for crops for human consumption as it does not apply where crops are used for livestock feed (Newton, Creissen, Havis and Burnett, 2019). Consumers of Scotch Whisky were reportedly indifferent to pesticide change involved in growing barley, which could be partly because Barley is heavily processed before it reaches the consumer and because it is a luxury item (Glenk, et a. 2012). Low uptake of biopesticides and the nanoformulations and microencapsulation technologies have been related to lower commercialisation of biopesticides which is less developed then chemical pesticides (Damalas and Koutroubas, 2018). Political influence was noted as being a powerful driver of change, especially when coupled with consumer and retailer demand but there was acknowledgement that adoption had increased to some extent in Europe, Asia and Latin America by the pressure applied on the supply chain from NGOs, retailers and consumers (Barratt et al. 2018).

In summary it is clear that multiple barriers exist to uptake of IPM, which matches the complexity of the supply chain. All stakeholders (growers, processors, agronomists, merchants, retailers, regulators, policy makers, NGO's, consumers) are critical to overcoming these barriers within uptake of IPM and a collaborative approach is needed to support behavioural change among growers (Barnes *et al.*, 2016).

5.6.3.6 Evidence gaps

The majority of the evidence focuses on farmer and grower perception on the risks of uptake of IPM. Other barriers where there is less evidence include insufficient supply chain engagement and communication to share knowledge, and unintended consequences of IPM, such as the importance of timing relating to cultivation or irrigation (Hill 1989). The influence of networks in leading to behavioural change is an important area that requires more attention, which will allow us to see the likelihood of other farmers and growers in implementing IPM. There is a lack of evidence on the whole farm economic benefit of IPM. A further barrier could be viewed as the lack of communication between researchers and the farming community. Research is driven by publication, rather than applied outcome, which continues to result in academic advances failing to be taken up by farmers, whilst innovations made by farmers and agronomists are overlooked (Moss, 2010). Additionally, the UK farming industry is in a state of change with EU Exit likely having a large impact on the farming industry which could be explored.

5.7 **Research question 6:** What are the enablers to uptake of IPM measures or approaches?

5.7.1 Research question 6: Headlines

The following headlines have been identified in the evidence in response to the fifth research question:

- The literature has described several enablers to the uptake of IPM approaches.
- Enablers include policy mechanisms such as restrictive pesticide policy and IPM incentivising policy.
- Knowledge exchange was seen as an enabler, including increased research efforts and educational initiatives.
- Consumer and market pressures were highlighted.
- Lastly pesticide resistance and additional environmental benefits of IPM were highlighted as key enablers to IPM uptake.

5.7.2 Research question 6: Overview of evidence

The evidence used to respond to this research question was from a number of different countries with the majority from the United Kingdom and mostly in the format of a scientific journal (Table 18). The following themes were identified from the evidence available to respond to the RQ;

- Policy on chemical pesticides can be an enabler to IPM adoption;
- Education and initiatives are a useful tool for IPM adoption;
- Continuing scientific research on IPM for consistent messaging is important;
- Resistance to chemical pesticides is a driver of IPM approaches;

Wider benefits of IPM are an important aspect for the uptake of IPM (

- Table 18).

The evidence is largely high quality and consistent in the key messages.

Table 17. RQ 6: Table of evidence.

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
Germany	3				
Hungary	1				
Ireland	2				
Netherlands					1
New Zealand	1				
North America	3			1	
UK	7	2	1	1	1

Other	11				

Table 18. RQ4: Main themes and supporting evidence.

Theme	Policy on chemical pesticides can be an enabler to IPM adoption			
	Yes		No	
	Number[13]	Quality[14]	Number	Quality
Number of articles that answer the RQ	27	4.8	1	2.6
Theme	Education and initiatives are a useful tool for IPM adoption			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	33	4.6	1	4.2
Theme	Continuing scientific research on IPM for consistent messaging is important.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	36	4.6	0	n/a
Theme	Resistance to chemical pesticides is a driver of IPM approaches.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	17	4.8	0	n/a
Theme	Wider benefits of IPM are an important aspect for the uptake of IPM.			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	11	5	0	n/a

[13] Number of articles which provide evidence for that response to the RQ.

[14] Average quality score of the group of articles providing evidence to the RQ (1 = low quality, 5 = high quality evidence).

5.7.3 Research question 6: Content of the evidence overview

5.7.3.1 *The role of policy interventions in enabling the uptake of IPM*

There are a number of ways in which policy can be an enabler for the uptake of IPM measures. There is consistent evidence to support pesticide policy as an enabler; this includes restricted registration and loss of products from the market (Chandler *et al*., 2011; Creissen, Jorgensen and Brown, 2013; Van Lenteren *et al*., 2018; Harvey, 2015; Moss, 2010; Creissen et al., 2018; University of Warwick and ADAS UK Ltd, 2011). There is also some evidence that in general, national policies and IPM specific policy are working as enablers for IPM adoption (Popp, Petö and Nagy, 2013; Lamichhane *et al*., 2017; Lefebvre, Langrell and Gomez-y-Paloma, 2015). However, there is more emphasis on the impacts of pesticide policy. There is general concern that there should be more policy initiatives aimed at incentivising IPM adoption rather than reliance on reduced availability of pesticides through pesticide resistance and fewer registrations (Lee, 2018; Andert, Bürger, Stein and Gerowitt, 2016). PAN Europe (2017) note that since 2007 Luxembourg, Belguim and France have been offering funding to farmers under the second pillar of the Common Agricultural Policy to take up pheromones and other IPM measures. The evidence highlights that this could help farmers to see IPM as a viable option per se, rather than being a second-best option to pesticides. There is also a push for improved policy in relation to biocontrol registration, in order to remove barriers in the markets and increase availability of this IPM approach (Van Lenteren, 2012; Lamichhane *et al*., 2018).

Incentives could be provided to growers to encourage IPM use, possibly facilitated by public and private partnerships (Brewer and Goodell, 2012). Additionally, financial incentives could offset the potential yield losses experienced by farmers and growers whilst developing their IPM approach (Kudsk, n.d.). Involvement of farmers and growers in policy creation could also help with gaining the buy in and trust of farmer and growers; Denmark and the Netherlands have championed this approach (Barzman and Dachbrodt-Saaydeh, 2011). IPM was viewed as a public good, in terms of the environmental benefits that it delivers, and this could provide the basis for financial incentives to growers (Newton *et al*., 2019). Way and Van Emden (1999) explain that farmers are more likely to use IPM on less productive areas such as field verges and difficult to access land, while Burger *et al*. (2012) report that where farmers may already be using IPM techniques, they are now able to log these officially through an Agri-Environment Scheme.

5.7.3.2 *Knowledge as an enabler to IPM uptake*

A lack of research or research clarity was identified as a barrier to the uptake of IPM measures. There is consistent evidence to support research clarity as an enabler. Strong research is particularly critical currently given the current reduction in the efficacy of pesticides and the potential of IPM as an alternative; if the evidence base is not strong there will be many pest management issues (Hinz et al., 2017; Creissen, Jorgensen and Brown, 2013; George *et al*., 2015; Barzman *et al*., 2015; Doonan, 2017). Topics suggested for further research include accuracy and practical application of thresholds, farmer motivations for uptake of IPM, consumer willingness to pay, and continued research into novel IPM approaches. Continued research is important due to the ever-changing climatic conditions and the incidence of invasive species, both of which farmers will have to combat (Demirozer *et al*., 2012).

Education and uptake initiatives have been identified as potential and tested enablers to uptake of IPM across much of the literature examined (Mansfield *et al*., 2019; Toma, Sutherland, Burnett and Mathews, 2018; Goldberger, Lehrer and Brunner, 2013; Cuthbertson, Qiu and Murchie, 2014; Demirozer *et al*., 2012; Arnó et al., 2008; Lamichhane *et al*., 2017; Doonan, 2017; Duggan *et al*., 2018). However, in order for education programmes to be successful, there must first be thorough research to avoid contradictory evidence and give clear messages to farmers (Newton, Creissen, Havis and Burnett, 2019). There are already a number of successful education initiatives including myFields.info (Giles *et al*., 2017), DEXiPM as part of the ENDURE project (Vasileiadis *et al*., 2013) and EuroWheat (Jorgensen *et al*., 2010); however there could be more widespread investment in initiatives in order to give clarity to farmers. It has also been suggested that more farmer-to-farmer initiatives should be set up to push innovation and provide support groups to encourage successful IPM adoption (Bürger, de Mol and Gerowitt, 2012). Improved education initiatives should be the next step from increased research efforts to promote IPM measure adoption.

5.7.3.3 *Resistance to pesticides as an enabler*

Pesticide resistance has also been identified as a strong enabler of IPM uptake, as it has reduced the number of possible chemical disease management strategies available. Alopecurus myosuroides (blackgrass) is a huge problem for farmers and growers and due to increasing resistance farmers and growers have fewer options to treat it, forcing them to uptake IPM (Moss, 2010). Farmers are finding that they have little choice but to turn to IPM (Parolin, et al., 2014; Fraser, Sharma and Bailey, 2011; Barzman *et al*., 2015). This pressure emphasises the importance of good research being readily available for farmers to enable them to implement IPM rather than exacerbate the resistance problem.

5.7.3.4 *Additional benefits of IPM uptake*

In addition to disease management, some IPM measures bring additional benefits to the crop or the environment; this added value can be an enabler for IPM adoption. For example, microbial bioinoculants can provide other crop benefits such as root growth promotion, drought tolerance, enhanced nutrition, and increased oil production in bioenergy crops, making them attractive to farmers (Stewart and Cromey, 2011). Witkowska *et al*. (2018) found that the use of net covers could bring many additional benefits such as protection against frost and improved soil quality. The study also found that net covers encouraged more efficient land use by increasing row numbers and reducing the spacing between them, as well as reducing incidence of black spot when the covers were removed to harden the foliage (Witkowska *et al.,* 2018). However, there is a need to carry out further UK based research on the efficacy of biosimulants in arable crops (Storer et al. 2016). Some more general additional benefits from IPM measures mentioned in much of the literature include operator and bystander safety, reduction in residues, short intervals between application and harvest and more specific pest management that protects non-target species (University of Warwick and ADAS UK Ltd, 2010; University of Warwick and ADAS UK Ltd, 2015). All these additional benefits can bring economic gains to the farmer through increased quality of the crop (Witkowska *et al*. 2018).

5.7.3.5 *Evidence gaps identified*

There are evidence gaps on effective policy interventions, particularly with newer approaches such as co-development and understanding what works for farmer initiatives in the UK. There is evidence of some early research looking into consumer willingness to pay for produce from IPM based operations. This stems from consumer concern about pesticide residue and possible health impacts of this (Leake, 2000). This research area should be developed further as it could be a significant enabler if there was a price premium similar to that for organic produce (Lengai, Muthomi and Mbega, 2019; Lefebvre, Langrell, Gomez-y-Paloma, 2015). There is a lack of funding on the impact of the reduced pesticide industry, which currently also provides a lot of support beyond provision of pesticides, but which is largely funded through sales. Increase in IPM uptake may therefore change associated cost of IPM uptake, e.g. through increase cost of access to knowledge (and associated informed decision making).

5.8 Research question 7: What IPM initiatives are there?

5.8.1 Research question 7 Headlines

The following headlines have been identified in the evidence in response to the seventh research question:

- Farmer and grower initiatives to encourage the uptake of IPM are generally seen as positives and enablers of the adoption of IPM across sectors.
- Farmer and grower initiatives vary in their aims, size, governance and funding mechanisms. Several key initiatives were highlighted within the UK (or Europe including the UK), notably the Voluntary Initiative, LEAF and ENDURE.

5.8.2 Research question 7: Overview of evidence

The evidence used to respond to this research question was predominantly from the UK and in the format of a journal (Table 19). Case studies have been produced to highlight different initiatives which can be found in Appendix 8.3.

Table 19. RQ7: Table of evidence.

Country	Type of Evidence				
	Journal	Book	Report	Website	Other
North America	2			3	
UK	3		1		
Other	1		2		

5.8.3 Research question 7: overview of content of evidence used to respond to RQ7.

5.8.4 Current initiatives

A number of articles reference the requirement put upon European Member States to reduce pesticide use due to Directive 2009/128/EC on the Sustainble Use Directive (SUDs) of pesticides. In the USA there is support from Federal Government for IPM led projects. In Europe, PAN (2017) comment on the benefits of the EU Agri-Environment Schemes for promoting IPM. PAN relies on lobbying and voluntary initiatives by farmers to create case studies which they can then promote via farming groups.

The National Institute of Food and Agriculture at the U.S. Department of Agriculture (USDA-NIFA) provides funding for four regional IPM centres that collectively serve the entire United States (Northeastern IPM Centre, 2020). The USA has a separate Biopesticides and Pollution Prevention Division, which promotes the use of biopesticides as components of IPM programs and coordinates the Pesticide Environmental Stewardship Program (Kumar and Singh, 2014). The University of California runs a state-wide IPM Program and provides online courses. Selected courses are approved by the California Department of Pesticide Regulation (DPR) for Continuing Education units (University of California, 2020). This appears to be similar to the UK BASIS training scheme which runs a BASIS Certificate in Crop Protection IPM course, a nationally recognised accreditation for advisors and users of pesticides.

A number of articles refer to weeds; IWMPRAISE is a Horizon 2020 project that supports and promotes the implementation of Integrated Weed Management (IWM) in Europe. The 6.6m Euro five-year IWMPRAISE project (2017 to 2022) aims to support and promote integrated weed management (IWM) in Europe (IWMPRAISE, 2020). The project combines activities centred on research, involving end users in a partnership with public research institutes and private SMEs, adopting a multi-actor approach.

In the UK, due to much lobbying from farming groups, IPM is an approach supported by voluntary initiatives rather than regulation. In Europe, there are Pesticide Action Plans which have been written into law. IPM in the UK is also promoted through quality assurance schemes such as Red Tractor (Barnes *et al*., 2016). The biggest potential influences on IPM adoption according to Barnes *et al*. (2016) are towards the end of the supply chain, i.e. supermarkets. Many UK supermarkets run their own assurance schemes on top of Red Tractor, where they can encourage IPM uptake.

LEAF is a well-respected UK voluntary initiative which promotes IPM through demonstration farms and events. To use the LEAF Marque label on product packaging, the farm must have passed the assurance scheme. LEAF aims to communicate "*practical, realistic and achievable solutions",* while working with others to find innovation and technologies to improve farm productivity, environmental enhancement and social acceptability (LEAF Marque Ltd, 2019; Rose *et al*., 2018).

Barzman *et al*. (2015) describes a number of European initiatives, namely, ENDURE research, PURE projects, Hortlink in the UK, LEAF, and a number of country based, farmer-advisor led research projects. Barzman *et al*. (2015) highlights that in Switzerland, it was in 1976 that farmer-adviser-researcher groups devised alternative crop protection strategies which eventually became mainstream nationally. It is now government policy across Switzerland and Europe to subsidise sustainable practices. The proportion of Swiss agriculture registered as contributing ecological services now reaches 98 % of the production area, 88 % of which is under integrated production, and 12 % under organic agriculture (Barzman *et al.,* 2015).

5.8.5 Farmers' interaction with initiatives

ENDURE showed that nearly all farmers using IPM techniques were active members of farmer organisations, whereas isolated farmers were less likely to engage in IPM (Barzman *et al.,* 2015). Many of the initiatives use the farmer-adviser-researcher model of feedback and engagement. On top of the grass roots research, support for IPM practices is growing from public pressure and increased support from Pillar 2 of CAP in the EU.

The literature did highlight some examples of smaller-scale action or corporate groups pushing for IPM among members and through research, e.g. Cambell Soup in the USA (Jacobsen, 1997; Witkowska *et al*., 2018; Ehler, 2006). However, many of the initiatives uncovered in the research are either led by or supported by the government or region in some way. Ten case studies have been produced to highlight examples of different initiatives (Appendix 8.3).

5.9 **Research question 8:** What is the extent of coverage of IPM in the UK?

5.9.1 Research question 8: Headlines

The following headlines have been identified in the evidence in response to the eighth research question:

- Until very recently there has been little monitoring of IPM adoption in the arable sector. Limited data is available for other sectors e.g. horticulture.
- Universal metrics that encompass the vast majority of IPM practices are required to quantify levels of adoption.
- All growers are practising IPM to some degree, but some have adopted significantly more IPM practices than others.
- IPM adoption needs to be monitored so that schemes to promote IPM can be critically assessed and evaluated.
- Overcoming barriers to IPM adoption requires support to meet evidence gaps.

5.9.2 Research question 8: Overview of evidence

This research question includes a common viewpoint that was expressed during the industry interviews that were completed to inform the search terms for this rapid evidence review. The industry participants can be found at appendix 8.1.2. As the research question refers to the UK, all evidence is from the UK. The main themes are:

- There are a lack of tools to measure the adoption of IPM by farmers,
- Surveys are key to monitor changes in IPM practice, and
- Effective communication is key to improving adoption of IPM.

For all research questions the evidence is consistent (**Error! Reference source not found.**).

Table 20 RQ8: Main themes and supporting evidence.

Theme	There are a lack of tools to measure the adoption of IPM by farmers			
	Yes		No	
	Number[15]	Quality[16]	Number	Quality
Number of articles that answer the RQ	5	4	0	n/a
Theme	Surveys are key to monitor changes in IPM practice			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	8	4.1	0	n/a
Theme	Effective communication is key to improving adoption			
	Yes		No	
	Number	Quality	Number	Quality
Number of articles that answer the RQ	4	3.9	0	n/a

5.9.3 Research question 8: Content of evidence overview

5.9.3.1 *Quantifying IPM in the UK*

There have been relatively few attempts to quantify the extent of coverage of IPM in the UK. It is widely assumed that some sectors (protected edible crops) are practicing much higher levels of IPM than other sectors (arable), as the potential for IPM uptake is much higher in an enclosed environment in which monitoring of pest levels, the effective use of biocontrol agents, and the control of the environmental conditions is far simpler to achieve than it is for field crops. There is also more impetus to adopt IPM in the fruit and vegetable sector due to pesticide residue limits and the lower number of active substances available compared to the arable sector. Therefore, the attention when considering improving IPM uptake across all crop production sectors focuses on arable farming. There have been several surveys and analysis of IPM reports/plans etc. since the SUD was introduced in 2009, all focussing on field grown, predominantly arable crops. Data on IPM uptake in the horticultural sectors has either not been collected or not been made available to the public as the research has been conducted privately.

To assess the coverage of IPM adoption in the arable sector it is important to consider potential issues surrounding the relatively recent use of the term IPM, and which activities are consistent with IPM. Many growers may be routinely practicing IPM but perhaps not recognising such activities as IPM (Doonan 2017; Bailey *et al*., 2009: Hillocks and Cooper

[15] Number of articles which provide evidence for that response to the RQ.

[16] Average quality score of the group of articles providing evidence to the RQ (1 = low quality, 5 = high quality evidence).

2012). Conversely, growers may consider themselves to be practicing IPM but when providing information, for example, on variety choice their practices do not align to best practice, as they are growing disease susceptible varieties (Stetkiewicz, 2017). Doonan (2017) found that of 15,000 IPM returns (all collected before July 2016), some 60% of respondents were altering or delaying drilling dates to reduce pest issues and 94% claimed to be practicing crop rotation. The view that all growers can be considered as practicing IPM to some degree is supported by a more recent study, which found that all surveyed arable farmers in the UK and Ireland had adopted IPM to some extent (minimum score 27.2/100, mean score of 65.1/100), but only 13 of 225 farmers (5.8%) had adopted more than 85% of what is theoretically possible, as measured by the newly developed IPM metric (Creissen *et al*., 2019). The study by Creissen *et al*. (2019) is particularly important as it has provided the sector with a simple and easily applicable tool to measure the adoption of IPM by farmers that can help increase the confidence of consumers and retailers in IPM (Lamichhane *et al*., 2018), case sudy 8.3.7.

The Voluntary Initiative for pesticides has made an attempt to help growers collate IPM measures undertaken and allow them to meet the requirement of SUD. However, this approach to encouraging the use of IPM plans may not be adequate, considering that 76% of farmers in Scotland, for example, have no IPM plan (Newton *et al*., 2019). It is important to note that during industry interviews that informed this rapid evidence review, the Voluntary Initiative IPM plan was considered by some to be a box ticking exercise that does not adequately encourage IPM planning and a systemic approach.

A survey of 384 growers, focussing specifically on IWM practices in the UK in 2016, reported the widespread use of non-chemical control methods for problems of controlling herbicide-resistant grass-weed control (Moss, 2018). These IWM measures included spring cropping (81%), stale seedbeds (78%), delayed autumn sowing (69%) and rotational ploughing (63%), representing a substantial increase in use of methods known to be particularly effective against grass-weeds such as black-grass since a previous survey in conducted in 2000 (Moss 2018). This study shows the value in monitoring the adoption of IPM practices, in that it demonstrates that the message is being received and acted upon by growers. Such surveys can also be used to validate the success of accreditation schemes such as LEAF who can, for example, use their data to report that 52% of LEAF Marque certified businesses carried out all 8 aspects of best practice of IPM, 38% UK LEAF members use biological control and 60% UK LEAF members take steps to minimise damage to beneficial species and other non-target species (Midmer, LEAF talks).

5.9.3.2 *Factors relating to the adoption of IPM*

When considering factors that relate to adoption of IPM practices, it is worth mentioning the work of Bailey *et al*. (2009), who conducted a farmer survey and found that many farmers do make use of a suite of pest management techniques (implying IPM practice) and that their choice of IPM portfolio appears to be jointly dictated by farm characteristics (farm type/land tenure) and Government policy (AES). Sharma *et al*. (2011) found that adoption of IPM technologies amongst UK farmers appears to be driven primarily by agronomic and climatic factors, with farms in the North East, East Midlands and South East having adopted more IPM technologies than those in Scotland, Wales and the South West. Regional differences are expected, due to the distribution of different farm types, climatic differences, varying pest and disease pressures and proportion of crops in the landscape etc. This raises an interesting point that the potential for IPM differs according to various factors; therefore, a metric which is scaled according to such factors may be the best approach to developing a scheme which incentivises growers to implement IPM. Additionally, Sharma *et al*. (2011) found that full-time, younger or less experienced, better educated arable farmers tended to adopt more IPM technologies, a finding that potentially supports the use of schemes to promote succession planning and implementation within farming households.

The high value of appropriate training and knowledge exchange of IPM-related information represents a consistent theme amongst the literature studied (Buurma and van der Velden 2016; Toma *et al*., 2018; Creissen *et al*., 2019). The consensus is that, if growers are not proactive in seeking information, they are less likely to be familiar and engaged with IPM, so action plans should be designed to encourage farmers to actively engage with professionals and peers through crop walks, open days and discussion groups. By staying up to date with current best practice advice, they can respond effectively to, for example, changes in pathogen variation and fungicide sensitivity (Newton *et al*., 2019).

6 Discussion

The overall aims of this report were to enhance Defra's understanding of IPM through a comprehensive review of recent evidence and provide best practice examples that can inform communication with growers. Through holding in-depth stakeholder interviews and meetings, key research questions have been created to focus the Rapid Evidence Assessment which was conducted. The research questions were:

1. Are IPM approaches effective at reducing pesticide use?
2. What combination of IPM measures are most effective at reducing pests?
3. What are the impacts of IPM on the wider environment?
4. What are the socio-economic impacts of IPM on the farming industry?
5. What are the barriers to uptake of IPM measures or approaches?
6. What are the enablers to uptake of IPM measures or approaches?
7. What IPM initiatives are there?
8. What is the extent of coverage of IPM in the UK?

For each question evidence was collected, assessed for quality and summarised. Additionally, any evidence gaps identified in the texts were included.

Are IPM approaches effective at reducing pesticide use?

The evidence collected was consistent and relatively exhaustive and indicated that IPM measures do in the majority of instances lead to a decrease in chemical pesticide use. This was consistent across different countries and sectors. Evidence gaps are limited but focus on new technologies and IPM measures, and a novel combinations of measures.

What combination of IPM measures are most effective at reducing pests?

There is a lot of evidence on the effectiveness of IPM measures and combination of measures. The evidence mostly focusses on single measures, but there are several papers which look at combinations of IPM measures. There was more evidence available on SUD principles on prevention and suppression, monitoring and evaluating. Additionally, many of the papers focussed more on the horticulture sector as this was leading in IPM in comparison to other sectors. As with research question one, more research is needed where novel technologies or measures are discovered. There is potential for more evidence and research within the arable sector as the sector is larger than horticulture with distinct barriers in terms of IPM adoption and on SUD principles of non-chemical mechanisms, pesticide selection, reduced pesticide use and anti-resistance management.

What are the impacts of IPM on the wider environment?

There were fewer pieces of evidence focussing on impacts of IPM on the wider environment and where there was, the main focus was on the impacts of reducing chemical pesticides. The evidence was relatively consistent in showing that IPM can improve biodiversity and improve soil quality without having an impact on yield. There is scope for additional research and evidence collection on the wider impacts of IPM measures (in addition to the impact of decreasing chemical pesticides). Additionally, much of the research is less applicable as it was not conducted in a United Kingdom environment, providing scope for focussing on the impacts of IPM in a United Kingdom context.

What are the socio-economic impacts of IPM on the farming industry?

The evidence of the socio-economic impacts mostly focussed on the economic advantage of decreasing the use of chemical pesticides. The evidence was also consistent in identifying the barrier to IPM uptake from the perceived financial risk of IPM not being effective from farmers and advisors. The evidence was mostly in a New Zealand and North American context which leaves gaps for additional research within the UK particularly with a focus on social impacts of IPM including information on human and social capital. It would be particularly interesting to explore the themes of technology and labour for example perceived time to adopt IPM against actualy time to adopt IPM. The UK is moving into a new phase of agri-environment scheme (post EU-Exit) making it interesting to understand how the adoption of IPM could be part of, or help farmer understanding of, land management plans which will likely be part of a future scheme.

What are the barriers and enablers to the uptake of IPM measures or approaches?

The evidence was focussed on barriers which could be categorised as economic, knowledge and supply chain influence. The evidence focusses largely on farmers and their perception of the uptake of IPM as risky both for production and farm economics. For enablers to encourage the adoption of IPM different international policies were identified as well as sharing knowledge and information about IPM. There is less evidence on the influence of advisors and agronomists which from the stakeholder interviews conducted for this research were identified as important for the uptake of IPM. Like the other research questions, it will be important to research future technologies and IPM measures to understand the uptake of IPM measures and approaches. Finally, the evidence was focussed on North America leaving a research gap in the United Kingdom, particularly with the changing political landscape which is likely to affect the farming community and their farm practice decisions. Additionally, evidence was searched for in English and excluded if not written in English which likely had an impact on the synthesised evidence. ADAS experts believe there may be additional useful evidence available in other languages, particularly French, where a lot of work on IPM has been completed. Willingness to pay studies as well as co-development of policy were highlighted as logical evidence gaps where research may be necessary.

What IPM initiatives are there?

Several initiatives were identified through interviews with stakeholders and the REA and ten were produced into case studies. Although there was some information on different platforms about initiatives there was a clear evidence gap in the evaluation and understanding of how initiatives can be best designed to be effective at increasing the uptake of IPM.

What is the extent of coverage of IPM in the UK?

The evidence based for the quantification of IPM uptake within the UK has a small evidence base. The evidence is more focussed on arable farmers as it is widely assumed that some sectors already have a high level IPM uptake (protected crops and horticulture). There is a large evidence gap in attempting to quantify IPM uptake in the UK.

Across all research questions there is a need for ongoing research and evidence collection to understand new technologies and IPM measures. Moreover, a lot of the relevant evidence focuses on North America which has some applicability, but caution must be used when applying these findings in a UK context. Consistency and quantity of pieces of evidence is highest for research question one which indicates that IPM decreased the use of chemical pesticides. In comparison some of the largest evidence gaps are on social and environmental impacts of IPM measures and the quantification of IPM measure.

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8 Appendices

8.1 In-depth interviews

8.1.1 Introduction

To ensure the protocol for the Rapid Evidence Assessment (REA) is suitable for collecting relevant data, a number of in-depth, face to face interviews have been conducted with key stakeholders. The interviews offered an opportunity to collect some high-level qualitative information on measuring IPM uptake and potential IPM initiatives that could be case studied. A total of 24 stakeholders were interviewed in 21 interviews. Stakeholders were invited to participate via email and a suitable time and location was agreed between the interviewer and the researcher. Where a suitable time/date was not available, a telephone or skype interview was held.

The majority of stakeholder interviews were conducted between week beginning 21st October 2019 and week beginning 4th November. All interviews were completed by November 15th due to the stakeholder's availability.

8.1.2 Methodology

8.1.2.1 *Survey design*

A semi-structured interview guide (appendix 1) was created to ensure consistency between interviews and to allow for flexibility in stakeholder responses, according to their expertise. The interview guide comprised three sections; the stakeholder, measuring IPM uptake, IPM practices and IPM initiatives and our future research. For the purpose of the interview, IPM was defined according to the SUDs framework. Prompts were used to elicit detailed exploration of answers and to allow specific questions to be asked of different stakeholders. Additionally, stakeholders were asked which countries they felt were relevant to include in the REA and for relevant publications to be included. Most of the interviews were carried out face to face (17) but telephone (5) or skype (2) interviews were conducted where travel distances or stakeholder availability was a problem. This flexibility has allowed the project to progress according to schedule.

8.1.2.2 *Sample selection*

The sample was designed to secure good representation of each stakeholder group: farmer/grower organisations, research institutes and universities, NGOs, industry (agchem companies and supermarkets) and agronomists. To get most value from the interviews, the wider ADAS and SRUC project team were asked to suggest potential stakeholders that fitted into the types of organisations of interest. Selection was also based on ensuring those interviewed had a broad understanding of different IPM pests (pathogens, weeds and insects) and plants (horticulture, cereals, combinable cropping, root cropping).

Table 1 sets out the organisational groups that have been represented in stakeholder interviews.

Table 21 Stakeholder organisation and interview format

Type of organisation	Number of stakeholders interviewed
Farmer/ grower Organisations	8
Research	6
NGO	4
Industry	2
Agronomist	4
Total:	**24**

8.1.2.3 *Data collection and analysis*

A team of three experienced social science research staff conducted the stakeholder interviews. Interviews were audio recorded, with the written consent of stakeholders, on a Dictaphone and the recording was uploaded to a protected file in line with data protection and GDPR and then deleted from the Dictaphone. Researchers took short written notes of interviews with stakeholder consent, which highlighted the key points of discussion and formed the basis of analysis.

Interviews were transcribed verbatim and uploaded onto Dedoose[17] where they were qualitatively coded. An initial coding framework was created to inform the research questions, search terms and inclusion and exclusion criteria. Additional codes were added after a meeting with the data collection team which highlighted some interesting themes. The qualitative findings were discussed with the ADAS technical team and an REA protocol was established and agreed upon with Defra.

8.1.3 Results

The main themes have been highlighted below and built into the REA protocol, Appendix 5.1. These include:

- measuring IPM: including defining IPM;
- identifying IPM initiatives;
- exclusion and inclusion criteria for the REA and
- relevant documents to be included.

Other recurring themes around the uptake of IPM were also captured during the interviews and are highlighted below.

8.1.3.1 *Measuring IPM uptake*

It was acknowledged by the majority of stakeholders across stakeholder groups that IPM is very difficult to quantify as it is a series of practices, some being physical practices and others being focussed on changes in cognition and how farmers and growers think about crop protection. An overarching issue identified was the differences in the definitions of IPM across stakeholders, meaning the evidence relating to the quantification of IPM can often focus on very different aspects.

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[17] www.dedoose.com

8.1.3.2 *Defining IPM*

The majority of stakeholders agreed that the SUDs definition is an appropriate way to define IPM, but it was evident that the interpretation of the SUDs definition varied between stakeholders. There was a common belief among stakeholders that IPM is a continuum and that most land managers will be practicing IPM to some extent, either intentionally or unintentionally. However, there were conflicting views where a farmer or grower should fall on this continuum to be considered as "practicing IPM". Generally, NGO's tended to see IPM as using pesticides as a last resort and felt that often when quantifying IPM, farmers and growers should be delivering more actions, relative to the other groups of stakeholders interviewed. Other stakeholder groups saw IPM more as a way of thinking and believed that pesticide use was a part of practising IPM. The quotations below provide an indication of the differing interpretations of the SUDs definition by different types of organisations.

"IPM is integrated so it's using as many different methods as possible to control our pests without resorting to chemical interventions, and only using those as a last resort. It can't be used alone, it has to be part of an integrated crop management programme. It's only one component of that, and they're so intertwined that you can't just practice IPM and not integrated farming, which will include those broader things like crop rotations and soil tillage."

Quotation 1 Definition of IPM from an NGO stakeholder

"We push back against maybe the organic sector and other NGOs who claim that pesticides are a last resort. Whereas if you read the definition its careful consideration of all tools"

Quotation 2 Definition of IPM from an industry stakeholder

"…this is about decision-making, this isn't really about pesticide use; this is about the decision-making process so how do you measure how people are making decisions"

"The only thing that makes it IPM is the fact you're considering it"

Quotation 3 Definition of IPM from a farmer or grower stakeholder

8.1.3.3 *The concept of 'true IPM'*

Several of the stakeholders discussed the concept of *"true IPM".* True IPM was a concept that emerged through interviews to differentiate between land managers who are practicing IPM, either unintentionally or as an extension of their usual practices, and land managers who put IPM at the centre of their decision-making process. "True IPM" was typically viewed as conforming to the SUD definition of IPM by using pesticides as a last resort after all other options have been considered. The IPM pyramid was referenced by some stakeholders to illustrate the holistic approach that was viewed as practicing "true IPM".

*"I would define IPM the same way as it's defined in the Sustainable Use Directive. I don't think many farmers in the UK practise **true IPM** because they're still heavily reliant on pesticides and the idea of IPM is that you deploy a whole range of other approaches and*

then, if you've still got a problem at the end, then you come in with the pesticides at the right time."

Quotation 4 The concept of true IPM from a research stakeholder

*"At some stage we all have to spray… but if that decision is being made with the best possible intent and every opportunity has been taken to make sure there is nothing else, then I believe that is **true IPM**"*

Quotation 5 The concept of true IPM from an agronomist

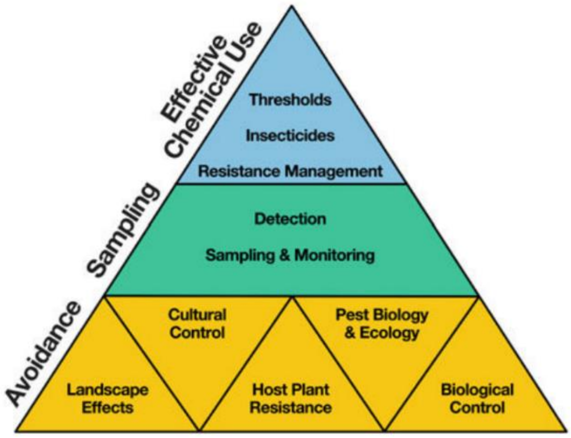


Figure 2 IPM pyramid (Fleischer, Hutchison and Naranjo, 2014)

8.1.3.4 *Variations between sectors*

There was an overall belief that IPM is tailored to each individual farm and crop type. Horticulture was frequently reported as being the most advanced farm sector for uptake of IPM and developed IPM practices. Stakeholders felt this was due to the ability to control the environment in glasshouses and issues that the sector has experienced with pesticide resistance. The arable sector was viewed as being more difficult to employ IPM practices due to the open environment and the tighter margins, reducing the farmer's ability to experiment with other practices.

"…horticulture, I would say that's the one that's probably pushing the boundaries. Certainly, as I said under glass and under plastic it's easier to release beneficials"

"The arable sector and the outdoor crop sector the services aren't there. The retailers, the way they're squeezing farmer's margins there's no room for a farmer to experiment. You start doing something you lose a fraction of your crop you're going to lose money"

Quotation 6 Variation of IPM between sectors from a farmer/ grower stakeholder

8.1.3.5 *Identifying IPM Initiatives*

The project team defined an IPM initiative as one aimed at increasing the uptake of IPM by farmers or growers. The research aimed to case study ten initiatives using information collected from the REA as part of the final report. The stakeholders discussed two main categories of IPM initiatives:

- Initiatives that worked directly with farmers and growers to increase the uptake of IPM measures – defined as "farmer initiatives" in this report.
- Initiatives which are more focussed on researching IPM with some aspects of knowledge exchange to encourage IPM uptake - defined as "research initiatives" in this report.

8.1.3.6 Farmer initiatives

The most common initiative identified during stakeholder interviews was LEAF (Linking the Environment and Farming) and LEAF Marque. Several stakeholders saw LEAF as providing information and knowledge exchange on IPM to encourage IPM uptake. The LEAF Marque is a certification underpinned by Integrated Farm Management (including IPM), which is audited. In Scotland the assurance scheme Scottish Quality Crops was highlighted. More general knowledge exchange was identified, including information from the farming media, the Voluntary Initiative and AHDB (including the AHDB Farmbench tool) as initiatives which encourage the uptake of IPM. More broadly, individual agronomists felt it was often part of their role to encourage the uptake of IPM. Finally, farmer representatives and agronomists felt that farming shows were an important part of encouraging the uptake of IPM mentioning shows: Croptech, Cereals and LAMMA.

8.1.3.7 Research initiatives

A larger number of initiatives were identified in this category and included:

- H2020 IPM decisions
- PelletWise Adama
- H2020 ENDURE National Institute for Agricultural Research
- FABulous farmers Agrii
- ASSIST CEH
- NIAB EMR Plum demonstration
- AMBER ADAS
- iFarm Agrii
- C-IPM H2020 National Institute for Agricultural Research
- SCEPTREplus

The table below provides a short description on each initiative identified.

Name of initiative	Lead organisation	Description
IPM decisions	ADAS	The project will create a 'one stop shop' delivering DSS, data, tools and resources through a pan-European online Platform and an 'IPM Decisions Network'. Funded by H2020
PelletWise	Adama	ADAMA founded the UK's Metaldehyde Stewardship Group (MSG) to promote safe responsible use of Metaldehyde. This includes guidelines for use and an IPM guide. Funded by Adama.
Endure	National Institute for Agricultural Research	ENDURE was originally a "network of excellence" funded by the EC during 2007 to 2010. It is now a self-funded European Research Group who work on IPM research and extension.
FABulous	Agro-environmental management centre	FABulous Farmers is a European project designed to support farmers in the transition to more agro-ecological practices on their farms. It focuses on reducing inputs, including pesticides. Funded by Interreg.
ASSIST	CEH	ASSIST has a broad remit focussing on feeding a growing population without causing unacceptable environmental damage. Part of this remit is to find ways to "combine nature-based and agri-tech farming system for improved production." Jointly funded by NERC and BBSRC.
Plum Demonstration Centre	NIAB EMR	A number of different research demonstrations including weed control demonstrations. Funded by different sources including Innovate UK, H2020 and AHDB.
AMBER	ADAS	Focussing on developing management practices to improve biopesticide performance, grower confidence & uptake. Funded by AHDB.
iFarm	Agrii	iFarms are a network of sites across the UK, kindly hosted by Agrii clients, where local farmers and growers can view demonstrations of new agronomic innovations and discuss how they can be put into practice on farm.

C-IPM	National Institute for Agricultural Research	C-IPM will create a forum for exchange and identification of IPM research and development priorities, provide recommendations on national and European research, connect existing initiatives, and coordinate joint transnational research calls.
SCEPTREplus	AHDB	The SCEPTREplus programme researches sustainable plant protection products for use in horticulture.

Table 22 IPM initiatives highlighted by interviewed stakeholders

A number of decision support tools were also mentioned including Rhiza by Agrii.

8.1.3.8 *Enablers to the uptake of IPM*

During interviews, stakeholders provided an insight into perceived enablers and barriers to the uptake of IPM by growers and farmers. The overarching themes are discussed in this section and section 2.3.4. Firstly, enabling factors are considered below.

8.1.3.9 *Knowledge, training and education*

Over half of respondents believed that knowledge exchange and education was important for increasing IPM uptake among farmers and growers. There was an acknowledgement that there is a lot of IPM information available online but farmer to farmer communication was viewed as the most effective platform for achieving IPM uptake. Therefore, stakeholders highlighted the importance of providing a platform and demonstration farms to facilitate discussion and allow for confidence and trust to be built. Stakeholders felt that this approach was helpful because it allowed farmers and growers to trial practices, discuss with peers and better understand the benefits and risks involved in the uptake of IPM. This was considered especially effective if the demonstration had a local context. The quotations below provide an indication of the importance of knowledge exchange between farmers.

"…a farmer saying, I took this risk, this is what happened, they can also say, this is what didn't work and this is what happened along the way. A lot of these practices, and you see this with soil as well, you make a change and something bad happens in the interim, but then you've got to trust that it's going to come back up again; the terminology, as the system sorts itself out, sort of thing. That is really powerful, because then if somebody does something and it doesn't work, they don't immediately panic and go back to doing what they were doing before and just have trust in the system".

Quotation 7 Importance of knowledge exchange to encourage IPM uptake from a farmer or grower stakeholder

"I think there's an importance for local information sharing and to get together with people that are facing the exact same conditions is more helpful than saying you should do a five year rotation of this and apply it everywhere. Localisation and local knowledge is more valuable than having some kind of over-arching 'this is the approach'"

Quotation 8 Importance of knowledge exchange to encourage IPM uptake from an NGO

Views varied on the responsibility for providing education and training. The majority of stakeholders believed that there was a role for government to support training to help encourage IPM uptake and several commented that a higher level of Government support in other European countries had been effective at increasing IPM uptake. Some farmer organisations or independent agronomists emphasised that they felt responsible for educating the farmers and growers that they interact with to increase their knowledge on IPM. The quotations below focus on stakeholder perceptions on the responsibility of providing more education and training on IPM.

"With a little bit of encouragement from the government, we could have gone a lot further on professional training."

Quotation 9 the government's role in professional training from a supply chain stakeholder

"Government support for the most part. Consumer support and retailer support and the political will"

Quotation 10 view on why other countries have been more successful in encouraging IPM uptake from an NGO stakeholder

8.1.3.10 *Loss of effective pesticides*

Most stakeholders identified the loss of available pesticides as an enabling factor to increase the number of farmers and growers practicing IPM. The loss of pesticides was two-fold; through changing legislation with a number of actives not being re-registered for use and secondly, due to pesticide resistance.

"People have perhaps been forced down the IPM route because the herbicides that they were using five years ago don't work anymore. So they have to try using cultural control or something like that."

Quotation 11 Loss of effective herbicides as an enabler of IPM uptake from a farmer organisation stakeholder

"…more recently we recognise the direction of travel from Europe is that we will see more and more actives lost and so we are looking far more at IPM, at breeding, technological solutions, cultivation techniques."

Quotation 12 Loss of actives as an enabler for IPM uptake from a farmer organisation stakeholder

8.1.4 Barriers to the uptake of IPM

8.1.4.1 *Economic barriers*

The majority of stakeholders identified economic barriers to the uptake of IPM. Stakeholders perceived pesticides as relatively cheap and effective which discouraged farmers and grower's trialling or taking risks using alternative measures. It was believed that the risk of potential loss of the crop was a large barrier to trialling non-chemical crop management. Pesticides are viewed as being cheap and effective by farmers and growers and they reportedly spray or are encouraged to spray, as an "insurance policy". Additionally, a number of stakeholders also mentioned that for some IPM measures upfront investment in equipment may be necessary which can be a barrier.

"It's often easiest and cheapest to spray. And it's the risk factor that I continue to learn. If you're using it as an insurance policy, you talk to some agronomists, and it's their livelihood as well, because if they make the wrong decision, the farmer gets it wrong, they've lost that job or you lose trust."

Quotation 13 Economic barriers of IPM uptake from a farmer/ grower stakeholder

"I think the problem with the natural pest regulation is that we can't quantify it as readily as we can the chemical, so if we say to somebody, apply this chemical then we can also say you're going to get 50% control or whatever. Whereas with the more biological control methods or natural control methods, we don't have that quantification at the moment to give the farmers the security that they need to be risk averse."

Quotation 14 Economic risks as a barrier from a research organisation

8.1.4.2 ***Agronomy advice***

Stakeholders identified agronomists as both an enabler of IPM uptake and a barrier to IPM uptake. The potential risk of crop loss was also seen as a barrier to agronomists giving advice on non-chemical alternatives as if the alternatives were not effective that would reflect poorly on the agronomist. Additionally, several stakeholders noted that often agronomists are paid by pesticide disturbers which can lead to a conflict of interest and a barrier to decreasing the amount of artificial pesticides used.

"We have recently employed a distributor agronomist who was getting fed up with the way he was having to work, so he has joined us, and he says it's just a complete breath of fresh air…[Interviewer: Because he was being encouraged to sell products?]… Yes."

Quotation 15 Distributor agronomists' conflict of interest from an agrnomist stakeholder

8.1.4.3 ***Supply Chain***

More than half of the stakeholders mentioned that growers and farmers felt pressure form the supply chain, in particular supermarkets to produce "*attractive*" food which showed no signs of pest and diseases. Ultimately this was felt to be due to consumer demand and public perception on what they deemed appropriate for consumption and the amount of money they will pay for produce. Stakeholders noted that there is an opportunity for broader education and knowledge exchange with the public which the government could have role in.

"Regarding vegetable production as it's all about saleable yield then growers may use more pesticides to protect their profits. This is all due to pressure from the supermarkets. The same is true of ware potatoes that are also sold based on appearance"

Quotation 16 Supply chain pressure as a barrier to IPM uptake from a Research Institute.

8.2 REA Protocol

8.2.1 Research questions

Key research questions were developed by the project team considering Defra's detailed objectives from the ITT, clarifications from the inception meeting and the views of stakeholders interviewed (*Table* **1**). Definitions of key words and phrases have been agreed (*Table* **2**) which will be used throughout the project.

REA research questions	Defra Objectives			
	What works in IPM?	Best practice examples on IPM initiatives?	Provide an overview of the extent and coverage of IPM practice in the UK	IPM interventions by impact (positive, negative, no impact)
Are IPM approaches effective at reducing pesticide use?	x		x	x
What combination of IPM measures are most effective at reducing pests?				x
What are the impacts of IPM on the wider environment?	x			x
What are the socio-economic impacts of IPM on the farming industry?		x		x
What are the barriers to uptake of IPM measures or approaches?	x	x		x
What are the enablers to uptake of IPM measures or approaches?	x	x		x
What IPM initiatives are there?	x	x		
What is the extent of coverage of IPM in the UK?			x	

Table 23: Rapid Evidence Assessment research questions

Table 24: List of definitions

Key Term	Definition
IPM Practices/ Measures	*Refers to the individual action that is taken by a farmer or grower, for example, crop rotation, cover crops, monitoring.*
IPM approach	*Refers to not only individual practices but also the mind-set of the farmer and grower, for example, an IPM approach covers a suite of IPM practices and a holistic view of pest management*
IPM Initiative	*Refers to an organised effort by government, industry or farmer organisation to promote IPM, for example, the LEAF marque. Excluded from this definition would be an individual agronomist who promotes IPM to their farmers.*
Pests	*Refers to pests, weeds and diseases. Does not include vertebrates.*

8.2.2 Search criteria

Several search engines will be used; Science Direct, Google scholar, Google, Open Grey, Defra project pages along with literature identified from the interviews and by ADAS and SRUC research. Each engine has been tested in order to select search engines producing the most relevant publications. Published and unpublished literature will be included in the REA and this is expected to be collected both internally by ADAS and SRUC and also through stakeholder interviews (where the participant has permitted access). There will be no exclusion criteria on the age of the publications suggested by stakeholders.

The project team will document the date of each search, noting the amount of hits and the top 100 titles and authors for each search engine. 100 titles will allow for enough resource to critically appraise the evidence in the detail necessary to fulfil the aims of the project. In order to avoid the duplication of work, researchers will document their searches on a shared google document. Below is the list of research questions, highlighted in Table 2, with a related concept map and search terms.

As outlined by Defra in the ITT, evidence will be included from the UK, Ireland, and climatically or geographically similar areas, such as parts of the United States, New Zealand and North Western Europe and where growing conditions are likely to be replicable in the UK. Stakeholder interviews also provided an indication of relevant countries to be included in the REA which have been incorporated into the inclusion criteria.

Inclusion	Rationale
Studies which concentrate on IPM	*IPM is the main focus of the REA*
Countries – Belgium, Denmark, France, Germany, Hungary, Ireland, Lithuania, Netherlands, New Zealand, North America, Sweden, Switzerland	*Countries most often suggested in stakeholder interviews with similar geography and climate to the UK*
All farm commodities where PPPs are used for the purpose of pest control.	*Farm commodities (crops) that are* relevant to the countries outlined above.

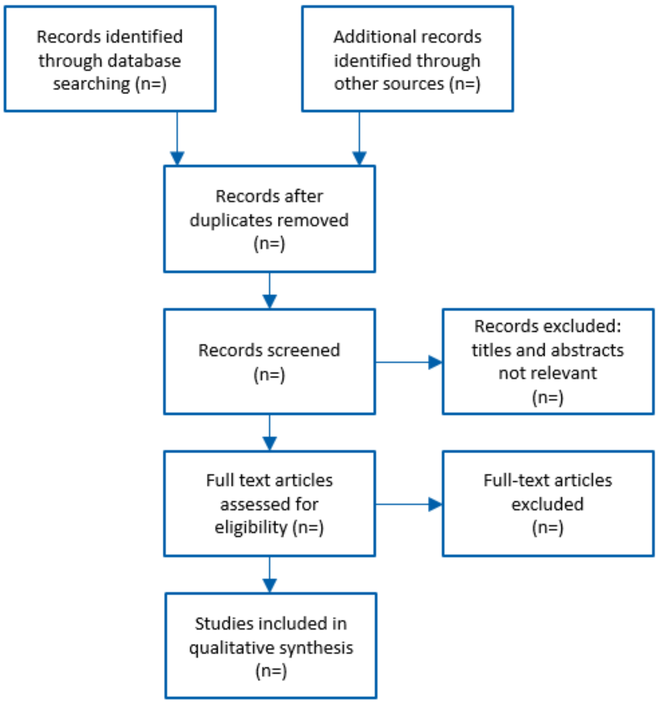
Table 25: Inclusion criteria

Exclusion	Rationale
Biocides and vertebrates	Agreed with Defra at inception meeting
Evidence not written in English	Research team English speakers and REA focussed on UK
Any pesticides/ chemicals not used for plant protection	Out of project scope
Publications before 2010	To highlight most relevant evidence. Evidence pre 2010 is included as part of the evidence collected from the stakeholders and project team.
Crops not grown in the UK	Out of project scope
Impacts related to Human Health	Out of project scope
Food Consumption	Out of project scope
Impacts on wider society	Out of project scope

Table 26 Exclusion criteria

Tables 3 and 4 detail the inclusion and exclusion criteria which are relevant across all research questions for the REA. The inclusion and exclusion criteria will be applied by researchers after the top 100 titles have been collated. European projects, published data and unpublished data that stakeholders have suggested in interviews have been collated and will be included in the REA based on the eligibility criteria. The process that the search will follow is outlined in figure 2 below. The PRISMA diagram will be followed for each research question.

Figure 3: PRISMA diagram displaying how the REA will be conducted



8.2.3 Search Terms

Boolean search terms will be used to develop searches that are created in order to combine key words. A concept map for constructing search strategies has been used to frame and organise search terms,

Table 27). Columns across indicate 'AND', terms on rows below are synonyms and indicate 'OR' in the search term. The operator 'AND' is used to combine key words together, producing relevant search results, OR is used to broaden search results by including synonyms. Search terms have been developed for each research questions, tables 6 – 13. If the organisations databases do not allow this a simple search will be conducted and relevant publications will be included. All search terms were tested and alterations made to search terms where they did not generate relevant publications in the top 20 hits.

Table 27: Boolean search term explanation

Operator	Search example	Result
AND	IPM AND Impact	Find documents with both 'IPM' and 'impact'.
OR	IPM OR 'Integrated Pest Management'	Find documents with either IPM or Integrated Pest Management
Phrase	'Integrated Pest Management'	Find documents with the exact phrase 'Integrated Pest Management'
Multiple character	Increas*	Find documents with 'increase', 'increasing'

Key research question 1: Are IPM approaches effective at reducing pesticide use?

Table 28: Boolean search operators for research Q1

	Key search words (AND)		
Synonyms (OR)	IPM	Pesticide	Change
	ICM	Fungicide	Reduc*
	IDM	Herbicide	Increas*
	IWM	Insecticide	Use*
	Integrated Pest Management	Molluscicide	Utili*
	Integrated Crop Management	"Plant Protection Product"	Application
	Integrated Disease Management	"Plant Growth Regulator"	Usage
	Integrated Weed Management	PGR	
		"Cultural Control"	
		Nematicide	
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Pest Management" OR "Integrated Crop Management" OR "Integrated Disease Management" OR "Integrated Weed Management" AND pesticide* OR fungicide* OR herbicide* OR insecticide* OR molluscicide* OR "Plant protection product" OR "Plant growth regulator" OR PGR OR "Cultural Control" OR nematicide AND change OR reduc* OR increas* OR use* OR utili* OR application OR usage			

Key research question 2: What combination of IPM measures are most effective at reducing pests?

Table 29: Boolean search operators for research Q2

	Key search words (AND)			
Synonyms (OR)	IPM	Measure*	Weeds*	Reduc*
	ICM	Action*	Diseases*	Increas*

	IDM	Practice*	Pathogen*	Chang*
	IWM	Approach*	Pest*	
	Integrated Pest Management	Effectiv*		
	Integrated Crop Management	Strategy		
	Integrated Disease Management			
	Integrated Weed Management			
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR "Integrated Disease Management" OR "Integrated Weed Management" AND measure* OR action* OR practice* OR approach*AND effectiv* AND strategy AND pest*OR weed* OR disease* OR pathogen* AND Reduc* OR Increas* OR Chang*				

Key research question 3: What are the impacts of IPM on the wider environment?

Table 30: Boolean search operators for research Q3

	Key search words (AND)		
Synonyms (OR)	IPM	Impact*	Environ*
	ICM	Affect*	Wildlife
	IDM	Effect*	Water
	IWM	Increas*	Soil
	Integrated Pest Management	Reduc*	Air
	Integrated Crop Management	Benefit*	Biodiversity
	Integrated Disease Management	Harm	Pollinators
	Integrated Weed Management	Disadvant*	Invertebrates
		Advant*	"Non-target plants"
			Birds
			Insect*
			"cultivation techniques"
			"climate change"
			Bees
			Parasitoid*
			Predator*
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR "Integrated Disease Management" OR "Integrated Weed Management" AND impact* OR affect* OR effect* OR increas* OR reduc*OR benefit* OR harm OR disadvant* OR advant* AND environ* OR wildlife OR water Or soil OR air OR *Biodiversity OR Pollinators OR Invertebrates OR "non-target plants" OR birds OR insect* OR "cultivation techniques" OR "climate change" OR bees OR parasidoid* OR predator*			

Key research question 4: What are the socio-economic impacts of IPM on the farming industry?

Table 31: Boolean search operators for research Q4

	Key search words (AND)		
Synonyms (OR)	IPM	Impact*	Soci*
	ICM	Affect*	Economic*
	IDM	Effect*	Knowledge
	IWM	Increas*	Train*
	Integrated Pest Management	Reduc*	Cost*
	Integrated Crop Management		Business*
	Integrated Disease Management		Profit*
	Integrated Weed Management		
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR “Integrated Disease Management” OR “Integrated Weed Management” AND impact* OR affect* OR effect* OR increas* OR reduc* AND soci* OR economic* OR knowledge* OR train* OR cost* OR business* OR profit*			

Key research question 5: What are the barriers to uptake of IPM measures or approaches?

Table 32: Boolean search operators for research Q5

	Key search words (AND)		
Synonyms (OR)	IPM	Uptake	Barrier*
	ICM	Utili*	Risk*
	IDM	Adopt*	Constraint*
	IWM	“Take up”	Challeng*
	Integrated Pest Management	Use*	
	Integrated Crop Management	Usage*	
	Integrated Disease Management		
	Integrated Weed Management		
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR “Integrated Disease Management” OR “Integrated Weed Management” AND uptake* OR use* OR usage OR adopt OR “take up” OR utili* AND barriers OR risk* OR constraints OR challeng*			

Key research question 6: What are the enablers to the uptake of IPM measures or approaches?

Table 33: Boolean search operators for research Q6

	Key search words (AND)		
Synonyms (OR)	IPM	Uptake	Enabl*
	ICM	Utili*	Catalyst*
	IDM	Adopt*	Facilitat*
	IWM	“Take up”	Motivat*
	Integrated Pest Management	Use*	Benefit*
	Integrated Crop Management	Usage	
	Integrated Disease Management		
	Integrated Weed Management		
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR “Integrated Disease Management” OR “Integrated Weed Management” AND			

uptake OR use* OR usage OR utili* OR adopt* OR "take up" AND enablers OR catalysts OR facilitat* OR motivat* OR benefit*

Key research question 7: What IPM initiatives are there?

Table 34: Boolean search operators for research Q7

	Key search words (AND)		
Synonyms (OR)	IPM	Initiativ*	UK
	ICM	Project*	United Kingdom
	IDM	Programme*	England
	IWM	Campaign*	Scotland
	Integrated Pest Management	Network*	Wales
	Integrated Crop Management	Intervention*	Northern Ireland
		Scheme*	
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR "Integrated Disease Management" OR "Integrated Weed Management" AND initiative* OR project* OR programme* OR campaign* OR network* OR intervention* OR scheme* AND UK OR England OR Scotland OR Wales OR "Northern Ireland"			

Key research question 8: What is the extent of coverage of IPM in the UK?

Table 35: Boolean search operators for research Q8

	Key search words (AND)		
Synonyms (OR)	IPM	Uptake*	UK
	ICM	Use*	England
	IDM	Coverage	Scotland
	IWM	Extent	Wales
	Integrated Pest Management	Adoption	Northern Ireland
	Integrated Crop Management	Utili*	
	Integrated Disease Management	Usage	
	Integrated Weed Management		
Search Term: IPM OR ICM OR IDM OR IWM OR "Integrated Crop Management" OR "Integrated Pest Management" OR "Integrated Disease Management" OR "Integrated Weed Management" AND uptake* OR use* OR coverage OR extent OR adoption OR Utili* OR Usage AND UK OR England OR Scotland OR Wales OR "Northern Ireland"			

8.2.4 Evidence screening

After the hits have been downloaded for each search term the first phase screening will rank the publication title by 'clearly relevant', 'clearly not relevant' or 'uncertain'. Second phase screening will commence with these publications and this involves reading the abstract or the first paragraph of the 'clearly relevant' and 'uncertain' publications. Evidence that is clearly relevant or uncertain is then obtained in full.

8.2.5 Data collection

This refined list of results will be used in the evidence extraction and all items that have previously been excluded will have a clear reason for the exclusion. To ensure consistency between evidence reviewers 10% of the searches will be assessed by two reviewers, if inconsistencies arise these will be raised and a conclusion on inclusion or exclusion will be made clear. For each relevant publication the following information will be captured:

- Author
- Title
- Date of publication
- Abstract/ first paragraph
- Crop commodity
- Pest of interest (invertebrate pest, weed, disease)
- IPM measure(s) discussed
- IPM component(s) discussed (prevention and suppression, monitoring, informed decision making, non-chemical methods, pesticide selection, reduced pesticide use, anti-resistance management, evaluation)
- Country of research
- Main findings for each research question
- Quality of evidence (see below)

A PRISMA flow diagram will be used to display publications that have been considered as part of the REA, an example is shown below.

8.2.6 Quality assessment of evidence

The database of relevant publications will be created in a systematic way, to ensure that data extraction is consistent. To assess the quality of evidence, information will be collected on:

- Type of evidence
- Research design used
- Population studied
- Geographical context
- A score of 1-5 (1 being not at all, 5 being completely) for each criteria set out in table 14.

The researchers will make a professional judgement, based on the below principles of credible research enquiry, to ensure that high quality evidence is included in the REA[18]. Publications will be graded based on the principles in table 14.

Table 36: Principles of credible research

Principles of quality	Associated questions

[18] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291982/HTN-strength-evidence-march2014.pdf

Transparency	Does the study present or link to the raw data it analyses? What is the geography/context in which the study was conducted? Does the study declare sources of support/funding?
Appropriateness	Does the study identify a research design? Does the study identify a research method? Does the study demonstrate why the chosen design and method are well suited to the research question?
Cultural sensitivity	Does the study explicitly consider any context-specific cultural factors that may bias the analysis/findings?
Validity	To what extent does the study demonstrate measurement validity? To what extent is the study internally valid (within the sample)? To what extent is the study externally valid (within the wider population)? To what extent is the study ecologically valid (within the environment)?
Reliability	To what extent are the measures used in the study stable? To what extent are the measures used in the study internally reliable? To what extent are the findings likely to be sensitive/changeable depending on the analytical technique used?
Cogency	Does the author 'signpost' the reader throughout? To what extent does the author consider the study's limitations and/or alternative interpretations of the analysis? Are the conclusions clearly based on the study's results?

8.3 IPM initiative Case studies

8.3.1 Cisgenically modified late blight resistant potato

8.3.1.1 Key Points

- Potato variety is key to increasing resistance to late blight however there are currently market and commercial barriers to the choice of the most resistant varieties.
- Disease monitoring is vital to reduce pesticide use which in turn can lessen the environmental impact of spraying pesticides.
- Cisgenically modified late blight resistant potato and IPM 2.0 fungicide strategy are effective at protecting crops and reducing fungicide use.

8.3.1.2 Background

Potato late blight causes millions of Euros of damage every year to potato crops across the EU. It is caused by the oomycete Phytophthora infestans. It is currently the most important disease in potato production and, although there are resistant potato varieties available, market forces and consumer preference have stopped these from being widely utilised.

This initiative aimed to understand whether there would be reduced fungicide usage when a cisgenically modified late blight resistant variety is used along with a regime of pathogen population monitoring for virulence to the resistant genes and a “do not spray unless” fungicide strategy (IPM 2.0). This fungicide strategy is based on three principles: knowledge of resistant genes within the potato; P infestan population monitoring, as knowledge of the type of virulence and to which resistant genes this affects is vital to protecting the crop; and fungicides to supplement the protection from the resistant genes when necessary.

Telem et al. (2013) define cisgenesic modification was a scenario where the subject plant is genetically modified using a natural gene from a crossable (sexually compatible) plant. This is beneficial as only the desirable genes are introduced compared with traditional breeding where undesirable genes can also be introduced (Telem et al., 2013).

8.3.1.3 Initiative governance

The research was conducted by Wageningen University & Research, Teagasc and the School of Biological Sciences at University College Dublin. The initiative is part of the Assessing and Monitoring the Impacts of Genetically Modified Plants on Agro-ecosystems (AMIGA), funded by the European Commission in the Framework programme 7. THEME [KBBE.2011.3.5- 01] under grant agreement no. 289706.

8.3.1.4 Activities

In order to test the hypothesis, the researchers used a cisgenically modified late blight Desiree potato, a conventionally bred highly susceptible Desiree potato and a conventionally bred Sarpo Mira which are highly resistant. Field evaluations were completed in the Netherlands and in Ireland in 2013, 2014 and in Ireland in 2015. The three potato types were tested under a variety of regimes, these were IPM 2.0; the local common practice where fungicides were applied on a near weekly basis; and an untreated control scenario. The combinations of potato breed and late blight treatment mean that there are nine treatments. The nine treatments were replicated seven times in the Netherlands and twelve times in Ireland.

The late blight was assessed visually at intervals. The visual assessment showed that there was close to zero late blight present on the potatoes for all tests except the untreated control which had increasing severity of late blight.

The external conditions to the test were also monitored. The weather conditions in the Netherlands and in Ireland were favourable for late blight. For the Netherlands, 2013 was an average year for the infection and 2014 was an extreme year for the infection. In Ireland 2013 had extreme temperatures and heavy rainfall which disrupted the late blight season until August and September when the infection was severe. Infections were average in 2014 and 2015.

The results of the experiment found that the performance of the weekly spraying schedule and the IPM 2.0 schedule were the same, however there was significantly less fungicide sprayed in the IPM 2.0 strategy. In Ireland there was no need to spray fungicides on the cisgenically modified resistant potato and only 8.6% of the normal spray volume (from the weekly spraying schedule) was needed on the cisgenically modified resistant potato in the Netherlands. Epidemics in the Sarpo Mira potatoes could also be controlled under the IPM 2.0 strategy where fungicide was rarely used and no more than 30% of the volume of weekly spray routine fungicide was used when fungicide was necessary. Again, showing a marked reduction. The fungicide application was normal as expected for the susceptible Desiree potatoes, with the IPM 2.0 strategy there was only a 9% reduction in dose rates of pesticide.

8.3.1.5 Lessons learnt

Overall this study highlighted the importance of potato variety and the role that cisgenically resistant potato varieties can have in the fight against diseases. It also highlighted the importance of monitoring of pest populations and their virulence to inform spraying decisions within the IPM 2.0 strategy. The IPM 2.0 strategy had many benefits including reduced fungicide usage and less damage to the environment. The average environmental damage under the IPM 2.0 strategy compared to the weekly spraying strategy was reduced by 58% on susceptible Desiree, 92% on resistant Sarpo Mira and 99% on the cisgenic Desiree. The environmental impact of each strategy was measured using environmental impact points.

There should perhaps now be efforts to increase the market share and awareness of cisgenically resistant potatoes by encouraging the cisgenic modification of already commercially successful breeds of potato. This should be encouraged through reviewing of regulation relating to these processes. Awareness should also be raised to improve perceptions of cisgenically modified crops and the IPM 2.0 fungicide strategy in order to increase uptake by farmers and the industry.

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8.3.2 DEXiPM

8.3.2.1 *Key Points*

- DEXiPM is a program designed by researchers for researchers used to assess the sustainability of different cropping systems
- It uses 75 different basic criteria and 86 aggregated criteria
- The system allows for economic, environmental and social sustainability to be balanced when developing innovate IPM measures

8.3.2.2 *Background*

The adoption of Integrated Pest Management (IPM) is being encouraged in order to reduce pesticide use. This shift emphasises the need for in-depth research on the effects and use of various IPM measures. However, researchers have been faced with budgetary and time constraints meaning that the most innovative measures have not been studied to a level where they can be recommended to farmers (Endure, 2010). DEXiPM aims to fix this issue by providing a hierarchical multi-criteria model to conduct ex ante qualitative assessments of the sustainability of new IPM systems (Angevin, Pelzer and Messéan, 2017). The program is designed to be used by researchers and was originally developed for field-crop systems (Angevin, Pelzer and Messéan, 2016).

8.3.2.3 *Initiative governance*

DEXiPM was developed by scientists at INRA, France's National Institute for Agricultural Research but is based on and implemented using the decision-making program DEXi which was developed by the Jozef Stefan Institute in Slovenia. The program has been used in several European research projects including ECOGEN, SIGMEA, Endure and PURE (Angevin, Pelzer and Messéan, 2017).

8.3.2.4 *Activities*

DEXiPM models the sustainability of cropping systems around the three pillars of economy, environmental and social. The use of the three pillars allows the socio-economic context surrounding cropping systems to be considered. This can then be used to identify barriers to innovation and possible policy issues and solutions. It also allows for the researcher to not only assess if the system is feasible today but also in the future within different contexts.

The model has a deep branching structure with 75 basic criteria and 86 aggregated criteria which allows for very specific systems to be tested (See Figure 1). For example, to measure the social sustainability of a system the model considers likelihood of adoption, system and society. Within likelihood of adoption the market access, farmer reluctance, access to technologies and support are considered. The model can also weigh criteria in line with researchers' priorities and accept knowledge gaps which can be filled later by expert knowledge (Angevin, Pelzer and Messéan, 2017).

8.3.2.5 *Lessons learnt*

One success of the environmental use of DEXi software has been the development of DEXiFruits and DEXiPM-Grapevine as a result of the effective use of the DEXiPM program. DEXiPM-Grapevine was developed for the PURE (Pesticide Use-and-risk Reduction in European farming systems with Integrated Pest Management) (Metral, Dubuc, Deliere and Lefond *et al*., 2015).

Interviews conducted with groups who design maise and winter cropping systems identified DEXiPM as the only assessment method which considers so many themes linked to sustainability. Other strengths include the context of the assessment being explicitly explained, conflicts in goals in assessments are revealed and its ability for use when talking to different stakeholder who have different aims (Pelzer, Fortino, Bockstaller and Angevin *et al*., 2012).

Some weaknesses of DEXiPM include the complexity of the models and a lack of sensitivity of the model in some cases. This complexity is due to the number of indicators considered within the decision tree which the user must enter. Adding to this complexity many indicators must be estimated which can be particularly difficult for social aspects (Pelzer, Fortino, Bockstaller and Angevin *et al*., 2012).

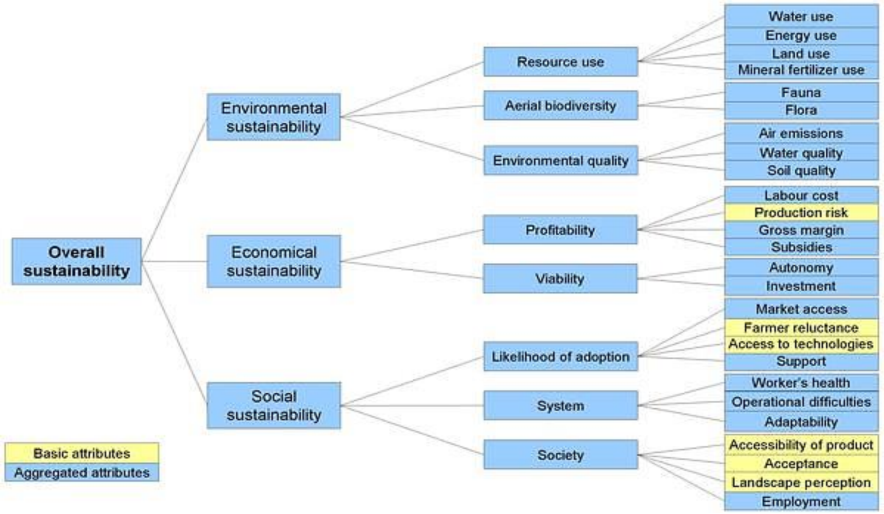

Figure 4 DEXiPM Tree of output parameters (Angevin, Pelzer and Messéan, 2017)

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8.3.3 ENDURE

8.3.3.1 *Key Points*

- The ENDURE network brings together key organisations and individuals across Europe who work on integrated pest management (IPM) and related issues.
- It provides resources (information, tools and services) to those interested in IPM.
- It collates research and highlights areas for further development within pest management.

8.3.3.2 *Background*

The ENDURE Network of Excellence, formed in 2007, brought together 300 researchers representing 10 EU countries and 18 organisations. Their funding, from the European Commission, was awarded under one of the commission's priorities – Food Quality and Security.

Their objectives were to: build a community of crop protection researchers that would last, provide solutions to specific problems for end-users, work on a sustainable and holistic approach to pest management and be up-to-date with, and help inform, policy.

Although the Network of Excellence programme ended in 2010, the group continued to collaborate with 15 partners and the website and services are maintained.

8.3.3.3 *Initiative governance*

The ENDURE project started as a Network of Excellence and was financially supported (€11.2m) by the European Commission between 2007 and 2010. It provided a mechanism for members to work together and after 2010 the partners decided to self-fund it as a European Research Group.

The initial 18 partner organisations were from across Europe including research institutes, advisory services and universities. A representative of each organisation sits on the Governing Council; it is at this level that the decisions were made on behalf of the network. There was one named coordinator.

8.3.3.4 *Activities*

The Network acts as a resource for IPM projects and offers services in five areas:

- **Communication** which includes a website, an electronic newsletter, targeting of advisers, and information centre. The information centre is a service for farmers, agronomists and advisers and is free to access.
- **Research** which is collated together and easy to access – includes information on pests, weeds and diseases. The Network also hosts other platforms including EuroWheat, EUResist and EuroBlight.
- **Education and training** are offered in the form of summer schools to post-graduate students, a training guide has also been developed.
- **Support to policy** Endure has been asked to provide expertise to the European Parliament, participates in the Sustainable Use Directive Experts Forum, and co-organises policy seminars.
- **International relations** The Network has made connections with universities and research institutes around the world and has organised networking sessions and international conference. The 2010 conference attracted 350 attendees.

For the initial Network of Excellence period 2007-2010, a record of deliverables/activities was maintained which have been divided into three categories: integrating activities, research activities and dissemination activities.

8.3.3.5 *Lessons learnt*

As the group continued to operate after their funding period, it shows the members felt there was value in maintaining the relationship.

Being multinational meant there was an ability to share best practice from different countries. This was demonstrated in their series of case studies where they looked at making crop protection strategies more sustainable and reducing reliance on pesticides. Topics covered included: foliar diseases in wheat, whiteflies in tomatoes and all major pest problems in grapevines.

The group believed that one of their most important roles was to get the information down to the advisors and other end-users and encouraged a Network of Advisers.

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8.3.4 AMBER

8.3.4.1 Key Points

- Highly focused research project, working to be fit for purpose for a clearly defined segment of the horticulture, and more broadly agriculture industry.
- The availability of data, evidence, accessible research and project information is excellent. Provides a key learning resource for industry wide stakeholders.The cross-industry intelligence team, having representatives from academia, industry and independent advisory services, mitigates potential and perceived research bias.
- The research was driven by industry growers, working to facilitate support and engagement.
- Ongoing monitoring and evaluation of practice uptake resulting from the project, would be invaluable to clearly demonstrate the impact of the project..

8.3.4.2 Background

A wide range of damaging organisms affect crop production, including disease-causing microbes (fungi, bacteria, viruses,) arthropods (insects and mites), plant parasitic nematodes, slugs and snails. These pests reduce crop yields and quality, and if they are not controlled properly they result in serious financial losses for growers and inferior produce for customers. Specifically, plant pests cause serious problems for growers of horticultural crops.

Historically, growers have relied heavily on synthetic chemical pesticides for pest control. However, pest and diseases have evolved resistance to some pesticides and new safety regulations have led to the withdrawal of many chemical products. Consequently, both effective pesticides and strategies for control are in short supply.

Plant health and crop protection is one of four key priorities identified by the Agriculture and Horticulture Development Board (AHDB) in horticulture. Here Biopesticides and Integrated Pest Management (IPM) have been identified as sustainable and safe mechanisms for plant health and crop protection. Biopesticides and IPM had, in the time prior to the establishment of the AMBER project, limited opportunities for development within existing horticultural businesses.

Application and Management of Biopesticides for Efficacy and Reliability (AMBER) is a research project designed to identify practical ways for growers to improve the performance of biopesticides for managing plant pests and diseases in IPM programmes within the horticultural industry, specifically protected edible and ornamental crops. It is a five-year program conceived and funded by UK Horticulture, growers of protected edible and ornamental crops.

The overarching objective of the project is to have UK growers adopting the new practices that are demonstrated to improve the performance of individual biopesticide products within commercial integrated pest and disease management (IPDM) programmes.

To develop management practices and improve biopesticide performance, grower confidence and the uptake of biopesticide practices, the research aims to capture the benefits of biopesticides and to mitigate for their downsides; for example biopesticides often work more slowly than conventional pesticides, can have lower levels of efficacy, and are more sensitive to environmental conditions.

8.3.4.3 *Initiative governance*

AMBER is led by the UK AHDB and funded through levy funds from UK growers (project code CP158). The research is via consortium with: Warwick Crop Centre; RSK-ADAS; Silsoe Spray Application Unit; together with biopesticide strategists and IPM consultants.

8.3.4.4 *Activities*

The research programme is organised around four key points of focus:

1. **Spray application:** Examining the relationship between water volume and % of spray retained on crop.
2. **Biofungicide performance:** generating new knowledge on biofungicide persistence to improve timing of application.
3. **Bioinsecticide performance:** developing new knowledge on how pest population growth rates influence biopesticide application strategy.
4. **Knowledge exchange:** through all stages of the programme working to explain the science, then ensuring the evidence is communicated and circulated through training and education.

These are planned to be undertaken through six core research stages:

Case studies: Worked to examine biopesticides, pests and diseases, application equipment, commercial nurseries and crops.

Benchmarking: Here the performance of different biopesticides used by partner growers IPM programmes were ranked. Which in turn led to the identification of areas with potential to optimise biopesticide performance. The benchmarking identified a series of areas to work on, including: spray applications, quantifying persistence of activity, relating biopesticide effectiveness to environmental conditions, compatibility with pesticides and natural enemies.

Biopesticide performance improvement: Work here is designed to, i) develop practices that growers can use to improve biopesticide performance, ii) complete targeted work on specific crops requested by industry sectors (e.g. mushrooms).

Improved management system: This stage is concerned to test the effectiveness of new management practices on the commercial nurseries of our case-study grower partners.

Extrapolation to other crops: Here promising findings from improved management system will be applied to other crops. It is anticipated to include the investigation of the interactions of biopesticides in whole IPM systems (e.g. the compatibility of biopesticides with each other).

Whilst it is not entirely clear what stage the research project has reached, beyond having completed benchmarking and entering the Biopesticide performance improvement phase, there is clear evidence of a wealth of outputs. These include Case Studies, Lectures, Presentations and other resources available via the Warwick Crop Centre-AMBER Project website (https://warwick.ac.uk/fac/sci/lifesci/wcc/research/biopesticides/amberproject/)

Other notable demonstrations of research impact activities include:

- The Grower Magazine Feb/March 2018: Best Practice Tips for Application of Biopesticides
- An ornamental biopesticide spray application workshop October 2018: Held at Bordon Hill Nursery
- Ornamentals conference 2019: one-day event offering insights into biopesticides and the AMBER project. The event aimed to

inform, guide and demonstrate best practice when using biopesticides.

- Bioprotectant field vegetable workshop 2020: Held at Warwick Crop Centre

8.3.4.5 Lessons learnt

A key enabling factor here is the research being driven by industry growers. Allowing levy funding to be invested in the research programme and working to facilitate support and engagement.

In addition, this is a highly focused research project, working to be fit for purpose for a clearly defined segment of the horticulture. Meaning there is a direct link between research and its intended audience and objectives. Yet, the insights may have much broader impacts for agricultural systems and practices.

The sheer wealth of available data, evidence, accessible research and project information is excellent. The project is working to provide a key learning resource for industry-wide stakeholders.

Furthermore, the collaborative nature of the project and the cross-industry intelligence team, individuals from academia, industry and independent advisory services, works to mitigate potential and perceived research bias.

The project would have been greatly strengthened by more explicit interim evaluation, and specifically by the measuring of impact of knowledge exchange activities and the implementation of practice (i.e. the core objective of the programme).

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8.3.5 OSCAR Cover Crop and Living Mulch Toolbox

8.3.5.1 *Key Points*

- High achievability, through well-defined deliverables and project objectives
- Clear and direct relationships between research activities and output
- Deliverables that are fit for purpose, meeting a demand in an assessable format.
- Weaknesses here are in the need for post-project reflection and evaluation, specifically for demonstrable impact of the toolkit.

8.3.5.2 *Background*

The Optimising Subsidiary Crop Applications in Rotation (OSCAR) project is a response to the need to improve sustainability in farming systems particularly through soil care and improvement, but not at the expense of productivity.

Broadly, the OSCAR project aimed to improve practices of conservation agriculture across a range of farming environments and systems (Baresel *et al*., 2012) in Europe. Focusing on developing improved ways of integrating subsidiary crops as living or dead mulches or cover crops with the main crops in rotations so as to simultaneously improve crop nutrition, health, and productivity through improved soil sustainability (e.g. increase soil fertility and reduce erosion) and reduce the use of inputs.

Subsidiary crops are understood to deliver multiple ecological services by increasing the duration of soil cover in the rotation overall while increasing species diversity, minimising the use of tillage and agrochemicals, enhancing biological Nitrogen fixation and soil Carbon content, and both reducing water demand in dry climates and improving soil workability in wetter climates.

In addition, the project aimed to advance knowledge and build evidence in the sustainable management, production and use of biological resources (microbial, plant and animal). Which in turn would work to provide an evidence base which can contribute to the development and implementation of new and existing policies and regulations for safer, eco-efficient and competitive products and services for agriculture and related industries.

8.3.5.3 *Initiative governance*

The OSCAR project was a collaborative research programme in agronomy, supported by the European Commission under the Seventh Framework Programme for Research.

The project was led by Technical University of Munich, Germany, and the Organic Research Centre, UK. Whilst the OSCAR as a whole involved 20 partners across nine European countries, Morocco, Brazil as well as the international research centre ICARDA. In total the project coordinated 11 field experiments and 3 long-term experiments, across different climatic regions in Europe and Brazil assessing economic and ecological impact of each initiative (April 2012 - 31st March 2016).

8.3.5.4 *Activities*

At its heart the OSCAR project worked to demonstrate the impact and value of subsidiary cropping through scientific research. The core deliverable set out was to develop a comprehensive, publicly available knowledge base and Decision Support Tool.

More broadly, the project aimed to i) reduce fragmentation of existing knowledge by consolidating information in a central, user-friendly environment; ii) generate knowledge and evidence to support the enhancement of sustainability in low-input, organic, and conventional farming systems. A secondary objective aimed to encourage multilingual stakeholder exchange and dissemination during and beyond the lifetime of the project so as to capture farmer experience.

The Cover Crop and Living Mulch Toolbox (https://web5.wzw.tum.de/oscar/toolbox/database/index.html) is the resulting publicly available knowledge base and Decision Support Tool. The Toolkit has four key interactive elements: i) Decision Support Tool; ii) Subsidiary Crop Database iii) A cover crops and living mulch wiki; iv) Research Publications database.

Decision Support Tool: By specifying your own species requirements (i.e. your aims, objectives and your farming system) together with your region through the online questionnaire the tool makes recommendations regarding appropriate cover crops for implementation: species ordered by their relevance to your requirements.

Subsidiary Crop Database: The purpose of the database is to make available the results of the OSCAR subsidiary crop screening and that of other screening programmes. It is a large interactive database of information on cover crops (e.g. botanical description, uses and cultivation etc.) which can be filtered by geographical region and species requirements (e.g. high/low biomass, nitrogen release rate etc.).
Comprises:

- Lists of all common and scientific names
- Brief descriptions of the species
- Listing of all the field experiments in which the respective species has been tested, with reports on the results available to download.
- The main characteristics of each species, summarising all available evaluation results and all tested accessions.
- A list of the main characteristics of the single accessions, summarising all available evaluation results.

A cover crops and living mulch wiki: species mixtures management toolbox. Within this you can locate and access information on appropriate machinery, best management and economics of subsidiary crops.

Research Publications database: relevant academic/ scientific research.

Evaluative reflection of the OSCAR resources have been described as a farmer-friendly, communal resource (wiki) for subsidiary crops. Furthermore, as comprehensive and hugely detailed; with botanical and agronomic information on more than 100 subsidiary crops, including white clover, alfalfa, barley and buckwheat (The BHU Future Farming Centre, Information Bulletin, 2016 V3 July). Furthermore, while the climatic / geographical areas are only in the EU, it is seen as being of great value beyond. As the selection of an EU region that is climatically similar will produce relevant outputs.

In reflection of its broader aims, the performance of subsidiary crops that are underutilised or new to Europe and the UK were examined. Resulting in the identification of several new Vicia and Lathyrus species as performing particularly well in economic and ecological terms.

8.3.5.5 *Lessons learnt*

The OSCAR project clearly demonstrates the degree to which well-defined deliverables and objectives with direct links to research practice and outputs can work to facilitate the successful delivery. Similarly, the practical identification of an industry need and evidence/knowledge gap worked to ground the project in very clear bounded delivery aims.

Success of the toolkit is dependent on three key attributes:

1. Usability of the platform (i.e. it being farmer-friendly)
2. Perceived relevance to the user: that it can be used by individuals in a way that it is specific to their soil, their objectives and their technological infrastructure
3. Fit for purpose: that it works to provide accurate information

Limitations to the success of the toolkit might be attributed to the focus on practices of conservation agriculture. Social science research would suggest that a framing that focused on soil improvement across the spectrum of farming styles would make the Toolkit more accessible (feel more relevant) to a wider range of farmers and land managers. However, this is speculation as the extent to which the toolkit and resources are made use of by the agricultural community is unclear.

Subsequently, it is suggested that a measure of impact would be most useful to the ongoing promotion and success of the toolkit. Furthermore, there is a need more broadly for post-project reflection and evaluation. The limited reflection on and evaluation of the project certainly creates a barrier to understanding what ongoing development may be needed, the degree of impact the toolkit is having and thus the overall success of the initiative.

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8.3.6 Linking Environment and Farming (LEAF) Marque Certification

8.3.6.1 Key Points

- Linking Environment and Farming (LEAF) are a charitable membership organisation who run an assurance scheme known as the LEAF Marque Certification.
- The certification is based on the nine principles of integrated farm management.
- There are many benefits to farmers other than being accredited from being part of the scheme including financial and social.
- The LEAF Marque Certification has certainly been a factor in increasing use of integrated pest management approaches in the UK.

8.3.6.2 Background

The UK government have pledged to try to reduce pesticide use in their 25 year Environment Plan in order for growers to provide more 'public goods' such as improved water quality and increased biodiversity. Therefore, various organisations have introduced initiatives to help with this target. One of these organisations is Linking Environment and Farming (LEAF). LEAF run an assurance scheme called the LEAF Marque Certification which aims to get its members to consider the nine principles of integrated farm management (IFM) which includes integrated pest management (IPM). LEAF targ*et al*l types of farming with their LEAF Marque certifications.

Alongside the LEAF Marque Certification LEAF also run demonstration farms and other educational schemes to raise awareness of many different aspects of sustainability within farming. As part of this the LEAF Marque Certification is the main method LEAF have to ensure and measure uptake of their IFM principles.

8.3.6.3 Initiative governance

LEAF is a global membership organisation based in the UK. LEAF is a registered charity which is funded through memberships, grants, trust, traded services and sponsorship from the NFU, NFU Mutual and Garfield Weston Foundation. LEAF lay out the foundations of the LEAF Marque Certification within its LEAF Marque Strategy document. However, the certification is audited on-farm by an independent auditor. There are many stakeholders supporting the initiative in order to make it work, these include; farmers, brands and retailers, supply chain and consumers.

8.3.6.4 Activities

The LEAF Marque certification recognises the most sustainable agricultural systems and products. The certification is based on LEAF's nine principles of IFM which are:

- Organising and Planning
- Soil Management and Fertility
- Crop Health and Protection
- Pollution Control and By-product Management
- Animal Husbandry
- Energy Efficiency
- Water Management
- Landscape and Nature Conservation
- Community Engagement

IPM comes under the Crop Health and Protection principle. LEAF report that 190,809 hectares of crop on LEAF Marque Certified businesses have a Crop Health and Protection Policy. To comply with this, farms must adhere to this statement: “IFM uses and encourages continual improvement in pest control measures that have minimal impact on the environment and human health and which promote sustainability and profitability. A well established and managed crop will be more competitive with weeds, more resilient to attack from pests and diseases and should require fewer plant protection products.”

8.3.6.5 *Lessons learnt*

The LEAF Marque certification is quite successful as 39% of UK fruit and vegetables are produced under the certification. The certification currently contains 375,679 hectares worldwide where 305,465 hectares are within the UK. LEAF also use their LEAF Marque on their demonstration farms which are used as an education tool for growers.

In 2017 The Countryside and Community Research Institute (CCRI) conducted an evaluation of the LEAF Marque Certification which focussed on the added value to farmers of adopting the certification. The evaluation involved interviews with thirty-seven participants. All of the participants felt that the scheme had more value to their businesses than they had first anticipated. The participants reported that the processes allowed for managers to critically reflect on their strategic direction and improve their choices in terms of sustainability and economics. It was also reported that incremental savings could be made due to the focus on IFM, for example for energy efficiency participants made savings of between £10,000 and £17,000 per year. Significantly participants reported being able to access higher value supply chains and markets with 23% receiving a price premium.

The evaluation also suggested improvement in biodiversity on the farms of the participants. Participants reported a marked improvement in observed farmland birds, insects and mammals. The LEAF Marque also helped with regulation and accreditation schemes which will have also improved the sustainability of the farms. Importantly the participants reported an 8-20% fall in the use of plant protection products and a rise in the use of biological controls. Therefore, evidencing that the LEAF Marque Certification is somewhat successful in encouraging use of IPM approaches.

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8.3.7 Measuring the unmeasurable? A method to quantify adoption of Integrated Pest Management practices in temperate arable farming systems

8.3.7.1 *Key Points*

- A metric was produced to quantify the uptake of IPM measures.
- The process involved a farmer survey and stakeholder engagement through workshops.
- The metric is likely to be applicable to a wide range of climates if adjusted accordingly.

8.3.7.2 *Background*

Integrated pest management (IPM) covers a broad range of measures which vary significantly in their requirements of effort and technical knowledge, therefore almost all farmers in the UK will be practicing IPM to some degree (Creissen *et al.*, 2019). However previous attempts to measure uptake of IPM have either failed or are a self-evaluation such as the voluntary Initiative. Therefore, in order to increase IPM uptake it is important that current uptake levels are understood.

This project aimed to produce a metric that could quantify IPM adoption in the UK. It would be used to look at the farm system level and the individual farm level. The metric would aim to be flexible to cover a range of different farming systems within the arable sector and different pests allowing it to be used by a large range of stakeholders.

8.3.7.3 *Initiative governance*

This project was supported and funded by the Scottish Government Strategic Research Programme, Rural Business Research (England), Department for Agriculture, Environment and the Marine (Ireland) and the Department of Agriculture, Environment and Rural Affairs (Northern Ireland) who acted as research partners. The project was led by the Scottish Rural College and supported by researchers from the University of Reading, Agri-Food and Biosciences Institute for Northern Ireland and Teagasc. There were also farmers who completed a survey and stakeholders who were involved in weighting the identified measures within the project.

8.3.7.4 Activities

In order to create a metric to measure IPM adoption a methodology was followed to collect and analyse data. Firstly, a farmer survey was conducted looking at farmer engagement with specific IPM practices, farmer socio-demographics and farmer attitudes towards and perceptions of IPM. In England, Northern Ireland and Ireland the survey was conducted by face to face interviews and in Scotland it was conducted via a postal survey. 225 surveys were conducted in total.

Secondly there were workshops held with panels of stakeholders to determine weighting of individual IPM measures to show which ones had a larger impact. The weighting used the question from the farmer survey that related to specific IPM practices. There were two stages to the weighting, firstly sub-components of questions were ranked where the question covered more than one method of IPM. Next each question was given a score to reflect its relative importance to IPM. This done as a percentage with the total six questions making up a 100% contribution to IPM. These weightings were then sent on to a different panel of stakeholders to review and provide their own weightings. The results from this were then analysed with stakeholders being split into four categories; farmer, independent agronomist, merchant agronomist and other, where other represented researchers, policy makers and anyone else who didn't have a commercial interest in IPM.

In terms of the weightings from the expert panel the larger the contribution of the IPM measure the less variance there was between weightings. The most weighting (47%) was given to question 8 which referred to activities designed to prevent weeds, disease and insects/molluscs and lower weightings were given to factors which influenced IPM planning.

Using the metric, the rest of the farmer survey data was analysed, and it was found that, the results gave a normally distributed bell-shaped curve with a skew towards higher IPM scores. This suggested that farmers are already implementing a number of IPM measures. However, very few farmers scored over 85 out of a possible 100 meaning that there is still room for improvement.

8.3.7.4 ***Lessons learnt***

One success of the project was that the weighting process was more robust than it has been in all previous projects attempting to create this metric. The use of two different stakeholder panels helped to capture the variety in stakeholders and perspectives which can have an influence on IPM. Previous projects have internally decided the weightings meaning that they could be more affected by researcher bias.

The farmer survey found that there was a gap between farmer perceptions of IPM and farmer practices. Whilst farmers generally had a positive perception of IPM there were other barriers to actual adoption of measures including financial and infrastructural. There is also evidence that some gaps exist between perceived and actual use of IPM methods. This means that some farmers may perceive themselves to be practicing IPM when they are not and vice versa. Therefore there may be some bias within the reporting on the stakeholder survey in this project.

It is currently unknown whether the metric is applicable to other countries or climates, but it has been suggested that it would be possible to conduct the weighting exercise again in order to make the metric applicable to a wider range of climates.

To further the study the researchers propose the inclusion of questions relating to barriers and enablers of IPM adoption to see where there is commonality of these. They also suggest looking at financial barriers using the Farm Business Survey Data and correlating this with the metric scoring.

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8.3.8 SCEPTREplus

8.3.8.1 Key Points

- SCEPTREplus aims to deliver applied research that can support the approval of plant protection products.
- It looks at biological and integrated techniques, including practices which are broader than IPM.
- It aims to introduce new products to widen the options available to producers and increase resilience.

8.3.8.2 Background

SCEPTREplus focusses on delivering applied research which can support the approval of plant protection products for the fruit, vegetable and ornamental sectors – focussing on minority crops. Research is focused on high priority disease, pest and weed problems and aims to develop IPM programmes. It is a 4-year project, ending in 2020 (although trials funded under the project will continue beyond this date).

The project looks at both chemical and biological methods of control, following on from work covered by the initial SCEPTRE and MOPS programmes. Also considered are physical crop protection methods as well as looking at new modes and timings of applications.

For 2020 (the final year of the programme) the projects advertised will look at:

- Flea beetle control in brassica crops
- Mussel scale control in apples and pears
- Mirid bug control on tomatoes
- Spidermite and macrolophus control in hardy nursery crops
- Leafhopper control in herb crops

In addition, as a result of the loss of certain actives, new seed treatments will be trialled to determine their suitability to protecting crops from spinach leaf-spot, leek damping-off and onion neck rot.

8.3.8.3 Initiative governance

SCEPTREplus is a consortium, funded by AHDB (£1.65m) which is chaired by the director of Agri-Food Solutions and includes ADAS, NIAB, EMR, Stockbridge Technology Centre and the University of Warwick. In-kind funding has also been contributed by agrochemical and biopesticide manufacturers.

Decisions on which trials to take forward are determined using AHDBs gap analysis and through consultation with the industry. The structure of the project allows for flexibility depending on the outcome of previous years.

For the final year, 2020, 15 pest and disease targets were chosen across the horticultural sectors. These topics then go out to tender, and research organisations submit bids to carry out the trials.

8.3.8.4 Activities

The project will have funded over 50 trials with the final reports being available to the public on the AHDB website. Trials have included the treatment of weeds such as black nightshade in blackcurrants, canker in cherries and western flower thrips in verbena. A bio-insecticide was trialled through the programme to replace a withdrawn product and should help reassure producers that their crops could be protected despite another product due to be withdrawn. The product is suitable for both organic and conventional growers and can be used on leafy vegetables, stone fruit, soft fruit and field vegetables. Further research to see if it is effective against gall mite will be available in 2020.

At November 2019, SCEPTREplus trials had helped to secure extensions of authorisations of minor use (EAMUs) for 14 products. In order for a product to secure an EAMU, data must have been collected on the residues and there must be a case that supports it. As a consequence, an EAMU has been submitted. This sort of trial represents how pesticides can still be used within IPM as long as there is careful consideration of all available options and the 'standard product' is no longer the only option. The trial also highlighted the potential of other products, which require further study.

8.3.8.5 Lessons learnt

The consortium is careful to look only at products that have a high chance of being readily available to growers once authorisation has been granted. The products are considered as part of an integrated approach to ensure their sustainability and future for UK producers. Where appropriate results are extrapolated to other crops in order to get the most value from the project and benefit each crop sector.

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8.3.9 Voluntary Initiative

8.3.9.1 *Key Points*

- The Voluntary Initiative is an industry-led scheme which aims to promote the sustainable use of pesticides.
- Integrated Pest Management Plans are a key part of the Voluntary Initiative are can be filled out by all types of growers across the UK.
- The Voluntary Initiative publishes an annual milestone report to detail progress.

8.3.9.2 *Background*

The UK government have made a commitment to the Sustainable Use Directive (SUD). The SUD sets out a framework of community action to achieve a sustainable use of pesticides through rules to lessen the human health and environmental impact of pesticide use. The SUD promotes the adoption of integrated pest management (IPM) and requires that growers implementing pesticide use have the correct high standard of training, the correct equipment and consider pest protection options other than pesticides. The UK government have also drawn up their 25-year environment plan which includes growers providing more 'public goods' including a cleaner environment. Reducing pesticide use is key to helping maintain a healthy environment.

The Voluntary Initiative (VI) was set up by the farming industry in 2001 to promote good practice in the use of pesticides through voluntary action, as a response to government plans to introduce a pesticide tax. The VI's current purpose is to support the government effort to implement the SUD principles. The VI integrated pest management plans (IPMP) are designed to be completed by all growers and can be adapted to any farm type including livestock if necessary.

The strategic aims of the VI are as follows:

- To ensure that industry demonstrates continued commitment to best practice in pesticide use within the context of Integrated Pest Management with the aim of minimising environmental impact and ensuring the availability of crop protection solutions in the future.
- For the VI to be seen as the centre of excellence on pesticide stewardship and best practice by government, industry and stakeholders.

The strategic priorities of the VI are:

- The quality of water abstracted for drinking is the highest priority with a focus on herbicides used in oilseed rape and grassland as well as working with the Metaldehyde Stewardship Group on this pertinent issue.
- Insecticide stewardship to reduce the risk to bees and other pollinators and potential restrictions on insecticide use. This links to Integrated Pest Management, new approaches and the provision of messages on the use of a holistic approach to crop protection.
- National Action Plan for the Sustainable Use of Pesticides – the VI is a delivery mechanism for the UK NAP, reviewing and improving current measures and developing new approaches.
- Integration of messaging with other initiatives.

8.3.9.3 *Initiative governance*

The VI is an industry- led initiative which aims to promote the responsible use of pesticides through IPM. It is sponsored by the Agricultural Engineers Association, Agricultural Industries Confederation, Country Land and Business Association, Crop Protection Association, National Association of Agricultural Contractors, the National Farmers' Union, NFU Scotland and the Ulster Farmers Union. Collectively since 2001 over £86 million has been invested in the VI by the agricultural industry.

The VI's IPM Management Plans (IPMP) were created by the NFU as a method to encourage UK growers to take up IPM. This is part of the UK Government's commitment to the Sustainable Use Directive.

The VI also have other schemes relating to pesticide use including National Register or Sprayer Operators (NRoSO), National Sprayer Testing Scheme (NSTS) and various stewardship schemes such as The Good Neighbour Initiative.

8.3.9.4 *Activities*

The main activity of the VI are the IPMP's which are to be filled out annually online by all growers to monitor their use of IPM measures. There is an alternative IPMP for Scottish growers which is more applicable to them. The IPMP's are voluntary but are often a requirement of assurance schemes.

The IPMP's present many benefits to growers including demonstrating adherence to the Code of Practice for Using Plant Protection Products identified in cross compliance SMR 9, helping with identifying areas for improvement on farm which can improve on-farm decision making, and to demonstrate the UK farming industries commitment to the SUD. The data from the IPMP's is collected by the NFU and analysed to create a summary of UK IPM usage.

The plans themselves have seven sections which cover current crop production, pest, weed and disease management, current cultural practices, catchment issues and plant protection measures. The plan also asks for details about the different types of pesticide resistance, crop rotations, soil testing, and water protection measures as well as farm demographics.

8.3.9.5 *Lessons learnt*

The VI publishes annual milestone reports detailing progress. In their 2017-2018 annual report it states that between March 31st 2017 and March 31st 2018 there were 1,639 new growers completing IPMPs making it to a total of 16,820 growers using the plans across the UK. The VI also got involved in various water projects to push improvements in water quality such 'Think Water' and the 'Oilseed Rape Herbicides?' initiatives. In 2017-2018 the VI also worked with the BeeConnected initiative to try and raise awareness of the initiative through the farming unions and Red Tractor. The BeeConnected scheme could be used to evidence working with the 'Code of Practice for using Plant Protection Products'.

There are a number of papers from the early 2000's which describe how evaluating the VI can have its difficulties as there needs to be a way to separate the effect of the VI and the effect of external factors on farmers behaviour change and pesticide use (Garrod, Garratt, Kennedy and Willis, 2006). However, Garratt and Kennedy (2006) concluded that the VI could be successful in improving water quality, particularly in relation to pesticide handling off-field as this has been identified as an area where there is large run off from farmyards into water sources. Therefore, it is unclear from external sources whether or not the VI is successful, but it is still the most accepted IPM encouragement scheme.

The VI IPMP's are widely accepted in agriculture, possibly due to the of VI being an industry-led organisation.

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8.3.10 Dephy Network

8.3.10.1 *Key Points*

- A holistic view of IPM is required at a farm/landscape scale (i.e. not a field scale) to achieve widespread adoption and impact.
- IPM-based strategies enhance sustainability but can impact profitability during transition from conventional strategies.
- Transition requires education and peer-to-peer learning.
- Upscaling IPM at the country level would have consequences on international trade.

8.3.10.2 *Background*

Launched in 2009, the Dephy Network is one of the cornerstones of France's attempts to reduce pesticide use in agriculture (Agri Innovation, 2019). It was set up as part of the Ecophyto National Action Plan, in response to the EU SUD (2009/128/EC). The Dephy Network aims to re-design cropping systems with a holistic view of IPM; enabling farmers and agronomists to find their own solutions adapted to local context. Every farm is part of a group of 10-15 other local farms, supported by an expert IPM advisor acting as "network engineers".

The aim of the Dephy Network is to decrease pesticide use in agriculture across France by 50% before 2025 (Agri Innovation, 2019). Whilst specific objectives include being able to demonstrate that it is possible to reduce pesticide use and maintain use at low levels in agricultural systems in France; and being able to identify agricultural situations and strategies associated with the reduction pesticide use (ENDURE, 2016).

The Dephy Network consists of volunteer farmers in all agricultural sectors; arable crops, vineyards, orchards, vegetables (ENDURE, 2016). It is a partnership of farmers, advisors, and industry stakeholders. The project covers all pests, as it focuses on a holistic approach to IPM.

8.3.10.3 *Activities*

The activities of the Dephy Network can be split into two categories. Firstly there is a network of over 3,000 growers who are split into 250 groups, each accompanied by a network engineer with the purpose of conducting an individual or collective project which aims to reduce pesticides (Agri Innovation, 2019). Using these growers the network aims to demonstrate on-farm that pesticides can be reduced. As a result of this they have produced 142 'Trajectory Sheets', detailing experience and lessons learnt by farmers transitioning to holistic IPM.

The second part of Dephy Network activities is a testing network that conceive, test and assess different cropping systems where the use of phytosanitary products is extremely limited (Agri Innovation, 2019). For this part there are forty or so projects and more than a hundred partners and testing sites. They have produced 85 'Economic and Efficient Cropping Systems' reports, presenting the characteristics and performance of IPM systems as well as publishing results of findings, and scenario testing for future ambition. This has provided a large set of research from the network.

8.3.10.4 *Through the activities the project aims to have a mutualising of knowledge and to create an innovative experience that will benefit the farmers involved as well as the scientific community. Initiative governance*

Dephy is funded by the Ministry of Agriculture and the Ministry of the Environment, with the financial support of the National Office for Water and Aquatic Environments and by tax credits from the diffuse pollution charge allocated to financing of the Ecophyto plan. Key partners include ACTA as the operational lead who is supported by ; CAN DEPHY, DGAL, ARVALIS, ASTREDHOR, CTIFL, IFV, INRAe, ITB, ITEIPMAI, IT², Solagro, and Terres Inovia (Agri Innovation, 2019).

8.3.10.5 *Lessons learnt*

The Dephy Network has facilitated a drop of 14-43% in pesticide use (crop dependent 2010-2017) (Agri Innovation, 2019). Data from the research shows that low reliance on pesticides is possible, and that change from high dependence to low dependency is possible within a five-year time frame. However, this transition is difficult, and requires significant local support from experts. This support is something that could be improved to enable more of this sort of transition to low pesticide dependence.

The main factors affecting implementation low pesticide use in France are the presence of livestock; production for local markets versus industrial crops; and climate. The main management measures implemented by farmers with low pesticide use in France are temporary grassland which is usually used for livestock; crop diversification (crop and sowing season); cultivar diversification; delayed cereal sowing dates; reduced dose; reduced ploughing; and moderate application of fertilisers. Farms with low pesticide use always combine several management measures.

Transition requires education and peer-to-peer learning. This is something that should be improved and expanded in order to enable other farmers and growers to understand the process and have the confidence to reduce their pesticide use.

The project has benefitted the 3,000 farmers involved in the network and this benefit should spread to other farmers through knowledge exchange events. The results of the experiment should be applicable to many farm situations and therefore can be used to guide farmers through the transition (Agri Innovation, 2019).

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8.4 IPM measure effectiveness

Article Author(s)	Year	SUD principle	Name of measure or combination of measures	Single measure or combination of measures	Effectiveness on crop protection	Description of effectiveness	Impact on pesticide use	Description of impact
Alyokhin et al.	2015	Pesticide selection, Informed decision making	Threshold-based rotations of chemicals with different modes of action	Combination	Not measured	*In the field, the growers were able to achieve what they considered to be an acceptable reduction in beetle populations by using at-planting applications of thiamethoxam during the 2009 growing season, but then complained about its reduced efficiency in 2010. Subsequently, they also incorporated acetamiprid in the rotations of foliar insecticides with an acceptable level of success. However, their satisfaction with neonicotoid insecticides never compared with that during the first 4 years of their use.*	Not measured	*The described management plan was very basic, limited to replacing indiscriminate applications of a single active ingredient with threshold-based rotations of chemicals with different modes of action. In otherwords, the first-level IPM6 was applied within the 'pesticide treadmill' paradigm. Nevertheless, it allowed the control of Colorado potato beetles that were resistant to multiple chemicals, and even restored some efficiency to previously failed neonicotinoids. However, there was no return to the situation typical during the late 1990s, when a single at-planting application of neonicotinoid insecticides provided season-long Colorado potato beetle control.*
Arnó et al.	2008	Non chemical methods	nets in vents and double-door systems to reduce the entry of B. tabaci into greenhouses	Single	Positive	*An additional component of IPM strategies is the use of nets in vents and double-door systems to reduce the entry of B. tabaci into greenhouses, however compensations have to be made for the reduced ventilation this entails*	Not measured	*N/A*
Arnó et al.	2008	Prevention and suppression	resistant tomato varieties	Single	Positive	*The use of tomato varieties tolerant to TYLCD is useful in reducing economic impacts, but these varieties need additional protection from virus-transmitting insects during the first month after planting because they show reduced susceptibility to the virus rather than resistance. At present, there are no tomato varieties resistant to whiteflies. However, strong resistance is present in wild relatives and this might be introduced by breeding*	Not measured	*N/A*
Barclay et al.	2011	Prevention and suppression, Non chemical methods	AW IPM	Combination	Not measured	*3.2. The Mediterranean Fruit Fly. The Mediterranean fruit fly, Ceratitis capitata (Wiedemann), was chosen as an example pest because numerous AW-IPM programs that include the SIT have successfully targeted this species. These provide some practical experience against which to assess the model outputs. In addition, the Mediterranean fruit fly is relatively well studied in terms of its biology [29, 30], mobility and dispersal [31–35], ecology [36, 37], and so forth. The parameter values assumed here may vary with location and are presented only to illustrate the procedure. (...) Costs per unit area for the buffer (q) are \$130/ha/yr + 30% + \$120/ha/yr = \$28900/km2. Costs for the core, w, are zero. Benefits, v, in the core area are \$5000/ha/yr = \$500000/km2/yr. Benefits from the buffer, e, are zero. The quadratic relationship between the width of the core area A and the net profit (inequality (14)) is then (500000)x2 + 2(2)(2)(−28900) + 4(4)(−28900) = 0 for the breakpoint, which gives a break-even point at a width of*	Not measured	*N/A*

						1.2 km of the core area A for a biological buffer distance of 2 km. The units of x and d must be the same. This conforms to the upper right case in Table 2.		
Barnes et al.	2019	Prevention and Suppression, Informed decision making, Evaluation	IPM toolbox	Combination	Positive	*The innovation supply chain within the Scottish arable sector is complex and involves a multitude of influences, including influential lobbying and industry groups, such as the NFU and AHDB. The biggest influences on IPM adoption on the supply chain are towards the end of the chain i.e. supermarkets, maltsters, distillers. If any change towards increased IPM adoption is to take place the role of public research and advice has a direct and indirect role to play in supporting this change.*	Not measured	*what is clearly underlining the development of toolboxes is the requirement for an evidence-base to support deployment of the IPM toolboxes, but also to increase the transferability to the policy landscape.*
Barratt et al.	2018	Non chemical methods	Biological control	Single	Not measured	*Classical and augmentative biological control of insect pests and weeds has enjoyed a long history of successes. However, biocontrol practices have not been as universally accepted or optimally utilised as they could be. An International Organisation for Biological Control (IOBC) initiative brought together practitioners and researchers from widely diverse fields to identify the main limitations to biocontrol uptake and to recommend means of mitigation. Limitations to uptake included: risk averse and unwieldy regulatory processes; increasingly bureaucratic barriers to access to biocontrol agents; insufficient engagement and communication with the public, stakeholders, growers and politicians of the considerable economic benefits of biocontrol; and fragmentation of biocontrol sub disciplines. In this contribution we summarise a range of recommendations for the future that emphasise the need for improved communication of economic, environmental and social successes and benefits of biological control for insect pests, weeds and plant diseases, targeting political, regulatory, grower/land manager and other stakeholder interests. Political initiatives in some countries which augur well for biocontrol in the future are discussed.*	Not measured	*Recognition by some of the world's leading agricultural economies that pesticide use needs to be reduced, and/or used more sustainably bodes well for the future of funding for biological control research and its implementation. Although there is almost never enough funding, this is something that could possibly be resolved, or at least alleviated only by raising the profile of biological control globally. Funding agencies need to be convinced of the value (financial, environmental, social and cultural) of investment in biological control research. In augmentative biological control, the situation has changed in the last five years from a dip in uptake of biocontrol around the year 2000 (van Lenteren 2012) to much improved adoption (van Lenteren et al. 2017). This has come about by political developments in Europe and Asia, and also in Latin America. Demands of retailers and consumers, and actions by NGOs have helped to instigate this change. Furthermore, there are grounds for optimism that political change will in the future be instrumental in increasing availability of funds for research in biological control. Political leaders around the world are recognising the need to reduce pesticide use for the benefit of human well-being.*

Barzman et al.	2015	Prevention and suppression	Cropping systems	Single	Positive	*Prevention can be considered as the creation of cropping systems inherently less likely to experience significant economic losses due to the presence of pests.*	Decrease	*Lower impact due to lack of need*
Barzman et al.	2015	Prevention and suppression	Suppression complementing prevention	Combination	Positive	*Suppression, understood as the reduction of the incidence of pests or of the severity of their impact, complements prevention. This principle means that the aim is not to completely eliminate pests but to prevent any single one from becoming dominant or damaging in a cropping system.*	Decrease	*Lower impact due to lack of need*
Barzman et al.	2015	Monitoring	Detection technologies	Single	Positive	*Soil substrates, manure, and other amendments can now be screened with modern molecular multiplex technologies to qualitatively and quantitatively assess the disease situation (Van Gent-Pelzer et al. 2010; Sikora et al. 2012). Such diagnostic allows better decision-making regarding the choice of subsequent crops or cultivars. Been et al. (2005) developed a web-based tool that potato farmers can use to fine-tune their rotation strategies based on the detection of certain nematode pathotypes. For the detection of pathogens in latently infected seed and plants, however, new technologies with higher sensitivity are needed.*	Decrease	*Lower impact due to lack of need*
Barzman et al.	2015	Prevention and suppression	Plant breeding	Single	Positive	*Plant breeding for pest resistance is recognized as an important contributor to the development of prevention strategies. The use of pest-tolerant and resistant cultivars will help to decrease dependence on pesticides in arable crops.*	Decrease	*Lower impact due to lack of need*
Barzman et al.	2015	Monitoring		Combination	Positive	*Even resistance by pyramiding resistance genes in one cultivar can be overcome if no other measures to reduce selection pressure are applied. To avoid such an outcome, the use of new cultivars needs to be combined with continuous monitoring of emerging virulent biotypes and pathogens carrying resistance-breaking genes. Haverkort et al. (2008) showed the feasibility of this approach against Phytophthora in potato.*	Decrease	*Lower impact due to lack of need*
Barzman et al.	2015	Prevention and suppression	Rotation	Single	Positive	*Spatial and temporal diversification is key to minimizing pest pressure and achieving effective prevention. In organic arable crop farming, crop rotation is the most effective agronomic alternative to synthetic pesticides (Fig. 4). In annual crops, the manipulation of crop sequence to break the life cycle of pests through rotation with crop species belonging to different families is a major lever to strengthen robustness of cropping and farming systems.*	Not measured	*N/A*
Barzman et al.	2015	Prevention and suppression	Monitoring	Single	Not measured	*Beyond prevention, moving away from a pesticide-based strategy implies monitoring harmful organisms at regular intervals (Fig. 5) or upon issue of local warnings. The current reality, however, is that warning and*	Not measured	*N/A*

						forecasting systems are not available and affordable in all countries for all crops.		
Barzman et al.	2015	Monitoring	Thresholds	Single	Not measured	*While it is true that sound intervention thresholds play an important role in IPM, they are, however, not always applicable, available, or sufficient. In many cases, thresholds have not been established for weeds (Sattin et al. 1992). This is also the case for pathogens, particularly those that switch from a saprophytic to a pathogenic lifestyle depending on environmental events and climatic conditions (Underwood et al. 2007). In the past, many IPM programs have centered on threshold-based decisions. When decision-support systems are not in place or are not appropriate, however, the use of thresholds along with the concept of IPM are disregarded. It may be better in such cases to stress the importance of observation in general, of sound decision rules, and of the entire set of IPM principles. The practicability of threshold-based decisions against diseases and weeds now needs to be demonstrated and reconsidered. Although there have been efforts to define economic thresholds for weeds (Keller et al. 2014), there is no consensus regarding their applicability*	Not measured	*N/A*
Barzman et al.	2015	Non chemical methods	Biological control agents	Single	Positive	*biological control agents are well developed in protected crops, significant opportunities for their use still exist in other systems such as arable crops. The use of Trichogramma against the European corn borer Ostrinia nubilalis is one of the few successful examples. The target specificity of natural enemies is an environmental asset that nevertheless presents challenges for biocontrol producers who are not assured high returns on their investment. Also, the use and handling of biological control agents require fine-tuning and specific skills best addressed via public-private research initiatives, education, and training (ENDURE, 2010). Direct non-chemical measures can cause undesired effects on other components of the pest-weed-disease complex. Changes in pest management could therefore be associated with monitoring of secondary pests. The effective use of non-chemical alternatives requires a new mindset seeking synergies gained from the combined effect of alternative methods that may individually be less efficient or convenient than synthetic pesticides.*	Not measured	*N/A*

Barzman et al.	2015	Informed decision making	Training materials and guidance	Single	Not measured	*Made resources available in the accociated project, but not measure of effecte*	Not measured	*N/A*
Bawa	2015	Non chemical methods	Biological control	Single	Positive	*To provide an environmentally friendly Fusarium disease control system, the use of antagonistic microorganisms represents an alternative disease management strategy (Lugtenberg and Kamilova, 2009). The mechanisms adopted by biological control agents could be direct, indirect or mixed (Pal and Gardener, 2006). The use of bioagents was reported quite effective to control Fusarium wilt disease on tomato (Freeman et al., 2002).*	Decrease	*educating farmers on the appropriate use of cultural practices and their integration into other strategies*
Bawa	2015	Prevention and suppression	Resistant cultivars	Single	Positive	*The most cost-effective and environmentally safe method of control is the use of resistant cultivars where they are available. The use of resistant varieties is the best strategy for the disease control (Sheu et al., 2006) and also one of the most effective alternative approaches to controlling wilt disease (Singh, 2005). But, due to breakdown of resistance in the face of high pathogenic variability in the pathogen population, the usefulness of many resistant cultivars is restricted to only a few years (Kutama et al., 2011; 2013).*	Decrease	*The advantages of this method include saving the cost of chemical for control of the disease and enhancing cultivation of previously infested field.*
Beckie and Harker	2017	Informed decision making, Evaluation	Keep accurate records	Combination	Positive	*Keeping accurate records will help you make informed crop management decisions, especially pesticide choices, for each field.*	Not measured	*N/A*
Beckie and Harker	2017	Prevention and suppression	Practice strategic tillage	Combination	Positive	*The risk of weeds developing resistance to herbicides is shown to be highest in no-tillage, owing to greater herbicide use and weed seed bank turnover rate. In some regions, tillage is an essential method for managing some glyphosate-resistant weeds.*	Not measured	*N/A*
Beckie and Harker	2017	Prevention and suppression	Use weed sanitation practices	Combination	Positive	*Equipment sanitation practices reduce both immigration of weed seeds and spores into a field and HR gene (seed or pollen) dispersal across a field. Reducing weed seed load into the soil can be achieved directly by harvest weed seed control practices, which include chaff carts, direct-harvest crop residue baling, narrow-windrow burning and seed pulverisation*	Not measured	*N/A*
Beckie and Harker	2017	Pesticide selection	Rotate in-crop wheat and non-wheat herbicides	Combination	Positive	*Many HR grassy weed populations (e.g., wild oats) are able to tolerate herbicides using the same mechanism as wheat. Therefore, it is important to rotate in-crop wheat and non-wheat herbicides to delay or manage this type of resistance.* *Avoiding continuous cereal crop rotations and including nonselective herbicides such as glyphosate or glufosinate in HR crops will help to achieve this objective.*	Not measured	*N/A*

Beckie and Harker	2017	Pesticide selection, Anti resistance management	Use herbicide mixtures	Combination	Positive	*Herbicide mixtures, or tank mixes, can be effective in delaying resistance. They are most successful when herbicide mixtures that combine different sites of action meet the criteria of 1) similar efficacy, 2) similar soil residual activity, and 3) different propensities for selecting for resistance in the target species. For example, mixtures of Group 2 and 4 herbicides having overlapping control of some key broadleaf weeds have been shown to delay or manage resistance.*	Not measured	*N/A*
Beckie and Harker	2017	Evaluation	Scout fields before and after herbicide applications	Combination	Positive	*Scout your fields before in-crop herbicide application to determine what weeds are present, their distribution and abundance in order to customise an effective weed management plan. Additionally, scouting post-herbicide application will inform you of how successful you have been in controlling the targeted weeds. Whether using spreadsheet or mapping software, scouting data are important parameters to record annually.*	Not measured	*N/A*
Beckie and Harker	2017	Prevention and suppression	Focus on crops and practices that promote competitiveness	Combination	Positive	*Some traits include rapid emergence (the 'first up wins') and ground cover, rapid and extensive canopy closure, and plant height. Crop competitiveness is optimised by good agronomic practices such as precision fertiliser placement near or at time of seeding, optimum seed placement and seedbed conditions, and high crop seeding rate. Adopt the 'First up wins' approach.*	Not measured	*N/A*
Beckie and Harker	2017	Prevention and suppression	Ensure crop diversity is the foundation of your HRWM plan	Combination	Positive	*The core of an effective HRWM plan is crop diversity. Include weed-competitive species and those with varied growth cycles and maturities in your crop plan – a mix of dicots and monocots, winter and spring planted, cool and warm season or annuals and perennials. While this approach ensures herbicide diversity, it also helps to provide different seeding and harvesting dates, and selection pressures on weed communities.*	Not measured	*N/A*
Benbrook	2012	Non chemical methods	Genetically engineered, herbicide resistant and insect resistant crops	Combination	Negative	*Led to increased herbicide use and resisistant weeds*	Increase	*Herbicide-resistant crop technology has led to an increase in herbicide use in the United States between 1996 and 2011, while Bt crops have reduced insecticide applications. Overall, pesticide use increased*
Benfield-Zanin et al.	2015	Pesticide selection	Biopesticides	Combination	Positive	*Broad review of different actives in biopesticide actions*	Not measured	*N/A*
Beres et al	2011	Prevention and suppression	Cultivar resistance	Combination	Positive	*All commercially available solid-stemmed spring and winter wheat cultivars developed to date derive resistance from the line S-615, but two other sources exist2. The second resistance source is derived from a durum cultivar, Golden Ball, and all studies show that resistance in Golden Ball is Insects and Diseases more stable and 'solid' across a range of environments than cultivars derived from. The third sourceis derived from Agropyron elongatum L., but attempts to transfer this*	Decrease	*integrated strategy to manage wheat stem sawfly consists of diligent pest surveillance, planting solid-stemmed cultivars, continuous cropping with appropriate pre-seed residue management, seeding rates no greater than 300 seeds m-2, 30 to 60 kg N ha-1, and harvest cutting heights of at least 15 cm to conserve parasitoids.*

						resistance to common wheat have failed. The recessive nature of the genes controlling resistance derived from leads to inconsistent pith expression in the field.		
Beres et al	2012	Prevention and suppression	Planting strategies	Combination	Positive	*Row spacing and seeding rates can influence WSS infestation rates, but this response varies between solid- and hollow-stemmed wheat cultivars. Luginbill and McNeal reported that narrow row spacing and high seeding rates reduced cutting by sawfly in the hollow-stemmed cultivar, Thatcher, but the same treatments reduced pith expression and led to increased cutting levels in the solid-stemmed cultivar*	Not measured	*N/A*
Beres et al	2013	Monitoring	Risk map and crop surveillance	Combination	Positive	*A neural network model to predict pith expression in solid-stemmed cultivars has been developed (Beres et al., unpublished; available online at ftp://ftp.agr.gc.ca/pub/outgoing/bb-stb) based on precipitation-related weather data and should be used in conjunction with the risk map.*	Not measured	*N/A*
Beres et al	2012	Non chemical methods	Biological control	Combination	Positive	*The female wasp immobilises a host larva with venom and deposits an egg nearby. The larval parasitoid consumes the host larva in about 10 days. The fully developed parasitoid larva spins a cylindrical cocoon and pupates within the stem. New adults emerge in August by chewing circular holes through the stem, seek new hosts, and produce another generation that will overwinter as pupae. Successful parasitism by this generation is dependent on crop maturity, which cues the host larva to prepare to overwinter at the base of the wheat plant.*	Not measured	*N/A*
Berini et al.	2018	Pesticide selection	Biopesticides	Single	Not measured	*Chitinases have fungicidal, insecticidal, and nematicidal activities. future development as biopesticides.*	Not measured	*N/A*
Blaauw, Polk, and Nielsen	2015	Informed decision making	behaviorally-based tactic termed IPM-CPR (Crop Perimeter Restructuring) that utilises border sprays for *H. halys*, groundcover management for *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae) and mating disruption for *Grapholita molesta* (Busck)	Combination	Positive	*significantly reduces the area managed by growers for control of stink bug, while simultaneously managing key pests at levels equal to current grower standard practices*	Decrease	*reduced insecticide usage by 25–61%*

Bockmann et al	2015	Monitoring	Yellow sticky traps for white fly monitoring	Single	Not measured	*Our results show that the actual density of whitefly nymphs and adults on the crop can be accurately described using trap catches. In all experiments correlations were significant and positive, and independent of greenhouse size and beneficial regime as long as whitefly nymphs were considered.*	Decrease	*Adequate monitoring may enable growers of large greenhouses to decide on pest management separately for parts of their greenhouse with the benefit of reduced applications of insecticides and accordingly introductions of beneficials.*
Bouvier, Debras, and Sauphanor	2011	Non chemical methods	Enhancement of biodiversity areas	Combination	Not measured	*Enhanced natural predator populations aligned with biodiversity increasing measures. Boundary hedgerows, planted ground covers, bird diversity supported and interplanted tree species to enhance biodiversity.*	Not measured	*Variable impacts on pest control due to pest assessed, biodiversity manipulation and growing system.*
Bradshaw and Hazelrigg	2017	Monitoring	Orchard monitoring	Combination	Positive	*However, despite most growers reporting at least some level of scouting their orchard using traps and other quantitative sampling methods, many did not report trapping specific pests that have established methods and thresholds for management.*	Not measured	*N/A*
Bradshaw and Hazelrigg	2017	Informed decision making	Decision support system		Not measured	*In previous, unpublished stakeholder surveys, the NEWA network and UVMAP's facilitation of its use in Vermont through network support and station maintenance has been highly rated, and is consistently held as among the most important services that UVMAP provides to growers. NEWA apple scab models may also help to best determine the severity of infection periods where protectant fungicide coverage was suboptimal. For infection periods where protectant fungicide residue is in question, decision support models may improve timing of post-infection, selective fungicide application to reduce pathogen resistance development to fungicides and improve disease management (Cooley et al. 2013, Beckerman et al. 2015).*	Not measured	*N/A*
Bradshaw and Hazelrigg	2017	Monitoring	Sticky traps	Combination	Positive	*scouting weekly using traps and sampling of foliage and fruit to monitor pests*	Not measured	*N/A*
Brainard et al.	2013	Non chemical methods	Strip till versus Conventional Till	Single	Positive	*Emergence. The short-term population dynamics of summer annual weeds under ST, compared with CT, systems is strongly influenced by effects of tillage on seed germination and emergence. The germination of most summer-annual weeds is stimulated by tillage through a variety of mechanisms, including soil aeration, increased N mineraliza tion, exposure of seeds to light, and increases in soil temperature (Mohler 2001). In untilled zones, soil temper atures are often lower (Hoyt 1999; Overstreet and Hoyt 2008) than they are in tilled zones, especially where cover crop or crop surface residues are present (Wagner-Riddle et al. 1997). Lower temperatures and lack of germination stimuli typically result in lower germination and emergence of most agricultural weeds in untilled areas relative to tilled areas. For example, Barralis and*	Not measured	*N/A*

						Chadoeuf (1980) observed 12% total emergence of germinable weed seeds following tillage compared with 8% from undisturbed soil. Likewise, reduced emergence of weeds under ST, compared with CT, systems has been observed in pickling cucumber (Wang and Ngouajio 2008), carrot (Brainard and Noyes 2012), corn (Hendrix et al. 2004), and cabbage (Haramoto and Brainard 2011)		
Brainard et al.	2013	Non chemical methods	Strip till versus Conventional Till.	Single	Negative	*After 4 yr in a vegetable cropping-system experiment, comparing CT to ST systems with alternate strip locations, the density of dandelion did not differ between tillage systems, but the ST system had a greater density of horsenettle (D. C. Brainard, unpublished data).*	Not measured	*N/A*
Brainard et al.	2013	Prevention and suppression	Strip till versus Conventional Till.	Single	Negative	*In most CT vegetable crop systems, growers rely on a combination of herbicides and cultivation to kill emerged weeds. Under ST management, cultivation is either not used or is less effective than it is under a CT system because crop and cover crop surface residues can interfere with soil movement required to sever, bury, or uproot seedlings (Mohler 2001). Therefore, even though ST systems often result in reduced emergence of summer-annual weeds, compared with emergence in CT systems, the weeds that do emerge in the BR zone usually have higher survival rates under ST management than they do under CT systems.*	Increase	*To compensate, nonorganic growers rely on more-extensive use of herbicides under ST systems (Hoyt et al. 1996; Luna and Staben 2002)*
Brownbridge and Buitenhuis	2019	Non chemical methods	Biological controls	Combination	Not measured	*There have also been reports of a lack of consistency in microbial efficacy, particularly at times of heavy pest pressure (Arthurs and Heinz, 2006; Ugine et al., 2007). This reinforces the strategy of using biocontrol agents in a preventative vs. curative manner, and of integrating microbial insecticides with other control agents to deliver the desired level of protection. Inclusion of additional natural enemies enhances the durability and reliability of a biocontrol program, allowing WFT to be managed at levels on par with, or better than, conventional pesticides.*	Not measured	*Although leaf scarring may still be too high for commercial production, the results demonstrate that superior protection was obtained using the combined vs. individual treatments [of biopesticides], with the microbial insecticides providing control via their effects in contrasting environments, i.e., on the foliage (fungi) or in the growing medium (nematodes). Since thrips may occur as part of a pest complex, some growers release generalist (soil-dwelling) predatory species at the start of a crop cycle to provide additional control of thrips as well as other soil pests such as fungus gnat larvae. A combination of these natural enemies form the foundation of biologically-based IPM programs for WFT. However, these soil-strategies do not provide 100% control of thrips. Consequently, additional control measures are needed to mitigate foliar stages*
Bruce et al.	2017	Prevention and suppression	Plant defence activators	Single	Positive	*can partially suppress B. cinerea, attack by herbivores, root knot nematodes. Antifeedants can reduce tomato leaf miner.*	Decrease	*there are potential new solutions for protection of crops but they are more complicated to deploy. Levels of control are not as high as with a pesticide. Need to be incorporated into a wider IPM startegy*

Buitenhuis	2014	Non chemical methods	Biological control	Combination	Positive	*Control agents Augmentative biocontrol - In crops with short production cycles, natural enemies are often not expected to establish. High numbers are introduced and pest control is achieved mainly by the individuals that have been released rather than their offspring. Establishment of biocontrol ecosystem - In other crops, natural enemies are released at the beginning of the production cycle and pest control relies on establishment of natural enemy populations throughout the growing season.*	Not measured	*The systems approach to IPM depends on strategic selection of methods, taking into account the three main factors, right plant, right environment and right control agents, combined with innovative approaches to enhance their effectiveness. The resulting combination should be carefully considered for potential interactions – positive and negative – to see what delivers the most effective and economical pest control solution. Using the systems approach, I think we can build more robust IPM programs and identify areas of weakness that have to be addressed by research or innovation.*
Bürger et al.	2012	Evaluation	Linear Mixed Effects Modelling	Single	Positive	*The objective of the research we present was to develop and test a method to analyse pesticide use monitoring data appropriately in order to (1) gain insight into the relationship between crop management and pesticide use, (2) integrate external sources of variability into the analysis and quantify their effect, and thereby (3) make a large data pool accessible for further interpretation which will develop further because this kind of monitoring has recently been made mandatory throughout Europe.*	Decrease	*Our results confirmed that pesticide use variability is mainly caused by external sources, but pesticide use intensity is significantly connected to crop management, mainly to preceding crop, seeding time and cultivar characteristics. Pesticide use was smaller when preventive measures typical for IPM were applied.*
Burger, de Mol, and Gerowitt	2012	Prevention and suppression	Resistant cultivars	Single	Positive	*Fields which were managed with typical IPM characteristics like late seeding and resistant cultivars were treated with a lower pesticide intensity*	Decrease	*Fields which were managed with typical IPM characteristics like late seeding and resistant cultivars were treated with a lower pesticide intensity but these lower inputs are typically used only on less productive sites.*
Burger, Stein, and Gerowitt	2016	Prevention and Suppression	Crop rotation	Single	Positive	*increased crop diversity reduced pesticide use*	Decrease	*increased crop diversity reduced pesticide use*
Chattopadhyay, Banerjee and Mukherjee	2017	Reduced pesticide use, Non-chemical methods	Biopesticides	Combination	Positive	*the application of biopesticides is not complicated; however, it requires proper training and knowledge about the pests/pathogens*	Decrease	*advantages of bacterial insecticides over synthetic chemicals, including biosafety (safe for non-target organisms including human), eco-friendly (tendency to biodegrade), economic (low cost to develop) and good compatibility with IPM programs*
Chauhan, Singh, and Mahajan	2012	Prevention and suppression	Clean crop seeds and equipment	Combination	Positive	*minimising disturbance of soil by vehicles, machinery, wildlife, and livestock is central to preventing noxious weed establishment.*	Not measured	*N/A*
Chauhan, Singh, and Mahajan	2012	Prevention and suppression	Seeding dates	Combination	Positive	*Earlier seeding of spring crops can improve their ability to compete with weeds. If weeds can be controlled, earlier seeding of winter wheat and other fall-seeded crops can also be advantageous for yield potential.*	Not measured	*N/A*

						However, other management options must be considered for the control of early seeding-related diseases		
Chauhan, Singh, and Mahajan	2012	Prevention and suppression	Cover crops	Single	Positive	*A number of cover crops, including legumes (alfalfa, sesbania, sunhemp, clover, soybeans, lupins, and cowpeas) and non-legumes (sunflower, rapeseed, rye, buckwheat, and sudan grass), have been found to suppress and smother various weeds by crop competition or allelopathic interaction*	Not measured	*N/A*
Chauhan, Singh, and Mahajan	2012	Prevention and suppression	Intercropping	Single	Positive	*Intercropping of short-duration, quick-growing, and early-maturing legume crops with long duration and wide-spaced crops leads to covering ground quickly and suppressing emerging weeds effectively*	Not measured	*N/A*
Chauhan, Singh, and Mahajan	2012	Prevention and suppression	Crop rotation	Single	Positive	*The benefits of crop rotation depend on the selection of crops and their sequence in the system. Continuous cultivation of a single crop or crops having similar management practices allows certain weed species to become dominant in the system and, over time, these weed species become hard to control*	Not measured	*N/A*
Cook et al.	2013	Non chemical methods	Trap crop of turnip for OSR	Single	Not measured	*We tested the potential of turnip rape (TR) trap crops, planted as borders to the main OSR crop to reduce pollen beetle numbers in a field scale experiment conducted over three years on two sites. We found evidence that the strategy worked well in some years, but not others. This tactic is probably practically and economically worthwhile only for organic growers*	No Effect	*N/A*
Cook et al.	2013	Informed decision making	ProPlant Model	Single	Not measured	*Use of the proPlant DSS could therefore focus monitoring effort to when it is most needed. It could also help to reduce unnecessary sprays in cases where beetle numbers are approaching threshold but consultation of the system returns a poor immigration risk forecast or an immigration complete result. The proPlant tool is now freely available to growers and crop consultants in the UK via the Bayer CropScience website*	Not measured	*Both systems performed reassuringly well in prompting monitoring that would detect breaches of spray thresholds for pollen beetles in OSR. However there were considerable reductions provided by proPlant in the need for consultation of the system (30%) and advised monitoring days (34-53%) in comparison with current advice. Use of the proPlant system could therefore save growers and crop consultants time and money. It could help to reduce unnecessary insecticide applications by preventing insurance sprays when beetle numbers are approaching threshold, and by forecasting the end of migration, when sprays are not necessary even if the crop is still at the damage susceptible stage.*
Cook et al.	2013	Monitoring	Decision support system	Single	No effect	*They concluded that monitoring populations of beetles along only one transect in one part of the field is probably not sufficient to achieve reliable data for spray decisions." "The decision support (DSS) tool ProPlant expert uses a phenological model in combination with local meteorological data to produce forecasts up to*	Decrease	*"It [DSS] is used widely in mainland Europe and users in Germany reported spraying less insecticide than those not using the system (Johnen et al., 2006)." "A small impact survey (10 respondents) from the first year of its release indicated that users found the tool informative*

						three days in advance of the risk of pollen beetle immigration, with predictions of the start and completion of migration (Johnen et al., 2010; Johnen and von Richthofen, 2013), allowing monitoring to be more accurately timed and therefore less onerous."		*and helpful (Ferguson and Cook, 2014). Respondents found that the forecasts corresponded with events in the field and reported that the tool increased their confidence in decision-making. Moreover, using the DSS reduced eight out of ten users' estimation of pollen beetle risk and seven believed they had used fewer sprays for pollen beetle control as a result (Ferguson and Cook, 2014)."*
Cook et al.	2013	Prevention and suppression	Trap crop	Single	Positive	*"Host plant odours can be exploited in IPM strategies to reduce pollen beetle damage. Trap cropping utilises attractive cultivars to move pests away from the main crop (see Objective 4). Pollen beetles show a preference for turnip rape (B. rapa) over oilseed rape (B. napus) (Hokkanen et al., 1986; Buchi, 1990; Cook et al., 2004a) and turnip rape hence can act as an efficient trap crop. Evidence from Project PI0340 and Cook et al. (2004b; 2007c) has shown that turnip rape is more attractive than oilseed rape in the bud stage and this is likely to be due to the release of two behaviourally-active compounds; phenylacetaldehyde and indole (Cook et al., 2007c)"*	Not measured	*N/A*
Cook et al.	2013	Non chemical methods	Biological control	Single	Positive	*"Larval parasitism has the potential to significantly impact pollen beetle populations, and rates in excess of the c. 32% threshold required for successful pest control (Hawkins and Cornell, 1994) have frequently been observed. Indeed, levels of parasitism of up to 97% (in unsprayed crops) were observed from data collated during the EU Project MASTER (Ulber et al., 2006), and average levels were in the 25-50% range in the UK, Germany, Sweden and Poland. From studies investigating parasitism by P. morionellus on spring OSR crops in Finland between 1985 -1995, Hokkanen (2008) estimated that on average between 20-40% of pollen beetles were removed from the new generation by parasitism, and that parasitoids were able to effectively lower pollen beetle abundance when 30-40% larval parasitism rates were exceeded."*	Not measured	*N/A*
Cook et al.	2013	Non chemical methods	Predators	Single	Positive	*"The burrowing species, Clivina fossor has also been reported to cause significant larval mortality (up to 65%) in laboratory studies (Schernéy, 1959, 1961). Warner et al. (2008) observed spatial associations between pollen beetle larvae and the carabids A. similata and N. brevicollis in the field, providing further evidence for these species as important predators of the pest.*	Not measured	*N/A*
Cook et al.	2013	Non chemical methods	Pathogens	Single	Positive	*"Soil treatment with B. bassiana can halve pollen beetle overwintering survival rates (Hokkanen, 1993) and N. meligethi also causes substantial overwintering mortality (Hokkanen and Lipa, 1995). In laboratory and*	Not measured	*N/A*

						semi-field experiments, Husberg and Hokkanen (2001) showed that direct exposure of pollen beetle larvae and adults to M. anisopliae could cause mortality rates in the range of 70-88%, and although indirect exposure via soil innoculation had little effect on emerging insect numbers, latent infection rates in the range of 49-100% were observed."		
Cook et al.	2013	Prevention and suppression	Trap cropping	Single	Positive	*"In comparative experiments on small plots, several cruciferous plants have been shown to be more attractive to pollen beetle than spring-sown OSR, including: turnip rape (Brassica rapa) (Hokkanen et al., 1986; 1989; Buchi, 1990; Cook et al., 2006b), Brassica juncea (Kaasik et al., 2014b), Brassica nigra (Veromann et al., 2012; Kaasik et al., 2014a) and Sinapis alba (Kaasik et al., 2014b)." "Simulations using a spatially-explicit individual-based model indicated that a perimeter trap crop was the most appropriate arrangement (Potting et al., 2005) and using a turnip rape trap crop comprising c. 10% of the area, Cook et al. (2004b) showed that spring OSR plots with a trap crop had significantly reduced populations of pollen beetles compared with plots without a trap crop; populations were maintained below threshold levels and bud damage was significantly reduced" "Turnip rape plants in the borders were significantly more infested by pollen beetles than OSR plants in the borders of control fields, supporting the increased attractiveness of turnip rape relative to OSR. However, the effect of the trap crop was inconsistent between sites and between years and this was attributed to differences in growth stage" "A turnip rape trap crop comprising c.10% of the area of the field planted as a border around the edge of the main OSR crop can be used to reduce the population of pollen beetles to below spray thresholds."*	Not measured	*N/A*
Cook et al.	2013	Non chemical methods	Flower-rich field margins	Single	Positive	*"Two studies assessing the influence of field margins on the biological control of pollen beetles in adjacent OSR crops have shown positive effects. Thies and Tscharntke (1999) observed that old field margin strips running alongside winter OSR fields increased larval mortality through parasitism by Tersilochus heterocerus, Phradis morionellus and Phradis interstitialis, and that larger, old fallows showed a more pronounced effect. Parasitism rates were further augmented in structurally complex versus simple landscapes. Buchi (2002) showed that parasitism rates of pollen beetle larvae caused by T. heterocerus were significantly higher in OSR fields next to flower-rich margins than in those next to extensively managed meadows"*	Not measured	*N/A*

Cook et al.	2013	Non chemical methods	Landscape	Single	No effect	*"Whilst some researchers have found reduced densities or plant damage associated with increasingly complex landscapes (Thies and Tscharntke, 1999; Thies et al., 2003; Gladbach et al., 2011), others have shown a positive relationship (Zaller et al., 2008b; Rusch et al., 2012c; Rusch et al., 2013b)." "Increasing proportions of woodland in the landscape are generally associated with higher pollen beetle densities and damage (Valantin-Morison et al., 2007; Zaller et al., 2008b; Zaller et al., 2009a; Rusch et al., 2012c; Rusch et al., 2013b). Grasslands have shown inconsistent results, with both negative (Thies and Tscharntke, 1999) and positive (Rusch et al., 2013b) relationships found between grassland proportion in the landscape and pollen beetle infestation or herbivory"*	Not measured	*N/A*
Cook et al.	2013	Monitoring	Action Thresholds	Single	Positive	*Action thresholds. Insecticides should only be applied if the crop is within its damage-susceptible growth stage and action thresholds have been breached. New action thresholds are based on crop plant density: <30 plants/m2 = 25 beetles/ plant; 30-50 plants/m2 = 18 beetles/plant; 50-70 plants/m2 = 11 beetles/plant and >70 plants/m2 = 7 beetles/plant (AHDB-HGCA Information sheet 18, 2013).*	Decrease	*Action thresholds. Insecticides should only be applied if the crop is within its damage-susceptible growth stage and action thresholds have been breached. New action thresholds are based on crop plant density: <30 plants/m2 = 25 beetles/ plant; 30-50 plants/m2 = 18 beetles/plant; 50-70 plants/m2 = 11 beetles/plant and >70 plants/m2 = 7 beetles/plant (AHDB-HGCA Information sheet 18, 2013).*
Cook et al. (a)	2013	Prevention and suppression	Sowing date	Single	Positive	*"Variation in sowing date is known to influence some pests through alteration of the synchrony between lifecycles and susceptible crop growth stages. For OSR, the difference between winter and spring sowing has the greatest effect, and spring sown crops in particular are more susceptible to flea beetle (Phyllotreta spp.) and pollen beetle damage (Alford et al., 2003; Dodsall and Stephenson, 2005)." "An early study had found that later sowing dates limited pollen beetle damage (Vasak, 1983), and it is possible that this was related to reduced fecundity of older beetles on the less advanced crops. Results obtained from Project IF0139 showed that the fecundity of beetle populations maintained on Raphanus sativus late into the season was indeed low (Skellern et al., submitted)."*	Not measured	*N/A*
Cook et al. (a)	2013	Prevention and suppression	Crop rotation	Single	Positive	*"The cumulative effects of rotation-related decisions made by individual farmers are likely to exert the greatest influence on pollen beetle (and natural enemy) abundance through landscape-scale processes, as differences in crop rotational frequency lead to corresponding changes in landscape areal crop proportions (Thies et al., 2008; Vinatier et al., 2012, 2013) (see Objective 4)."*	Not measured	*N/A*

Cook et al. (a)	2013	Prevention and suppression	Tillage	Single	Positive	*"Experiments in Sweden and Finland showed that overwintering survival of parasitoids was around four times higher from fallow or direct drilling treatments, compared with ploughing or disc-based non-inversion techniques (Nilsson, 1985; Hokkanen et al., 1988). Recent experiments (Ferguson et al., 2007) gave similar results with fallow treatments showing the highest survival rates, followed by non-inversion, and plough-based treatments the lowest. Other studies from Germany have also confirmed the detrimental effects of ploughing on parasitoid survival (Nitzsche and Ulber, 1998; Wahmhoff et al., 1999)." "Studies carried out as part of Project AR0316 , however, showed a beneficial effect of pre-OSR ploughing on Erigone and Oedothorax (Linyphiidae) populations, but no influence of post-OSR tillage regime. The same study showed no impact of pre- or post-OSR tillage on carabid numbers or species richness. Many carabid species over-winter in field boundary habitats and migrate into crops in spring and summer and thus may avoid autumn tillage-related injury, but if ploughing is used in the establishment of spring crops, more detrimental effects are seen (Büchs, 2003)." "This implies that the encouragement of low-disturbance tillage methods for the establishment of crops following OSR presents an opportunity to enhance parasitoid populations without having detrimental effects on generalist predators, and without having positive effects on the pest."*	Not measured	*N/A*
Cordeau et al.	2016	Non chemical methods	Biocontrol	Single	Not measured	*A review of the scientific literature on the existing products on the market reveal that biocontrol agents targeting weeds are weakly developed compared with biocontrol agents targeting other pests and diseases.*	Not measured	*Organic and integrated weed management do not rely on any single weed management techniques, unlike synthetic herbicides in conventional agriculture; consequently, bioherbicides should be assessed concurrently with other weed management techniques in cropping systems experiments.*
Cordeau et al.	2017	Non chemical methods	Bioherbicides	Single	Not measured	*Bioherbicide products are adapted from natural substances already present in the environment, so they are expected to be more environment-friendly. The half-life of bioherbicides is usually shorter than that of chemicals (Duke et al., 2000). However, that a product is naturally derived does not mean it is actually harmless. Certain natural toxins produced by plants or micro-organisms are present in the environment and can be a danger to animals, including mammals. The activity spectrum of natural toxins should be carefully evaluated*	Not measured	*N/A*
Creissen et al.	2019	Informed decision making, Reduced pesticide use, Monitoring	Quantifying uptake	Combination	Positive	*A metric to facilitate the benchmarking and monitoring of national IPM programmes*	Not measured	*Development of universal metric for quantifying adoption of IPM in temperate arable farming.*

Creissen, et al.	2018	Pesticide selection	Pre-stem extension fungicide applications	Combination	No effect	*Based on the findings described above the inclusion of a PSE fungicide application with in a foliar fungicide programme for the control of STB in Irish winter wheat must be questioned. Where they are included, they should only include fungicides that are either at low risk of fungicide resistance development or not used subsequently in the programme.*	No Effect	*N/A*
Creissen, Jorgensen and Brown	2016	Prevention and suppression	Varietal mixtures	Single	Positive	*Varietal mixtures designed to exploit beneficial ecological processes such as compensation and facilitation should be able to perform in a wider range of environments and will thus enable farmers to achieve high and stable yields by buffering against diverse and sometimes unpredictable stresses.*	Not measured	*N/A*
Crossland et al.	2015	Prevention and suppression	Minimum- and no-tillage	Combination	No effect	*CA practices, including minimum- and no-tillage, have increasingly been successfully employed in conventional farming systems achieving long-term benefits to soil quality and reduced production costs (Holland, 2004). However, these practices rely heavily on the use of herbicides to control weeds and have meant that reduced tillage has been difficult to implement effectively in organic farming systems where ploughing is often the primary method of weed control*	Increase	*CA practices, including minimum- and no-tillage, have increasingly been successfully employed in conventional farming systems achieving long-term benefits to soil quality and reduced production costs (Holland, 2004). However, these practices rely heavily on the use of herbicides to control weeds and have meant that reduced tillage has been difficult to implement effectively in organic farming systems where ploughing is often the primary method of weed control*
Culjak et al.	2017	Prevention and suppression	Trap crop	Single	Positive	*A 15% contribution of "Perko" trap crop to the oilseed rape can effectively suppress pollen beetle populations and maintain levels below the control threshold. Only 2.5% of oilseed rape in relation to 15,000 m2 of the total experimental area was affected with high pollen beetle population levels, and the control threshold was exceeded*	Not measured	*These results should be applicable to precise agriculture in countries with intensive production to minimise the negative effects of various agrochemicals.*
Cuthbertson, Qiu, and Murchie	2014	Non chemical methods	Conservation of natural predators	Combination	Not measured	*The re-discovery, and subsequent conservation, of the beneficial predatory mite, Anystis baccarum (Linnaeus) (Acari: Anystidae), in Bramley apple orchards in Northern Ireland offers a potential alternative control component for incorporation into integrated pest management strategies. Anystis baccarum readily feeds upon economically important invertebrate pest species including European fruit tree red spider mite, Panonychus ulmi (Koch) (Acari: Tetranychidae) and show a level of compatibility with chemical pesticides.*	Decrease	*Reduced chemical application; improved efficacy of natural predation by natural predators via increased understanding of natural predators. Increased compatibilty with chemical control options.*
DAFM	2014	Prevention and suppression	Sterile seed bed technique	Single	Positive	*The sterile seed bed technique involves cultivating the soil, and then leaving it for a period until an initial flush of weeds has germinated. The grower will then either lightly cultivate or use a total herbicide to destroy the weed cover, before the desired crop is planted/sown.*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Crop Rotation	Single	Positive	*Crop rotation involves the successive planting of different crops on the same land to improve soil fertility and help control troublesome insects, diseases and weeds. Whilst the continuous cropping of some crops can be successfully done without any major agronomic*	Not measured	*N/A*

						disadvantages e.g., spring barley, It is generally good practice to follow some degree of crop rotation. Continuous cropping of certain crops can result in higher input costs, lower yields, higher pest pressure and increased likelihood of resistance. For example, 2 or 3 successive crops of winter wheat will yield significantly lower than growing a winter wheat crop after a broadleaved break crop, due largely to effects of the "take all" fungus (Gaeumannomyces graminis).		
DAFM	2014	Prevention and suppression	Cleaning Machinery and equipment	Single	Positive	*Machinery can often be responsible for the transport of pests from field to field or farm to farm. Examples of this are situations like potato cyst nematode or beet cyst nematode being carried from one field to another on soil particles on machinery. Another example is where a combine harvester/baler transports wild oat seeds from one location to another.*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Clean potato boxes/growing trays etc	Single	Positive	*Good growing and storage hygiene is important to minimise the spread of many pathogens injurious to many crops. Pathogens such as "black leg" (Erwinia spp.) in potatoes, can be transmitted by debris etc.. on boxes. Steam cleaning can eliminate such possibilities. Similarly, cleaning and/or disinfecting growing trays, remains a useful way to reduce the initial source of inoculum. The same principle holds true for storage boxes and trays for all types of crop.*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Irrigation (applied to schedule)	Single	Positive	*Irrigation scheduling determines the correct frequency and duration of watering of the crop concerned. The goal in irrigation scheduling is to apply enough water to fully wet the plant's root zone but avoiding over watering. The soil is then allowed to dry out to allow air to enter the soil and encourage root development. Schedules can be constructed by using simple water balance sheets which consider how much water the crop utilises per day, how much rainfall occurs, the level of moisture in the soil etc.. Such schedules can be augmented by data from tensiometers, or more elaborate electron probe measuring devices.* *Efficient use of water can not only improve yield and quality, e.g., potatoes free of common scab (caused by Streptomyces scabiei), it can improve the overall crop health ensuring that the crop is less susceptible to a range of other crop pests*	Not measured	*N/A*
DAFM	2014	Monitoring	Soil testing (pH, nutrients, OM)	Single	Positive	*Soil analysis allows you to match fertiliser application to crop requirement ensuring optimum crop production. It also has the added benefits of reducing nutrient loss to the environment and growing farm profitability. Both macronutrient and micronutrient availability are affected by soil pH. In alkaline soils, N, K, Mg and Mo*	Not measured	*N/A*

						availability is increased, but P, Fe, Mn, Zn Cu, and Co levels are reduced.		
DAFM	2014	Informed decision making	Nutrient management programme	Single	Positive	*A nutrient management programme or plan is where the application of fertiliser/manure (artificial or by-product) is tailored to the specific requirements of the crop being treated and the target soil fertility index. This approach has many benefits in that the end user only applies as much fertiliser as will be utilised by the crop, thereby eliminating excess which could be subject to runoff and a cause of pollution. By applying as much fertiliser as will be utilised by the crop, when the crop needs it, you are ensuring that the crop is kept in optimum nutritional condition which can reduce its susceptibility to pests. This approach also has benefits from a financial perspective. However, in many situations the peak nutrient usage of the crop may exceed the actual amount of nutrition applied, therefore the availability of nutrient reserves becomes an important component of a well balanced and productive soil. However, application of N and P should not exceed those prescribed in the nitrates regulations (SI 610 of 2010 & the "Teagasc Green Book")*	Not measured	*N/A*
DAFM	2014	Non chemical methods	Protect beneficial organisms	Single	Positive	*In agriculture, a beneficial organism is any organism that benefits the growing process, including insects, arachnids, other animals, plants, bacteria, fungi, viruses, and nematodes. Benefits include pest control, pollination, and maintenance of soil health. Encouraging beneficial insects, by providing suitable living conditions, is a pest control strategy in itself. Depending on the beneficial organism targeted for protection, the method can vary from unsprayed areas of farms to cultivation of specialist areas with wild flowers or small seed plants. Research work conducted by Teagasc in Oakpark indicates that the use of minimum cultivation techniques can reduce aphid pressure on the established crop when compared to crops established with the more conventional approach (plough, till and sow).*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Full inversion tillage (plough)	Single	Positive	*This is usually an operation carried out using mouldboard ploughs. It essentially involves the turning of a depth of soil (usually 20-40cm) upside down. This results in the burial of what is termed "trash", which can comprise of crop debris which may harbour plant pests and other unwanted plant material such as diseases and weeds. E.g. the DAFM published "Code of Practice on the prevention and reduction of Fusarium Mycotoxins in cereals" recommends ploughing as part of a mycotoxin reduction/prevention strategy.*	Not measured	*N/A*

DAFM	2014	Prevention and suppression	Minimum cultivation	Single	Positive	*Minimum cultivation is sometimes referred to as "min till" and involves very shallow cultivation in as few a number of passes possible. It works on a principle which involves minimum disruption to the soil structure and is the opposite of inversion tillage. The main benefit from this practice is the improvement of soil structure which generally involves an increase in earthworm numbers but other advantages include lower aphid pressure and increased work rates. The full benefits of this practice are not seen for several years after embracing this option. Depressed yields are often experienced for the first few years. It should be noted that this practice can give rise to increased levels of grass weeds which can be problematic to control e.g. sterile brome and blackgrass. Increased slug activity can be a feature of this method of crop establishment. This system tends to work best for autumn based cropping but can give rise to establishment issues in very wet autumns.*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Management of crop residues	Single	Positive	*Crop residues are parts of the crop remaining after the crop has been harvested. These residues can include the root system, stubble (stems), stalks, leaves, straw and actual seed. Various cultivation techniques can be used to initiate or enhance microbial decomposition of crop residues. Management of these crop residues can have a positive effect on soil organic matter and decreases the likelyhood of soil erosion. Shallow cultivation using tine or disc based machines or consolidation using rolls and presses, permits weed seed and previous crop seeds to germinate which can then be controlled chemically prior to drilling. Ploughing helps to bury weed seeds and plant debris thereby breaking the weed/disease cycle.*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Choose disease resistant varieties	Single	Positive	*Host plant resistance relates to a plant's ability to resist pest damage. Some plants use their physical appearance as a deterrent such as plants that have hair covering their leaves or plants with a thick leaf cuticle. Some plants have resistance genes bred into them which enable them to fight infection or infestation. Therefore, considering a plants inherent ability to cope with stress or damage caused by a plant pest is important. Whilst a resistant variety can reduce dependence on the use of PPPs, one must also consider quality and yield parameters together with market and legislative requirements. For some diseases there are legal limits established, e.g., fusarium mycotoxins deoxynivalenol (DON) and zearalenone (ZON) in wheat intended for human consumption. There are also guidance limits established for feed grain. Trial research by both DAFM and Teagasc, Oak Park, show significant differences in between cultivars in their inherent resistance to diseases.*	Not measured	*N/A*

DAFM	2014	Monitoring	Use early warning/forecasting systems	Single	Positive	*Delaying intervention until treatment is absolutely necessary is feasible in some crop production contexts. A range of disease forecasting systems are available and can be quite useful to supplement observations made during site visits.*	Not measured	*N/A*
DAFM	2014	Monitoring	Monitor crops for pests/diseases	Single	Positive	*This remains the most useful and widely practiced option. Crops are treated on the basis of the presence or not of pests or whether threshold levels have been breached. However, sometimes crops require prophylactic treatment and so if one were to wait for certain diseases to appear it would be too late, e.g., late blight (Phytophthora infestans) in potato, downy mildew (Peronospora viciae) in field beans or leaf blotch (Septoria caused by Mycosphaerella graminicola) in wheat. Field monitoring should consider uneven distribution of crop pests and the presence of certain physical characteristics such as compacted headlands, sheltered areas and wet spots etc..*	Not measured	*N/A*
DAFM	2014	Monitoring	Use weather forecast to aid decisions	Single	Positive	*Weather has a major influence on the development of diseases and the prevalence of insect pests. Weather also plays a part on how effective intervention strategies are, e.g., likelihood of rain around the time of PPP application. The short to medium term weather forecast can and does influence the rates of application of PPP and the effectiveness of applied treatments. It could also influence PPP choice or indeed use of other control mechanisms*	Not measured	*N/A*
DAFM	2014	Monitoring	Use traps/sticky pads / lures	Single	Positive	*The use of various trapping techniques can serve to prove presence or not of an insect pest (to a lesser extent fungal spores). Ability to positively identify the insect pest is then required. Practical examples of trapping include, carrot fly (Psila rosae) traps and "layers mash" lure for slugs (molluscs)*	Not measured	*N/A*
DAFM	2014	Prevention and suppression	Some crops treated preventatively	Single	Positive	*Preventative treatments may be the best option to control a pest & can mean a lesser ppp loading than is required in a curative/eradicant situation.*	Decrease	*Preventative treatments may be the best option to control a pest & can mean a lesser ppp loading than is required in a curative/eradicant situation.*
DAFM	2014	Informed decision making	Some decisions based on pest thresholds	Single	Positive	*Some crops have well developed treatment thresholds for pests. Some of these thresholds are based on effects deleterious to yield while others are based on effects deleterious to crop quality. Other crops do not have well developed pest injury thresholds yet but work on thresholds is on going around the world. e.g., pollen beetle control in oilseed rape judged necessary if 3-5 beetles are present per raceem.*	Not measured	*N/A*
DAFM	2014	Non chemical methods	Use natural enemies	Single	Positive	*Natural enemies are organisms that kill or otherwise reduce the numbers of another organism. Natural enemies that limit pests are key components of many integrated pest management programs, particularly in protected crops. The most important natural enemies of*	Not measured	*N/A*

						insect and mite pests include predators, parasites, and pathogens. Examples of these are lady birds which prey on many aphid species and parasitic wasps which prey on whitefly		
DAFM	2014	Non chemical methods	Use crop fleeces	Single	Positive	*Crop fleeces can be multifunctional. They can protect crops from frost and cold conditions. They can serve to warm up the soil and vegetation thus encouraging and enhancing growth. Finally, depending on the type used, they can prevent the entry of certain insect pests. However, in some situations the use of a fleece can serve to create a micro climate of its own, which in turn can present issues regarding the proliferation of pests under the fleece or the occurrence of diseases often more virulent than in open air. Another issue around the use of fleeces, particularly for longer more protracted periods, is the ability of the grower to intervene with crop protection measures if necessary.*	Not measured	*N/A*
DAFM	2014	Non chemical methods	Use propane burners for weed control	Single	Positive	*Gas fired burners (either propane or butane) are sometimes used in weed control programmes for row crops. Some of these burners are handheld and hand operated while others are tractor mounted, depending on the application / scenario. It should be noted that this method may present a higher carbon footprint than many other methods. It should also be noted that propane burning is deleterious to organic matter levels in the upper profiles of the soil. Longevity of control is also an issue.*	Not measured	*N/A*
Damalas and Koutroubas	2018	Pesticide selection	Biopesticides	Combination	Positive	*Nanoformulations and microencapsulation technologies can improve the stability and residual action of biopesticide products*	Decrease	*biopesticides have not yet reached the desired level of use, whereby they could displace the dominance of chemical pesticides, given that the commercialisation of new products in the market is lagging behind. Nanoformulations and microencapsulation technologies can improve the stability and residual action of biopesticide products, and this could increase their field use. Regulations that promote registration of low-risk compounds with the provision of incentives could also facilitate commercialisation and availability of biopesticides in the market.*
Deliopoulos et al.	2010	Non chemical methods	Arbuscular mycorrhizal fungi	Single	Positive	*Root invasion by Globodera pallida: Microscopic examination of the root tissues 4 wk after planting in Experiment 2 revealed that AMF interacted significantly with nematicide (P < 0.001) to affect the numbers of juveniles invading the root system (Table 2). Although both factors also produced a significant main effect, this effect was much stronger for aldicarb than for AMF as demonstrated by the F-ratios of 186.8 and 3.2, respectively. Although mycorrhization as a main effect did not influence yield significantly, aldicarb-treated*	No Effect	*N/A*

						plots that received at planting 10 g/tuber of the mycorrhizal inocula G. intraradices or G. mosseae showed a trend (P = 0.097) for higher yields (both over 30 tonnes/ha) than those plots that did not receive AMF treatment at planting (27.1 tonnes/ha)		
Dib et al.	2010	Non chemical methods	Natural enemies	Single	Negative	*Efficient pest control using conservation strategies requires sound knowledge of the dynamics of the pest and its natural enemies (NE). New management practices aimed at favoring natural regulation, especially augmentative approaches, need to be developed.*	Not measured	*Undefined, but likely outcome is that the overall suggestion is that outside of small scale, organic farming, reliance on natural controls is likely to be ineffective and have a delitarious effect on yield and quality*
Doonan, H.	2017	Prevention and suppression	Crop rotation	Single	Positive	*Crop rotation has increased in recent years due to the 'three crop rule' introduced in 2015 under the Common Agricultural Policy (CAP). This requires farmers receiving basic farm payments and farming over 30 ha of arable land to grow at least three different crops in an annual rotation to encourage biodiversity on the farm. Development of blackgrass (Alopecurus myosuroides) resistant to many herbicides used in arable rotations, particularly winter wheat and winter oilseed rape crops, has led to an increase in the area of spring cereal crops grown. The majority of blackgrass emerges in the autumn, so if a spring crop is grown this gives an opportunity to cultivate the soil to encourage successive flushes of blackgrass which can then be destroyed by cultivations or non-selective herbicides. Work done by Dr Stephen Moss and Dr Peter Lutman has shown that growing spring crops can reduce blackgrass populations by an average of 88% over time.*	Not measured	*N/A*
Doonan, H.	2017	Prevention and suppression	Delayed drilling	Single	Positive	*Delaying drilling was used by 60% of respondents as an IPM measure. Delaying drilling allows weed seeds to germinate and be destroyed either by spraying or cultivations before drilling. However delaying drilling carries obvious risks, especially on heavy land with changeable weather when the opportunity to drill a winter crop can be delayed (with yield implications) or even lost.*	Not measured	*N/A*
Doonan, H.	2017	Prevention and suppression	Soil cultivations	Single	Positive	*Soil cultivations are used by around half of growers as an IPM measure. Under minimum tillage (min till) scenarios weed seeds stay near soil surface rather than being distributed vertically through the soil profile. This tends to lead to higher blackgrass populations as freshly shed seed is retained near the soil surface from where young blackgrass seedlings can easily emerge in the following crop.*	Not measured	*N/A*
Doonan, H.	2017	Informed decision making	Pest thresholds	Single	Positive	*With all weeds, pests and diseases there is a population number below which it is uneconomic to apply PPP as the economic penalty to the crop is less than the cost of the PPP and application costs.*	Not measured	*N/A*

Doonan, H.	2017	Prevention and suppression	Varietal diversity	Single	Positive	*Most wheat growers grow 3 or 4 varieties at most to spread risk. Varietal choice is influenced by the end market the grower is selling to, soil type, geographic location in the UK, and physical proximity to the processor. The place in the rotation (some varieties perform better as a first or second wheat) and the practicalities of growing numerous varieties and the ability of the grower to keep varieties separate after harvest are also key influences. Yield and disease resistance are also important considerations in varietal choice. All wheat varieties on the AHDB Recommended List are given disease resistance ratings for the most common diseases of between 1 to 9 where 1 is poor and 9 is excellent. For Septoria tritici all wheat varieties have resistance scores of between 4.3 and 6.8.*	Not measured	*N/A*
Doonan, H.	2017	Non chemical methods	Beneficial organisms	Single	Positive	*It is recognised that some insects predate on insect pests for example the parasitic wasp Ichneumon spp. lays its eggs in immature aphids. The eggs hatch and the wasp larvae develop inside the growing aphid eventually killing it. Beneficials are used widely in covered horticultural crops where closed environments means their release and numbers can be monitored and controlled.* *In arable systems, there are no data to indicate how many beneficials are present in a particular field or farm and numbers will vary depending on weather, cropping and habitat availability. Some beneficials such as ground beetles Carabidae spp. are generalist predators providing background control for a wide range of pests e.g. aphids, fly eggs and larvae, slugs and weed seeds. Others are more pest specific for example lacewings Neuroptera spp. predating on aphids. Studies have shown that a lacewing larva can consume up to 1500 aphids in its lifetime.* *However, with both generalist and specific beneficials, in arable situations, whilst it is accepted that they are useful, there are little data to indicate how many predators are required to prevent or control a pest outbreak or ultimately how effective they are as an alternative to PPPs and so the uptake of beneficals, mainly by provision of habitats, is low at 38%.*	Not measured	*N/A*
Doonan, H.	2017	Prevention and suppression	Crop density	Single	Positive	*Crop density was another measure used by growers to reduce weed, pest or disease incidence. There is an optimum number of crop plants established per m2, below which economic optimum, yields will not be achieved and above which crop competition will occur. By increasing plant numbers per unit area, weed competition is increased. In some cases, if pest numbers (for example slugs) are predicted to be high, a percentage of the crop can be 'lost' to pests. However, it*	Not measured	*N/A*

						is difficult to predict what this loss might be and what the final plant population will be. The downside is that denser crops create a microclimate which is generally more favourable for disease development and spread and so more careful management and potentially more PPP inputs may be required. This is, therefore, one of the less commonly used IPM measures, being used by only 17% of respondents.		
Dun-chun, Jia-sui and Lian-hui	2016	Informed decision making	Modelling		Positive	*model of plant disease management*	Decrease	*model increases agricultural productivity and improves food quality but also to protect the ecological environment and natural resources.*
FAO	2020	Prevention and suppression	Crop rotation; inter-cropping	Single	Positive	*If you plan to grow the same crops regularly, you will need to rotate them. Different crops needs particular nutrients in the soil and use these up at a particular level in the ground. At the same time, each kind of plant attracts its own particular pests and diseases, which soon become established around the crop. If you grow the same kind of crop in the same place season after season, the nutrients that the plant needs are quickly exhausted, the plants grow weak and stunted and quickly come under attack from waiting pests and diseases. Crop rotation is important if the rotation reduces inoculum. Crop rotations should be observed since there are many pathogens that survive on numerous types of both living and dead plant materials. Some crops, such as sorghum, pearl millet and maize, may drastically suppress weed population and reduce its biomass. Pearl millet may exhibit residual weed suppression in the following crop. It is obviously necessary to evaluate which rotations can be grown successfully in the agro-ecological zone to maximise yield and pest control.*	Not measured	*N/A*
FAO	2020	Prevention and suppression	Use of adequate cultivation techniques	Single	Positive	*Burning plant residues and ploughing the soil is traditionally considered necessary for phytosanitary reasons: to control pests, diseases and weeds. In a system with reduced mechanical tillage based on mulch cover and biological tillage, alternatives have to be developed to control pests and weeds and Integrated Pest Management becomes mandatory. One important element to achieve this is crop rotation to reduce the pest-risks associated with monocultures, interrupting the infection chain between subsequent crops (different sowing dates and distances between fields with the same crops) and making full use of the physical and chemical interactions between different plant species. Synthetic chemical pesticides, particularly herbicides are, in the first years, inevitable but have to be used with great care to reduce the negative impacts on soil life. To the extent that a new balance between the*	Not measured	*N/A*

						organisms of the farm-ecosystem, pests and beneficial organisms, crops and weeds, becomes established and the farmer learns to manage the cropping system, the use of synthetic pesticides and mineral fertiliser tends to decline to a level below that of the original "conventional" farming system		
FAO	2020	Prevention and suppression	Use of pest resistant/tolerant cultivars and standard/certified seed and planting material	Single	Positive	*Plant breeding has resulted in the development of a large number of varieties that are resistant to several kinds of diseases. Breeding is based on access to plant genetic resources, which can be conserved in the field and in gene-banks. Wild cultivars have low economic benefits in most cases, but often show resistance to locally occurring biotic and abiotic stresses; and cross-breeding of these varieties can result in the development of varieties that can perform better, by out-competing weeds, without the application of large doses of pesticides. A sustainable seed system will ensure that high quality seeds of a wide range of varieties and crops are produced and fully available in time and affordable to farmers and other stakeholders. Access to certified seeds will improve the uptake of farmers of higher-yielding varieties which can withstand stress and thus decrease environmental problems that are caused by use of pesticides*	Decrease	*Cross-breeding of these resistant varieties can result in the development of varieties that can perform better, by out-competing weeds, without the application of large doses of pesticides*
Fennell, Fountain, and Paul	2019	Monitoring	Reflective ground coverings, modification of crop light conditions, UV/light polarity manipulation, attration trapping	Combination	Not measured	*We can qualitatively say that a reduction in pest incidence was observed in the majority of studies, however the magnitude of different attenuations and, therefore, an estimation of the magnitude change in pest load, is difficult to compare between studies. This is because the light environments were often not well characterised, probably due to the need for specialist equipment and considerable effort involved in making calibrated solar spectral measurements*	Not measured	*Three studies [on UV] reported the effect on Diptera with two demonstrating significant reductions in trap captures. Smaller-scale studies showed that insects from across the taxa had a reduced preference for entry into structures that transmitted less UV. Alate morphs of the potato aphid (Macrosiphum euphorbiae (Thomas)) (Legarrea et al., 2012c), greenhouse whitefly (T. vaporariorum) (Mutwiwa et al., 2005), and silverleaf whitefly (Bemisia tabaci Gennadius) (Costa and Robb, 1999) had a strong preference for chambers clad in UV-transmitting materials compared to those clad in UV-attenuating materials when presented with both in a choice test. Similarly, western flower thrips (F. occidentalis) was nine times more likely to enter a chamber clad in UV transparent materials (Kigathi and Poehling, 2012). Feeding thrips were also shown to rapidly respond to attenuation of UVB, showing reduced preference for tunnels with high UVB.* *Remarkably, reduced pest activity was observed under claddings that transmitted as much as 40% of the ambient solar UV.*

Fradgley, et al.	2014	Prevention and suppression	Shading effect of crops	Combination	Positive	*Grain yield was reduced by both early season and later season weed competition. Resultant post harvest weeds were suppressed throughout the season by the shading effect of crops with high mid season Leaf Area Index (LAI), and high stem density indicating tillering ability. Crop height did not directly suppress weeds but is correlated with a greater LAI. Weeds were suppressed at an early stage by crops with good establishment rates*	Not measured	*N/A*
Fradgley, et al.	2014	Non chemical methods	Participatory breeding programme	Single	Negative	*For the first trial year including only the Hungarian selected lines, there were significant differences among varieties (P<0.001) and Alchemy had the highest average yield. Across all trial entries grain yield was correlated negatively with yellow rust infection on the flag leaf at heading (P<0.001) and with reduced green leaf area during grain ripening (P<0.001). In current trials including locally selected lines, some of the selected lines had significantly lower yellow rust infection than the average of the original CCP and of the control variety Alchemy (P<0.001). There was also greater early ground cover (P<0.005) and (LAI) at tillering (P<0.05) in some lines compared to Alchemy and the original population. Crop cover was also correlated negatively with early weed cover (P<0.05). These observations suggest that it is possible to select lines with enhanced resistance to local disease and the ability to compete with weeds at an early stage.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	the use of natural predators via habitat enhancements	Single	Positive	*beetle banks and field margins*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Prevention and suppression	Rotating crops	Single	Positive	*For example, the VI introduced Crop Protection Management Plans (CPMPs) and which were included in the ELS until recently. Within the VI there is also an emphasis on the type of pesticide to employ as well as the adoption of non-chemical pest management such as rotations, cultivation practices, and the use of disease resistant varieties.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Prevention and suppression	Treat seeds/seedlings	Single	Positive		Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	Field Margins	Single	Positive	*There has also been a growth in the use of natural predators via habitat enhancements such as beetle banks and field margins to undertake pest management.*	Not measured	*N/A*

Fraser, Sharma and Bailey	2011	Prevention and suppression	Adjusting Time of planting	Single	Positive	*No description provided*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Prevention and suppression	Using Disease Resistant Varieties	Single	Positive	*There is high adoption of crop rotation, the pre-treatment of seeds prior to drilling and the use of disease and pest resistant varieties.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Prevention and suppression	Using Different Varieties in the Field	Single	Positive	*There is high adoption of crop rotation, the pre-treatment of seeds prior to drilling and the use of disease and pest resistant varieties.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	Hand rogueing	Single	Positive	*No description provided*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Pesticide selection	Rotate Pesticide Classes to Avoid Resistance	Single	Positive	*The VI introduced Crop Protection Management Plans (CPMPs) and which were included in the ELS until recently. Within the VI there is also an emphasis on the type of pesticide to employ as well as the adoption of non-chemical pest management options such as rotations, cultivation practices, and the use of disease resistant varieties.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Reduced pesticide use	Spot Spraying/spraying field edges	Single	Positive	*No description provided*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	Cultivation or using rotary hoe for weeds	Single	Positive	*For example, the VI introduced Crop Protection Management Plans (CPMPs) and which were included in the ELS until recently. Within the VI there is also an emphasis on the type of pesticide to employ as well as the adoption of non-chemical pest management such as rotations, cultivation practices, and the use of disease resistant varieties.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	Using Flower Strips to encourage beneficial insects	Single	Positive	*There has also been a growth in the use of natural predators via habitat enhancements such as beetle banks and field margins to undertake pest management.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	Bettle banks	Single	Positive	*There has also been a growth in the use of natural predators via habitat enhancements such as beetle banks and field margins to undertake pest management. Thus, as noted by Holland and Oakley (2007) insecticides are being simultaneously employed with other pest management strategies such as floristically enhanced field margins and Beetle banks which are promoted by various AEP.*	Not measured	*N/A*

Fraser, Sharma and Bailey	2011	Non chemical methods	Using Pheromones to monitor and control insects	Single	Positive	*No description provided*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Prevention and suppression	Using Mixed Varieties in the field	Single	Positive	*The VI introduced Crop Protection Management Plans (CPMPs) and which were included in the ELS until recently. Within the VI there is also an emphasis on the type of pesticide to employ as well as the adoption of non-chemical pest management options such as rotations, cultivation practices, and the use of disease resistant varieties.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Non chemical methods	Introduce predators/parasites of insect pests	Single	Positive	*There has also been a growth in the use of natural predators via habitat enhancements such as beetle banks and field margins to undertake pest management.*	Not measured	*N/A*
Fraser, Sharma and Bailey	2011	Prevention and suppression	Using a Trap crop	Single	Positive	*However, on closer inspection of the survey data it was observed that one of the factors is composed of a set of pest management technologies that have been adopted by very few of the farmers in the survey, the use of mixed varietal planting, predator introductions and the use of trap crops*	Not measured	*N/A*
Garthwaite	2015	Monitoring	Monitoring	Single	Positive	*A brief introduction to the history and methodologies employed by the pesticide usage survey teams is given. The main objectives, scope and statistical requirements of the surveys are outlined. Whilst the methodologies for the collection of pesticide usage data are beneficial in the monitoring of plant pests over long periods of time, the survey visits are unsuitable for the rapid reporting needed to evaluate and report on plant pests in real time. However, because of the EU requirements for all member states to monitor pesticide usage, the data collected from these surveys can also provide information on new and existing pest pressures, changes in established pest pressures and allows monitoring of farmers' and growers' behaviour.*	Not measured	*N/A*
Gent et al.	2013	Informed decision making	SIRATAC decision support system	Single	Not measured	*A powdery mildew risk index for grape was originally designed to prescribe fungicide application intervals. Initially, use of the index in California reportedly reduced fungicide applications by two to three per vineyard per season with equal or better disease control compared with prophylactic treatment (32). Adoption of this index has increased steadily since 1996, and in 2008 50% of California growers self-reported as using the index heavily, often, or sometimes (54); Oregon and Washington growers. What characterises growers' choice to use or not use the powdery mildew risk index? Lybbert & Gubler (54) found that among those not using the index, the primary reason cited for nonuse was a*	Decrease	*The justification for continued support for SIRATAC was less clear when similar patterns of insecticide use developed without using the system. Some consider that learning and simplified management without use of SIRATAC was a system failure (75). However, given that system use resulted in a change in grower behavior and the desired outcome (improved management) (66), defining success and failure (or acceptable or unacceptable impact) is not straightforward. In these examples, the development and deployment of predictive systems apparently helped to create*

						preference for a set application schedule. In contrast, users of the risk index cited better disease control as a primary motivation for adoption. Users did not assign greater importance to chemical cost savings than nonusers did, which is similar to responses in Oregon andWashington (Figure 3). reported 54% and 69% use, respectively, in 2011 and 2012 surveys (G. Grove & W. Mahaffee, unpublished results).		*opportunities for accelerated farmer learning by experience and, critically improved management, which is a measure of success in applied farm systems research (5).*
Giles et al.	2017	Non chemical methods	Incorporation of biological control into dynamic IPM programs	Single	Positive	*Review, but says... Clearly, more research is needed on landscape-level interactions between pests and natural enemies, but results from a few studies suggest that local and regional pest outbreak or pest suppression areas could be identified and this information could be integrated into dynamic web-based IPM decision support systems to optimise scouting and management efforts*	Not measured	*N/A*
Green and Owen	2011	Prevention and suppression	Herbicide resistant crops	Single	Not measured	*Weed management dramatically changed with the widespread adoption of GR crops. Using glyphosate in GR crops made weed management too simple and convenient. Importantly, the high initial efficacy of glyphosate declined with repeated use, and current glyphosate-based weed management systems are in jeopardy as evidenced by the speed at which weed populations are evolving resistance. Still, glyphosate has not lost all utility; it controls more weeds more effectively than other herbicides, but it can no longer be applied alone anytime on any weed anywhere. Most growers still do not have any GR weeds in their fields and have time to implement proactive HR weed management practices to help sustain glyphosate. However, growers need to act now to diversify the herbicides and tactics they use, the crops they plant, their cultural practices, and field hygiene measures.*	Increase	*HR crops will not replace the need for technical innovations, particularly the discovery of herbicides with new MOAs. Diversification will be much easier if growers can chose from among multiple effective and economical weed management options. In areas of the world that have not yet adopted GR crops, growers can learn from the experiences in North and South America. Growersmust not wait, but implement bestmanagement practices as soon as new trait and herbicide technologies are available. By using diverse weed management practices, growers will preserve the utility of herbicide resistance traits and herbicide technologies and help maintain profitable and environmentally sustainable crop production systems for future generations.*
Grettenberger and Tooker	2015	Prevention and suppression	cultivar mixtures	Single	Positive	*may increase yield or productivity through a variety of mechanisms*	Not measured	*strong potential to provide incremental benefits increasing yield, crop resiliance and sustainability*
Haye et al.	2016	Monitoring	Traps	Combination	Not measured	*Trials conducted in 2014 showed a significant reduction of SWD populations in raspberries (cv Polka) over a period of three weeks, when traps were placed in shady places at fruit height every 2 metres in the perimeter of the crop (density: 200 traps/ha; costs: 155€/ha).*	Increase	*Response to emergent new pest.*

Haye et al.	2016	Non chemical methods	Biological control	Single	Not measured	*Biological control can be a cost-effective and environmentally safe approach for the management of arthropod pests. Current control programmes for SWD rely primarily on pesticides, and these programmes may be challenged because abundant wild fruits can serve as a reservoir for this highly polyphagous and mobile pest to reinvade managed crops (Lee et al. 2015). Natural enemies may also proliferate in both crop and unmanaged habitats, potentially playing a unique role in lessening the fly populations in crop and uncultivated habitats.*	Not measured	*N/A*
Heijne et al.	2015	Non chemical methods	Exclusion netting for codling moth with apples	Single	Positive	*Both the total treatment frequency index (TFI) and that for insecticides only was reduced by covering orchards with nets to exclude codling moth in commercial orchards of the "Alt'Carpo" network. At the same time, damage by C. pomonella and Grapholita molesta dramatically decreased from about 3.5 to 0.2 % damaged fruits. However, the infestation of the damaging rosy apple aphid (Dysaphis plantaginea) increased from about 70 to 120 aphids per shoot in the non-covered and covered orchards respectively in mid-May in a non-insecticide treated orchard (Marliac et al., 2013).*	Decrease	*Both the total treatment frequency index (TFI) and that for insecticides only was reduced by covering orchards with nets*
Heijne et al.	2015	Non chemical methods	the use of an antagonist against conidia of Venturia inaequalis for apples	Single	Positive	*"In the trials during the summer season 2012, applications of both non-formulated and formulated conidia of C. cladosporioides H39, at weekly intervals, reduced scab on leaves and fruits, and was as effective as the copper-based spray schedule commonly used in organic farming. Spraying one day after predicted infection events was slightly less effective than calendar sprays. Also in 2013 during the primary season, calendar sprays of C. cladosporioides H39 were as effective as a copper-based spray schedule. Sprays after predicted ascospore infections significantly reduced scab incidence on leaves and fruits. However, such a schedule was less effective than calendar sprays"*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Sanitation	Single	Positive	*Effective for Leaf and glume blotch, Tan sport, Head scab, Take-all and Wheat streak mosiac virus for wheat, Effective for barley scald, net blothc, head scab and Barley stripe for Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Evaluation	Crop rotation	Single	Positive	*Scouting fields is an easy way to ensure that you are staying on top of yield-robbing diseases. Growers that scout their fields will benefit from scouting by 1) being able to make or not make pesticide applications in a timely manner and 2) learning about the disease issues associated with a particular field or variety. This information can be used in future seasons to better maximise productivity*	Not measured	*N/A*

Herbert and Flessner	2016	Prevention and suppression	Planting date	Single	Positive	*Effective for Powdery Mildew, Leaf rust, Head scab, Take-all, Barley yellow dwarf, Wheat spindle streak for wheat, Effective for powdery mildew, leaf rust, head scab and barley yellow dwarf for Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Balanced fertility	Single	Positive	*Effective for Powdery Mildew and Take-all for wheat, Effective for powdery mildew for Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Disease free seed	Single	Positive	*Effective for leaf and glume botch and loose smut for wheat, Effective for covered smut, loose smut and barley stripe for Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Resistant cultivars	Single	Positive	*Effective for Powdery Mildew, Leaf rust, Leaf and glume blotch, Tan spot, Head scab, Barley yellow dwarf, Wheat spindle streak for wheat, Effective for Covered smut, loose smut, powdery mildew, leaf rust, barley scald, net blothc, barley stripe, barley yellow dwarf for Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Seed treatments	Single	Positive	*Effective for Powdery mildew, leaf rust, leaf and glume blotch, loose smut for wheat, Effective for covered smut, loose smut, powdery mildew, leaf rust, net blotch, barley stripe in Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Fungicide Foliar	Single	Positive	*Effective for Powdery mildew, leaf rust, leaf and glume blotch, tan spot, head scab for wheat, Effective for powdery mildew, leaf rust, barley scald, net blotch and head scab for Barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	Insecticide Seed	Single	Positive	*Effective for Barley yellow dwarf for wheat and barley*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	reduction in the use of manure	Combination	Positive	*Effective at reducing slugs*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	shift to conventional tillage practices for at least one season	Combination	Positive	*Effective at reducing slugs*	Not measured	*N/A*
Herbert and Flessner	2016	Prevention and suppression	minimum tillage to reduce the amount of surface trash	Combination	Positive	*Effective at reducing slugs*	Not measured	*N/A*

Herbert and Flessner	2016	Prevention	burndown herbicide	Single	Positive	*An alternative strategy for managing stalk borer infestations is to apply a burndown herbicide at least 10 days before corn is planted. The slightly earlier burndown herbicide application means that a suitable alternative host (i.e., corn) will not be available to the stalk borer larva as it emerges from its herbicide-treated host. As a consequence of this action, the exposed larvae are subject to a much higher mortality rate from such factors as predation, starvation, and adverse environmental conditions.*	No Effect	*N/A*
Herbert and Flessner	2016	Monitoring	Yellow sticky card	Single	Positive	*Monitor the traps every 9 to 10 days, recording the number of western corn rootworm beetles on each trap. At each site remove the release paper from the unused side of the trap and re-install the trap on the corn stalk with the fresh side exposed. Install new traps every other visit.*	Not measured	*N/A*
Herrera-Reddy, Carruthers, and Mills	2017	Non chemical methods	Mowing and seed predation. Fire and seed predation	Combination	Positive	*Both integrated management strategies (BioControl + Mowing and Biocontrol + Fire) were more effective in reducing pod and seed production, and the seed bank density of Scotch broom than BC alone. seed predation by the Scotch broom seed weevil also appeared to be greater in integrated management plots compare to BC-alone plots, but these differences were not consistently statistically significant*	Not measured	*N/A*
Holland et al.	2012	Non chemical methods	biological control-Natural enemies	Single	Positive	*In year 1, by 14 d after inoculation the aerial natural enemies alone had caused substantial reductions (88%) in numbers of cereal aphids compared to where no natural enemies were present. In contrast, epigeal predators achieved a 31% reduction, although this reached 88% after 28 d. In year 2, both aerial and epigeal natural enemies achieved over 87% control after 14 d.*	Not measured	*N/A*
Holland et al.	2012	Non chemical methods	Conservation biocontrol	Combination	Positive	*Conservation biocontrol is one of them where semi-natural habitats are used by natural enemies of pests for overwintering, as source of alternative prey or hosts." "Three out of eight case studies demonstrated an increase in predation of crop specific pests through bordering Semi-Natural Habitat. One of these was ground predation in wheat fields in southern England.*	Not measured	*N/A*
Horner et al.	2011	Non chemical methods	Release of sterile insects	Single	Not measured	*SIT is a pestspecific method of insect control that can complement current Integrated Pest Management (IPM) strategies*	Not measured	*Not reported*
Horrocks et al.	2010	Monitoring	Pitfall trap, sticky trap and direct search	Combination	No effect	*There was a positive effect biologically, but no statistically significant effect. The negligible YDV differences between the IPM and conventional crops, reduction in the number of insecticides applied in the IPM managed crops and the negligible yield differences contributed to the farmers involved in this project becoming enthusiastic users of IPM with a keen interest*	Decrease	*Farmers determined their own IPM strategey and as a result, all participants used fewer crop protection chemicals and became enthusiastic users of IPM with a keen interest to preserve the beneficial predators in their cropping systems. This was not measured however.*

						to preserve the beneficial predators in their cropping systems. This was not measured however.		
Horrocks, Horne and Davidson	2018	Monitoring, Pesticide selection	An integrated pest management (IPM) strategy was compared with farmers' conventional pest management practices on twelve spring- and autumn-sown seed and forage brassica crops.	Combination	No effect	*There was a 35% reduction in the number of insecticides applied under IPM compared with conventional management, negligible crop yield differences, and the type ofinsecticides applied was different.*	Decrease	*There was a 35% reduction in the total amount of insecticides used on the IPM side compared to the conventional side and this was consistent for seed- and forage-brassica crops. On average across both seed and forage brassicas, 75% of the insecticides used on the IPM plots were selective compared to only 35% on the conventional system, where the majority of insecticides used were broad-spectrum.*
Hovmoller and Henriksen	2008	Prevention and suppression	Resistence	Single	Positive	*The implementation of variety and pathogen characteristics in an IPM approach is illustrated in Table 2, where the resistance groupings in Crop Protection On-line (CPO) are presented for five varieties. CPO is a web-based decision support system (DSS) for pesticide use in cereals (Hagelskjær and Jørgensen 2003), which is widely used by farmers and extension service in Denmark (Jørgensen et al. 2007). The resistance grouping has immediate influence on the CPO-recommended disease management strategy.*	Not measured	*N/A*
Jhala et al.	2014	Prevention and Suppression	Row spacing	Single	Positive	*Row spacing is an important cultural practice affecting weed control because corn in narrow rows will shade soil surface earlier than corn in wider rows. Once the canopy has closed, very little light reaches the soil surface or weeds beneath the canopy. The value of early canopy closure for weed control is especially evident when weed control program in corn is dependent on postemergence herbicides only.*	Not measured	*N/A*
Jhala et al.	2014	Prevention and Suppression	Crop Rotation	Single	Positive	*Crop rotation has been one of the most common methods of managing weeds. The more diverse the crop in rotation in planting time, growth habit, and life cycle, the more effective the rotation will be in controlling weeds. Thus, the selection of a crop in rotation that includes small grains, forages, and legumes is significant; however, such crops are no longer widely grown in the North Central USA. While modern rotations tend to include shorter cycles and fewer crops, a 2-year corn–soybean (Glycine max [L.] Merr.) rotation, especially if it includes a different tillage system for each crop, can help to manage some weeds. As in any rotation used over many years on the same field, certain weeds will often adapt to the rotation and*	Not measured	*N/A*

						become problem weeds or evolve resistance to herbicides over time.		
Jhala et al.	2014	Prevention and Suppression	Cover crops	Single	Positive	*Use of cover crops is another example of cultural control of weeds. Cover crops can be used for a variety of purposes including protecting the soil against erosion, improving soil structure, fixing nitrogen, feeding the soil biological life, and managing soil moisture [34]. A key soil health concept is that there should be something green and growing during as much of the year as possible. Grasses provide the long-lasting residue cover because they have a higher carbon to nitrogen ratio in their biomass compared to non-grass species. In addition, they improve snow catch in the winter and reduce wind erosion in the spring compared to the bare soil. Taller brassicas with broad leaves like rape, mustards, and canola will also effectively reduce wind erosion and catch snowfall, but they provide less residue. In conclusion, a healthy, vigorous corn crop with a high yield potential will be very competitive with weeds; however, competition from the crop alone is not sufficient to provide a season-long weed control. Other methods of control must be used in conjunction with cultural control measures.*	Not measured	*N/A*
Jhala et al.	2014	Non chemical methods	Mechanical Weed Control - tillage	Single	Positive	*Tillage is the most common method of mechanical weed control and it can be divided into two categories: (1) preplant tillage and (2) in-row cultivation. The purpose of preplant tillage is to kill all the weeds present before planting corn to give the crop a better start to compete with weeds during the initial stage. Field cultivators and discs are commonly used by growers, and they are highly effective for controlling weed seedlings if used properly. The in-row cultivation is used to remove weeds after the crop has been planted, usually using rotary hoe or an interrow cultivator. Rotary hoes are most effective on small-seeded broad-leaved weeds and grasses, but they are less effective on large-seeded broad-leaved weeds, such as giant ragweed, velvetleaf (Abutilon theophrasti Medik.), cocklebur (Xanthium strumarium L.), etc. Rotary hoes are usually operated at the speed of 13–19 km/h and should be used after planting the crop but before weeds have emerged or after weed germination. Another advantage of in-row cultivation is that they are useful when soil-applied herbicides fail to control weeds due to lack of rainfall. Several types of in-row cultivators are available in the market, but it is important to adjust the equipment to effectively kill as many weeds as*	Not measured	*N/A*

						possible in the interrow area while minimising the disturbance of the crop plants.		
Jhala et al.	2014	Non chemical methods	Flame Weeding	Single	Positive	*The efficacy of flame weeding was reported to be influenced by several factors, including the presence of protective layers of hair or wax and lignification [39, 40], the physical location of the growing point at the time of flaming [39,43, 44], plant growth stages [39, 45–51], the regrowth potential of plant species [39, 40], the technique of flaming [37], and the relative leaf water content of plant species [52]. Ulloa et al. conducted a series of studies where the authors intentionally flamed several agronomic crops such as field corn, popcorn (Z. mays L. var. everta), and sweet corn (Z. mays L. var. rugosa) [48–51, 53, 54]. Response to broadcast flaming varied among corn types, their growth stages, and propane dose.*	Not measured	*N/A*
Jhala et al.	2014	Non chemical methods	Biological Control	Single	Not measured	*The biological control approach makes use of the weed's naturally occurring enemies to help reduce the weed's impact on agriculture and the environment. It simply aims to reunite weeds with their natural enemies and achieve sustainable weed control. These natural enemies of weeds are often referred to as biological control agents. For example, a commercial bio-herbicide Colego, a fungal herbicide, has been used to control northern jointvetch (Aeschynomene americana L.) in rice (Oryza sativa L.) in the southern USA [57]. It is critical that the biological control agents do not become pests themselves. Considerable host-specificity testing is mandatory as per many government rules and regulations prior to the release of biological control agents to ensure that they will not pose a threat to nontarget species, such as native and agricultural plants. Not all weeds are suitable for biological control. Developing a biological control project requires a substantial investment, sometimes costing millions of dollars. Currently, there are no commercial products for biological weed control in corn, though this area offers great potential for new weed control options in the future.*	Not measured	*N/A*
Joop et al.	2018	Non chemical methods, reduced pesticide use	Biological control	Combination	Positive	*Augmentative biological control (ABC), invertebrate and microbial organisms are seasonally released in large numbers to reduce pests. Today it is applied on more than 30 million ha worldwide. Europe is the largest commercial market for invertebrate biological control agents, while NorthAmerica has the largest sales of microbials. A strong growth in use of*	Decrease	*healthier for farm workers and persons living in farming communities, no harvesting interval or waiting period after release of agents, sustainable as there is no development of resistance against arthropod natural enemies, no phytotoxic damage to*

						ABC, particularly of microbial agents, is taking place in Latin America, followed by Asia.		*plants, better yields and a healthier product, reduced pesticide residues [well below the legal Maximum Residue Levels (MRLs)*
Jorgensen et al.	2010	Informed decision making	EuroWheat	Single	Not measured	*The EuroWheat research platform is partly developed as a component of the ENDURE Virtual Lab activities (www. endure-network.eu). Many countries provide information about fungicide efficacy based on national field trials. EuroWheat has collected this information giving an overview of authorised products, their efficacy and resistance risk. It features:* *• Fungicide efficacy ranking – eight wheat diseases ranked by five different countries* *• Review on problems related to fungicide resistance* *• List of fungicide trade names and actives in different countries, given as a searchable feature* *• Survey on pesticide use and yield responses to fungicides in some EU countries*	Not measured	*N/A*
Kessel et al.	2018	Informed decision making	IPM 2.0 strategy	Combination	Positive	*The novel IPM2.0 strategy - GM potato blight resistance - was compared to local common practice (fungicide applications on a near weekly basis) and an untreated control. Overall, the IPM2.0 control strategy validated here reduced the average fungicide input by 80–90% without compromising control efficacy.*	Decrease	*Highlights role host resistance (in this case GM) can provide to commercial potato production systems and to society at large if employed as part of an integrated late blight control system.*
Kevan and Shipp	2017	Non chemical methods	Biological Control - cactus moth	Single	Not measured	*The most famous example of biological control of weeds is the use of a cactus moth, Cactoblastis cactorum, for control of prickly pear cactus (Opuntia spp.) in Australia [11]. This plant was introduced into Australia for the production of red dye that was produced by the cochineal insects that fed on the cactus. Also, the cactus made excellent hedgerows around fields and homes and was favored by gardeners, soon spreading throughout the country destroying the utility of millions of hectares of agricultural land. All attempts to control the "weed" using chemicals or mechanical means failed. However, this situation changed dramatically with the introduction in 1925 of a moth from South America that fed only on the prickly pear cactus, and the cactus was quickly destroyed. In 6 years, millions of hectares were restored for pasture use for sheep and cattle and for grain production. This is a good example of how an introduced plant species can become a pest and is also one of our best examples of using an insect to control a weed pest.*	Not measured	*Description of the control of invasive weed*
Kevan and Shipp	2017	Non chemical methods	Five insect biocontrol agents (two species of leaf beetles, one root-feeding weevil, and two flower-feeding	Combination	Not measured	*A more recent example of weed biocontrol is the control of the European invasive plant, purple loosestrife (Lythrum salicaria), which is commonly found in wetlands throughout North America and which causes changes in the resident plant community and wetland ecosystem. Five insect biocontrol agents (two species of*	Not measured	*N/A*

			weevils) were introduced [12]. In this case, several biocontrol agents were required to provide effective management of the pest by attacking different life stages (leaves, roots, and seed production) of the plant. Apart from insects as biological control agents, some fungi (as "bioherbicides") can be used.			*leaf beetles, one root-feeding weevil, and two flower-feeding weevils) were introduced [12]. In this case, several biocontrol agents were required to provide effective management of the pest by attacking different life stages (leaves, roots, and seed production) of the plant. Apart from insects as biological control agents, some fungi (as "bioherbicides") can be used. Three such bioherbicides (fungi) are registered for weed control in Canada. Colletotrichum gloeosporioides f. sp. malvae and Sclerotinia minor are used for broadleaf control, such as dandelions. More recently, the biocontrol agent (Chondrostereum purpureum) has been patented for management of deciduous "weeds" in reforestation sites and other areas where bush control is required [13,14].*		
Kevan and Shipp	2017	Prevention and suppression	Companion planting	Single	Not measured	*The use of companion planting can be broadly considered as biological control. It is practiced in a variety of ways that apply different ecosystemic interactions [10]. For weed control, companion plantings simply outcompete weeds by providing ground cover, others may discourage the growth of weeds by inhibiting their growth and reproduction.*	Not measured	*N/A*
Kevan and Shipp	2017	Non chemical methods	Biological control	Single	Not measured	*Classical biological control is used on 300 million hectares of land (8% of the agricultural land) [2]. Approximately 2000 species of exotic arthropod agents have been introduced for arthropod pests in 196 countries or islands during the past 120 years. Commercially, over 170 species are available for pest control. One of the first large-scale success stories for biological control of insect pests was the introduction of Rodolia cardinalis, the vedalia ladybird beetle, against cottony cushion scale on commercial citrus in southern California. The vedalia beetle has now been controlling cotton cushion scale for over 100 years in more than 50 countries. Successful use of biological control has not been limited to citrus crops. Biological control of phytophagous mites as serious pests of apples is becoming a common practice. Initially, the predatory mite, Neoseiulus fallacis, was released inundatively to control mite pests, but this proved to be impractical on a large scale. The biocontrol strategy then changed to a philosophy of conservation, augmentation, and transfer of natural predators from an orchard where biological control was established to new orchards [20]. A recent survey in Quebec, Canada indicated that more than 80% of the orchards have adopted this approach*	Not measured	*N/A*

Kevan and Shipp	2017	Non chemical methods	Trichogramma combined with other biocontrol agents or mating disruption	Combination	Positive	*Another parasitoid that is commonly used and commercially mass-produced is the egg parasitoid, Trichogramma spp. Several species of Trichogramma are released against a range of moth pests on important crops such as cotton, sugarcane, and maize and in processing tomatoes [5,6]. In most cases, Trichogramma does not always provide sole control of the pest, but when combined with other biocontrol agents or mating disruption (see below), effective pest control is achieved. Trichogramma minutum was even evaluated for control of spruce budworm in Canadian publicly owned forest land. Smith et al. [22] showed that T. minutum parasitised 70% of the larval spruce budworm and reduced defoliation by 50%. However, release rates were too high to be cost effective, especially with availability of other biocontrol agents such as Bacillus thuringiensis.*	Not measured	*N/A*
Kevan and Shipp	2017	Non chemical methods	Biocontrol of plant pathogens and insect pests by pollinator vectors	Combination		*Part of the problems of using some microbial/fungal biocontrol agents has been the delivery system. Technology has been developed for the delivery of biocontrol agents by managed pollinators of C. rosea, Trichoderma harzianum, Pseudomonas fluorescens, Bacillus subtilis, and possibly Metschnikowia fruticola against several plant pathogens, such as gray mold, fire blight, and mummy berry, which afflict a number of fruit crop plants [35–39]. Moreover, the formulation of the biocontrol agent aimed at the plant pathogen can be adapted to include bio-insecticidal agents, such as spores or toxins of the fungi M. anisopliae, B. bassiana and the bacterium B. thuringiensis (Bt) [40]. The combined, simultaneous delivery of both fungal disease antagonists and pest insect biocontrol agents has resulted in suppression of plant pathogens and several serious insect pests, such as tarnished plant bugs, peach aphids, thrips, and whitefly, while augmenting pollination and crop yields (review in Refs. [35–39,41]).*	Not measured	*N/A*
Kevan and Shipp	2017	Prevention and suppression	Trap crops	Single	Positive	*Trap crops are a wellknown means of inhibiting infestations by pests. The trap crop may be the same species as the crop, or a different species, and deployed around fields or within the crop. The strategy relies of the trap crop being encountered first by invading pests and, thus being colonised by the pest before it discovers the crop to be protected (i.e., trop crops at the perimeter). Trap plants may be planted within a crop to be protected and act so as to lure the pest from the crop. The individual or patches of trap plants can be treated so as to destroy the pest species. These sorts of strategies have been integrated widely into so-called push-pull strategies for pest control (well reviewed by*	Not measured	*N/A*

						Cook et al. [86]). Pushpull technology has been deployed for crop and livestock protection, with biological and chemical pest control as well as physical trapping. It exploits insect pest behavior and that of their natural enemies by making the protected resource relatively unattractive or unsuitable to the pests (push) while luring them to an intentionally deployed relatively more attractive source (pull) from which pests can be removed. The strategy may employ synthetic or natural repellents or attractants and is often integrated with other methods of control, including biological (Section 5).		
Khan and Anwer	2011	Non chemical methods	Bioinoculants	Single	Positive	*Use of bioinoculants to control plant diseases is an economically viable and ecologically sustainable method of disease management*	Decrease	*State-of-the-art technology available for the production of commercial formulation of bioinoculants*
Khandelwal et al.	2016	Non chemical methods	Micro emulsion based formulation carrying plant proteinase inhibitor (PI) protein were developed and was evaluated for safety and efficacy when applied to the plant surfaces	Single	Positive	*PI formulation composed of water: isopropanol: butanol (WIB) microemulsion was found to be effective against H. armigera and caused no adverse effect on the plants as compared to the other microemulsions in the study.*	Not measured	*N/A*
Klittich	2016	Non chemical methods, prevention and suppression	Non-chemical methods	Single	Positive	*Changes in the plant induced by silicon supplementation such as leaf toughness, photosynthetic metrics, leaf volatile signatures and leaf surface features. studies showed that L. trifolii populations can be reduced by silicon supplementation.*	Not measured	*Silicon supplementation has effects on plants that make the plant more resilient against insect attack*
Knodel et al.	2015	Prevention and suppression	Varied planting dates	Single	Positive	*" In the southern Great Plains, later planting dates and fall or winter tillage have reduced infestations of sunflowers by this pest" (Dectes stem borer) " Cultural control tactics, including delayed planting, altered plant population and cultivation, are useful for managing the sunflower stem weevil. Delayed planting of sunflowers until late May or early June has been effective in reducing densities of larvae in the stem. " " In the central Great Plains, later plantings usually have lower infestations than earlier plantings. However, in other locations, planting dates have to be adjusted for conditions such as moth flight and length of the growing season" (The sunflower moth) "To minimise the risk of all plantings being at their most susceptible stage at midge emergence, several planting dates should be used." (the Sunflower midge)*	Not measured	*N/A*

Lafond et al.	2013	Monitoring	Cropping system	Combination	Not measured	*The EcoViti project (ecoviti.vignevin.com) is thus two things at once: a method to design and assess eco-efficient (Keating et al., 2010) vineyards systems with regards to pesticides reduction and a coordinated network of experimentation, covering every French wineproducing area. The re-design of vineyards CMS is a major way to overstep limits in pesticide use reduction while keeping high economic performances. The methodology we propose in EcoViti is promising, with improvement to be done to ensure the emergence of truly innovative systems that would be more that new combinations of old techniques. The greatest benefit in this project however, is to impulse a global dynamic to research and development, through the opportunity to exchange ideas, point of views and experience and to integrate them in a common Knowledge Base.*	Not measured	*N/A*
Lamichane et al.	2017	Pesticide selection	Rotation of herbicides	Single	Positive	*Herbicide rotations and mixtures can delay herbicide resistance evolution in weeds.[28] Rotation of effective herbicidal modes of action is the most widely implemented herbicide-resistance management strategy. This practice can delay the evolution of herbicide resistance (except for non-target site resistance which may continue to evolve under this strategy).[42] There is increasing evidence that the use of effective herbicide mixtures is a better tactic than rotating different herbicidal modes of action.[28,42] Yet, neither tactic is likely to prevent herbicide resistance to evolve in weeds, and therefore is not a permanent solution*	Decrease	*Applying reduced rates of herbicides may support a more efficient use of herbicides.[35,43] Several studies have demonstrated that this tactic can maintain effective weed control and sustain economically acceptable crop yields.*
Lamichane et al.	2017	Prevention and suppression	Use of competitive crop genotypes	Single	Not measured	*The cultivation of competitive crop genotypes (rapid germination and emergence, vigorous seedling growth, rapid leaf expansion, rapid canopy development and extensive root systems) is a potentially attractive option for IWM, as their use does not infer additional costs. For example, crop genotypes with high competitive potential have been identified in cereal crops*	Decrease	*The use of competitive plant genotypes alone can result in a 50% reduction in recommended levels of herbicides in wheat. The adoption of HT crops will most likely reduce the focus on crop competiveness; due to the availability of effective herbicidal active substances for weed control such as glyphosate, and breeders will focus on other properties such as yield potential and disease resistance.*
Lamichane et al.	2017	Prevention and suppression	Crop Rotation	Single	Positive	*Crop rotation (i.e. temporal diversification) is very effective for managing weeds. Unlike monocultures, crop rotation can favor a more diverse composition of weed communities rather than those dominated by one or few weed species. Crop rotation allows alternative weed control strategies to be used, and enables alteration of patterns and timings of soil disturbance, light transmission through the crop canopy and natural enemies living in the crop, thereby diversifying the selection pressures on weed populations and making it ecologically more difficult for one weed species to dominate a weed community.*	Not measured	*N/A*

						As crop rotation and weed control strategies often interact,[50] diversity in crop system (which includes both the crops grown in rotation and the associated farm management practices) represents the best practice to mitigate risks related to herbicide resistance		
Lamichane et al.	2017	Prevention and suppression	Cover crops and intercropping	Single	Positive	*Significant benefits can be obtained in terms of weed control when a proper combination of crop species is grown together for spatial diversification.[63,64] Liebman and Dyck [64] suggested that intercropping offers weed control advantages over sole crops in two ways; they (i) suppress weed growth through competition and allelopathy and thus more effectively use available resources at the expense of weeds, and (ii) provide yield advantages either using resources that are not exploitable by weeds or using converting resources to harvestable material more efficiently than sole crops. Despite the advantages of intercropping, growing two or more crops simultaneously on the same field leads to more complex crop management and possible additional costs that may restrict their use by growers.*	Not measured	*N/A*
Lamichane et al.	2017	Prevention and suppression	Tillage, used with crop rotation and cover crops	Combination	Positive	*When tillage is used in conjunction with other cultural tactics such as cover crops and crop rotations,[50,65] it can markedly reduce weed population densities. It should be emphasised that no-tillage systems can also be viewed as part of IWM, as weed seeds left on the soil surface have a higher mortality rate, partly due to predation. Moreover, crop residues left on the soil surface can further suppress weed growth.*	Not measured	*N/A*
Lamichane et al.	2017	Non chemical methods	Biological control	Single	Positive	*Biological control aims to suppress weed populations below levels that cause economic injury instead of controlling them. Westerman et al. showed that predation by opportunist invertebrates can substantially reduce the weed seed stock on the soil surface (‘‘biological weed control’’ as ecosystem service). While there have been a number of successful biological control programs against crop weeds, biological control of weeds presents a range of challenges, including economic feasibility, effectiveness of the control agents, statutory and regulatory constraints for the registration of products, technological constrains in developing bio-herbicides, environmental constrains and difficulties in utilising pathogens and herbivores as biocontrol agents*	Not measured	*N/A*
Lamichane et al.	2017	Non chemical methods	Mechanical weeding	Combination	Positive	*Depending on soil characteristics and conditions, mechanical weeding has proven effective on a range of crops. ‘‘Intelligent’’ weeders that offer more advanced ways to control weeds without causing any damage to the crop are under development.[78–80] Therefore, the inclusion of innovative technologies, including advanced sensing and robotics, in combination with new crop*	Not measured	*N/A*

						systems, might lead to a breakthrough in physical weed control in row crops resulting insignificant reductions, or even elimination, of the need for hand-weeding.		
Leake	2000	Prevention and Suppression	Minimum- and no-tillage	Single	Positive	*The Lautenbach study recorded over 60 species of predatory mite. Increased activity was related to high humidity levels in the soil pores. Ploughing reduces both pore numbers and moisture retention, causing suppression of these predators. Other species such as earthworms, collembola and hymenopterous parasites were also shown to benefit.*	Not measured	*N/A*
Lengai, Muthomi and Mbega	2020	Pesticide selection	Botanical pesticides	Combination	Not measured	*The above examples demonstrate that botanical pesticides can make a significant contribution to sustainable manage- ment of crop pests in IPM programmes. Their activity against varied range of pests, their varied mode of action, activity in varied agro-climatic zones, seasons and crops, botanical pesticides can play a major role in maximising crop yields while safeguarding the environment, biodiversity and human health.*	Not measured	*N/A*
Lenssen et al.	2013	Prevention and suppression	Crop rotation diverisification	Combination	Positive	*Diversified, intensified cropping systems consistently reduced the soil water content available for the subsequent spring wheat crop under below average rainfall in north central Montana. Spring wheat in conventional and diversified cropping systems did not differ in incidences of root disease and infestations of weeds, but conventional systems harbored greater populations of both beneficial and predatory insects. Results from our study show that at field scale, pest–pest and pest–edaphic factor correlations occur, and that correlations of pest and edaphic factors with spring wheat yield can vary between conventional cereal and diversified crop rotations. Additionally, results with field-scale plots closely resemble results from smaller plot studies for soil water (14), residual nitrate (15), weed community (13), arthropods (20), Fusarium crown rot (10), and spring wheat yield and quality (14) when conducted under similar environmental conditions, validating the utility of both large- and small-plot research (9). For the 2 yr foliar disease data were available, wheat in diversified rotations had less foliar diseases than wheat grown in conventional rotations (Table 4). Wheat in diversified rotations had foliar leaf spots that were largely restricted to the lower plant*	Not measured	*N/A*

						canopy and did not progress into the flag leaf. Wheat in conventional rotations probably had more infected wheat residue from previous crops that served as initial inoculum source to infect wheat seedlings. Wheat grown in diversified rotations may be delayed in initial infection as wind-blown spores are more important for primary inoculum.		
Li et al.	2019	Non chemical methods	Mychorrizal fungi	Single	Positive	*Species specific arbuscular mychorrizal fungi had negative effects on weeds without affecting corn growth. Tillage and cover crop affected populations.*	Not measured	*AM fungi are unlikely to form standalone weed control methods. Could be valuable as a component of IPM systems*
Liu et al.	2019	Non chemical methods	Entomopathogenic fungi	Single	Positive	*Our results showed that B. bassiana ICMP 8701 was a suitable virulent strain with high mortality and short LT50 against TPP first instar nymphs and adults. The treatment of B. bassiana at sublethal concentrations can affect TPP reproduction, and these changes were also expressed in the next generation by accelerating the development of immature and decreasing reproduction of adult females. To the best of our knowledge, this is the first report to evaluate the lethal and sublethal effects of EPF on the life table of TPP.*	Decrease	*Primary research outside of commerical setting - limited meaningfulness.*
Lundin et al.	2012	Monitoring	Monitoring and threshold for thiacloprid application a late bud plus natural enemies.	Combination	Positive	*Insecticide treatments did not signiÞcantly decrease pest abundance or enhance yields in 2008, when only pyrethroids were used for chemical pest control. In 2011 (...) when the neonicotinoid thiacloprid was applied, pest abundances were clearly and consistently lower and seed yields higher in insecticide treated zones.*	Decrease	*Pyrethroids were shown to be ineffective. Thiacloprid was effective, but was limited to a single application and is now banned*
Lundina, Myrbeckb and Bommarcoa	2018	Prevention and suppression	Reduced Tillage, Early Seeding	Combination	No effect	*The average proportion of cotyledon area damaged by flea beetles was not affected by the tillage treatment. The increased amount of crop residues in zero tillage regimes has been suggested to reduce flea beetle crop damage (Milbrath et al., 1995; Dosdall et al., 1999). The amount of crop residues in our reduced tillage regimes was, however, limited in all treatments (see Fig. S1), and this likely contributed to the small differences in crop damage. There was a limited potential for crop residues in reduced tillage treatments to affect host plant location and create a*	Not measured	*N/A*

						more unfavorable micro-climate for flea beetles. Another factor contributing to the smaller than expected damage differences might have been that plant density generally was somewhat lower in the reduced tillage treatments, and a lower plant density tends to increase flea beetle damage per plant (Dosdall et al., 1999; Dosdall and Stevenson, 2005). We conclude that there is scope to further explore tillage methods for flea beetle control in SOSR that result in more crop residues. Such efforts must, however, be balanced against a need for minimised tillage and the increased amount of crop residues to not negatively affect crop germination or emergence (Soane et al., 2012; Arvidsson et al., 2014). Moreover, the effect of tillage was heterogeneous across the individual experiments (Table S2), and further investigations are needed to unravel the reasons for this variation. This heterogeneity across experiments, coupled with the fact that late seeding dates were not sampled in all experiments, might also have led to the trend for a tillage by seeding date interaction, despite that the effect of tillage on crop damage seemed fairly constant between the two seeding dates within each experiment (Table S2). An earlier seeding resulted in less crop damage caused by flea beetles. Earlier seeding also led to higher plant density. To disentangle whether a later seeding date had direct negative effects on plant density, or whether the lower plant density in later seeded plots was caused by increased flea beetle damage, it would be necessary to include insect pest control as an additional experimental treatment in future studies		
Majeed et al.	2017	Informed decision making, Non chemcial methods, Reduced pesticide use	Disease free seed and resistant cultivar	Combination	Positive	*Integrated disease control approaches such as cleaning of pathogen's sources, use of disease frees seeds and resistant cultivars is needed.*	Decrease	*Training and educating farmers about the basic characteristics of the pathogen and environmental influences on the disease development is necessary*
Mansfield et al.	2019	Informed decision making, Non chemical methods, Reduced pesticide use	Networks	Combination	Positive	*Cryptic IPM is present within the New Zealand pastoral sector: that is, farmers practise various elements of IPM but these elements are not integrated into a cohesive system, so farmers often fail to recognise pest impacts until significant economic losses have occurred. We identified important networks by which farmers, industry and researchers communicate and share information, and can develop strategies to raise awareness of IPM.*	Decrease	*We identified important networks by which farmers, industry and researchers communicate and share information, and can develop strategies to raise awareness of IPM. To encourage adoption, farmers need to feel ownership of pasture IPM.*

Melander et al.	2013	Prevention and suppression	Crop rotation	Single	Positive	*The crop rotation strongly determines the growing conditions for weeds, depending on the composition of crops; some weed species are favored whereas others might be disfavored. Weed control options also are linked to crop choice, and the spectrum of control tactics and active ingredients of herbicides usually expands with the diversification of the crop rotation (Melander et al. 2005). The strong impact of crop sequence on weed communities became particularly evident in an analysis of 257 fields selected across the U.K. by Bohan et al. (2011).*	Decrease	*using non-chemical methods can reduce pesticide use.*
Melander et al.	2013	Prevention and suppression	Cover crops	Single	Positive	*The key factor for successful weed management appears to be the fast development of a dense cover crop stand. This can be difficult to achieve in northern Europe where growing periods between crops are shorter as compared to more southern latitudes. Danish farmers attempt to meet this by broadcasting crucifer species 2 to 3 wk before harvesting cereals, aiming for an early establishment of the catch crop.*	Not measured	*N/A*
Melander et al.	2013	Prevention and suppression	Stubble management	Single	Positive	*The management of the stubble period between main crops has large implications for weed dynamics. Direct nonchemical methods such as mowing or stubble tillage can be used freely unless a cover crop has been established. Shallow postharvest tillage is an important component in NIT systems in Europe because it incorporates crop residues for decomposition and prepares the land for subsequent crops (Morris et al. 2010). Furthermore, weed growth is terminated, whereby the production of new weed seeds and belowground vegetative propagules are prevented*	Not measured	*N/A*
Melander et al.	2013	Non chemical methods	Mechanical control	Single	Positive	*Obviously, mechanical weed control ´ has no place in NT systems, but might have relevance in RT systems where some tillage precedes crop sowing. The loosening, uprooting, and burying mechanisms caused by cultivation can lethally affect weed plants, depending on timing and intensity of application (Kurstjens and Kropff 2001; Kurstjens and Perdok 2000; Terpstra and Kouwenhoven 1981). A new technology capable of precise placement of crop seeds is underway that has evolved from previous works on electronic crop seed mapping (e.g., Griepentrog et al. 2005). The technology uses GPS technology to create parallel or diamond crop establishment patterns, which enables interrow hoeing to be conducted in different directions, for example, offset to the seeding direction (Kverneland 2012). This could significantly improve mechanical control of intrarow weeds in both CT and NIT row-crop systems.*	Not measured	*N/A*

Melander et al.	2013	Non chemical methods	Thermal control	Single	Positive	*Thermal methods such as flaming, steaming, hot water, UV-radiation, laser cutting, microwaves, and freezing are generally energy-demanding technologies. They have low work rates and relatively high purchase costs and might require multiple treatments for satisfactory control, and flaming can cause fires under certain circumstances (Ascard et al. 2007). So far, no thermal methods studied under CT have demonstrated any potential for use in major agricultural crops such as cereals, pulses, and oil seed rape.*	Not measured	*N/A*
Mhlanga, Chauhan and Thierfelder	2016	Prevention and suppression	Row spacing	Combination	Positive	*Row spacing influences canopy cover, which in turn determines the amount of light that can penetrate to the ground (Bradley, 2006). For example, at narrower row spacing, the amount of light that reaches the soil surface is reduced, thus altering the microenvironment of weed seeds and ultimately the number of weeds that will emerge (Bradley, 2006). Because maize has larger seedlings compared to the weeds, narrow row spacing results in a more uniform spatial distribution of the maize plants, so that the crop intercepts light more efficiently (Flenet et al., 1996).*	Not measured	*N/A*
Mhlanga, Chauhan and Thierfelder	2016	Prevention and suppression	Competitive cultivars	Single	Positive	*Competitive cultivars are thought to confer some level of suppression on certain levels of weed infestations (Andrew et al., 2015). Traits of competitive cultivars include high light-intercepting leaf architecture, greater speed of development, enhanced partitioning of assimilates, improved plant height, and an ability to produce allelochemicals that inhibit weed growth and development (Christiansen, 1995; Wu et al., 1999). A lot of work has been done with other cereals such as wheat and barley, but limited work has been done in maize*	Not measured	*N/A*
Moss	2010	Non chemical methods	Tillage	Combination	Positive	*The results show that non-chemical control methods can give useful levels of weed control. They also highlight the great variability in efficacy between experiments, with negative control being possible. This can happen, for example, where mouldboard ploughing brings more seeds to the surface than it buries, with the consequence that the subsequent weed plant population is higher than where non-inversion tillage has been used. From this perspective, it is all too apparent that non-chemical control methods give, on average, levels of control that are very poor in comparison with herbicides. In addition, this poorer efficacy is not matched by correspondingly lower costs. It should come as no surprise that trying to 'sell' non-chemical control methods to farmers is such an uphill struggle.*	Not measured	*If the primary aim of IPM is to reduce pesticide use, then would it not be better to state this explicitly as the key objective? One could argue that other elements of IPM would then fall into place automatically. Whether this should be the primary aim, in a world with an increasing population and a finite land area subject to the negative consequences of global warming, must be questioned.* *It would certainly be easier to measure success or failure. For example, in the UK, pesticide usage surveys of arable crops show that the area sprayed with pesticides increased from 42.4 million spray ha in 1998 to 50.3 million spray ha in 2008, a 19% increase, whereas the weight of pesticides applied declined from 30,746 t to 18,758 t during the same period, a 39% decrease (Garthwaite et al. 2008).*

Mulhare, Creissen and Kildea	2018	Pesticide selection, Informed decision making	Decision support system	Single	Positive	*Both sites were deemed to be high risk based on levels of leaf wetness recorded early in the season neither DSS programmes, that were altered to reflect this risk, provided significantly better disease control or yield compared to the standard programme. This may be due to the superior activity provided by chlorothalonil against RLS. Alternatively given concerns surrounding the sensitivity of R. collo-cygni populations to both the azoles and SDHIs, the lack of difference between the treatments may reflect inferior activity provided by the mix partner(s) in all three programmes*	Not measured	*N/A*
Muller-Scharer and Collins	2012	Pesticide selection	Bioherbicides	Single	Not measured	*no real measurements, just a review of bioherbicides and their possible uses in integrated weed control*	Not measured	*N/A*
Muvea et al.	2014	Monitoring	Blue sticky traps	Combination	Positive	*Blue sticky traps and Lurem-TR can be an efficient tool for the monitoring of thrips populations on French beans with least influence on their natural enemies. Early detection and thrips monitoring tool to implement timely management strategies.*	Decrease	*The kairomone attractant, Lurem-TR, was able to increase thrips captures for all thrips species without influencing the captures of their natural enemies. Blue sticky traps with Lurem-TR can be used with a great deal of validity as an early detection and thrips monitoring tool to implement timely management strategies.*
Nawaz and Nazeer Ahmad	2015	Non chemical methods	Biotechnological Approaches to IPM	Single	Positive	*Biotechnological and genetic engineering approaches have been launched to support plant health, stabalise yield, and increase food safety along with other strategies of crop production. Biotechnology uses living systems and organisms to develop or make useful products or "any technological application that uses biological systems, living organisms or derivatives thereof, to make or modift products or processes for specific use" (Jhon and Maria 2001).*	Not measured	*N/A*
Newton et al.	2019	Anti resistance management	Resistence	Single		*Use of durable resistance is the obvious and most effective strategy to deploy in IPM. However, durable resistance in practice may take many forms and should be a product of its context, that is considering all the environment factors too, both natural and managed. There are very few examples of single major genes that have proved durable and the general strategy should be to not use them as the main component of a resistance strategy.* *Diversification schemes have been published in the past to encourage farmers to grow cultivars with different resistance genes in neighbouring fields.*	Not measured	*N/A*
Newton et al.	2019	Prevention and suppression	Seed treatments	Single	Positive	*Fungicides can be applied as seed treatments, foliar sprays or soil treatments (Matthews, 2000). The latter tend to have high costs and significant negative environmental impacts and so there are no current examples used in barley. Seed treatments are a targeted and effective way of addressing seed-borne*	Not measured	*N/A*

						problems. *Seed treatments can also have some effect in reducing trash and soil-borne diseases such as take-all. Seed treatments are an effective means of managing seed-borne barley health issues such as loose smut, leaf stripe and seed-borne net blotch. They can also help to manage Fusarium and Microdochium species in the context in which these pathogens can lead to seedling blights. They should always be used in conjunction with seed testing and with the purchase and drilling of seed of a high health status, for example as purchased through official* *certification schemes. Seed treatments should be used, as with other fungicide inputs, as part of an integrated package and should not be used to pull seed with known health issues up to acceptable levels of seed health.*		
Nicholas et al.	2011	Non chemical methods	Varietal diversity	Combination	Positive	*Increasing crop diversity at the field scale, through the use of varietal and species mixtures, can suppress pests while also increasing yield, quality, productivity, and stability (Newton et al., 2009; Vandermeer, 1989). Careful design of crop variety mixtures accounting for G3E effects is important to ensure combinations of traits that provide the complementarity and facilitation underlying these benefits (Newton et al., 2009). The effectiveness of variety mixtures is also sensitive to the scale at which components are deployed (i.e. the area below which crop genotypes are not mixed), although the nature of this response appears variable with many studies, showing a benefit from deployment at smaller scales but others being more effective when deployed at larger scales (Newton et al., 2009). These conflicting results may be accommodated by a common hypothesis if, in conjunction with the loss of apparent diversity at large deployment scales, it can be shown that a scale exists below which the additional diversity is no longer behaviourally or functionally resolved by the pest organisms. This leads to an optimum scale of deployment defined by the life-cycle and dispersal characteristics of the pest.*	Decrease	*For IPM to succeed in the UK, EU, and globally for major* *and minor crops, as it has done in many other countries* *globally (Landis et al., 2000; Pretty, 2005), a holistic,* *systems-based approach is needed that makes use of* *potential synergies between entomologists, pathologists,* *chemical ecologists, plant ecologists, phytochemists, plant* *geneticists, plant breeders, biotechnologists, agronomists,* *and mathematical modellers. This is a medium to long-term* *approach (Heinrichs et al., 2009), particularly when based* *on a foundation of durable pest and disease resistance in* *new crop cultivars. As explained previously, several crop* *protection strategies are now at a strategic 'tipping point'* *where pest biotypes are winning the co-evolutionary battles against current protection measures, exemplified by pests with greater ability to overcome both pesticides and R genes. To protect the long-term investment in plant breeding, biopesticide development, and IPM these strategies need to be integrated at the research level, then driven through to applied outcomes with commercial partners. This will also require a shift in research effort from*

								fundamental to applied aspects, with concomitant career rewards for scientists who move away from research driven by questions outside the ecological context and from publishing in high impact fundamental science journals. For optimal effectiveness and progress, fundamental and applied researchers need to work closely together across multiple disciplines, then design IPM products and strategies that are simple and affordable enough for farmers. Onfarm research with participating growers is the most convincing way to demonstrate that IPM really works at a local or regional leve
Nilsson et al.	2015	Prevention and suppression	Reduced tillage and Control thresholds	Combination	Positive	*Reduced tillage and a lower use of insecticides through the use of control thresholds lowered production costs. It also reduced labour hours; this could mean that, on a large farm, fewer employees would be needed, in turn leading to a substantial increase in profitability (Table 4). Plots sprayed to thresholds, especially in the ICM system, had more pest larvae which is important for the maintenance of the parasitoid populations (Table 9). Reduced tillage, and in particular direct drilling (Nilsson, 2010), can greatly increase the number of parasitoids emerging the following spring. If reduced tillage had been practised on all farmland surrounding the ICM experiments it is likely that the populations of univoltine parasitoids of many pest species would have been higher and the differences between parasitisation levels thus also greater.*	Decrease	*Pesticide inputs. The number of active ingredients of pesticides applied was greater in the schedule sprayed (STNii) system than in the other systems. In systems where thresholds for control of insects were used, the number of insecticide applications was more than halved. More herbicides were used in the ICM system with reduced tillage, because of the need*
Nilsson et al.	2015	Reduced pesticide use	Scheduled spraying	Single	No effect	*Application of insecticide at a dose lower than that recommended is one way of reducing pesticide input and the concept "ha-dose" is based on a comparison of the dose used that is recommended by the advisory services or mentioned in registration of the pesticide (Table 7). More variable doses could probably have been used as there is a "security" part in dose recommendations. Doses can usually be lowered at optimal use, without risking an increase in pest resistance. Schedule spraying (STNii) reduced the amount of stem damage considerably (Table 6), but did not eliminate pod midge damage. Prediction of the need to control stem-damaging insects could be improved by the use of decision support systems, e.g., ProPlant (Johnen et al., 2010), and the use of selective field traps, e.g., pheromone traps. It should be possible to achieve the same control of pests with the aid of control thresholds as with schedule spraying.*	Decrease	*Doses can usually be lowered at optimal use, without risking an increase in pest resistance*

Nilsson et al.	2015	Informed decision making	ICM system	Combination	Positive	*These experiments demonstrated that a farming system based on integrated crop management (ICM) principles, with non-inversion soil tillage and use of pest control thresholds to determine the need for insecticide application, can be recommended to farmers as a strategy to enhance natural enemy populations; it would improve natural control of economically-important pests of oilseed rape, and, at the same time, often get a better net return, use less resources and decrease environmental impact.*	Not measured	*N/A*
Owen	2011	Anti resistance management	Genetically engineeerd herbicide tolerant crop	Combination	Negative	*Leading the the development of herbicide resistant weeds, The evolution of multiple and cross resistances to herbicides is becoming increasingly more common. For example, common waterhemp populations with cross resistances to ALS inhibiting herbicides and multiple resistances to glyphosate are widely distributed throughout the Midwest (Owen 2009a; Patzoldt et al. 2005). Common waterhemp populations in Kansas and Iowa have evolved multiple resistances to PPO and ALS inhibiting herbicides (Falk et al. 2005; Owen 2009a). In Illinois, populations of smooth pigweed (Amaranthus hybridus) and kochia (Kochia scoparia) have evolved multiple resistances to PSII and ALS inhibiting herbicides (Foes et al. 1999; Maertens et al. 2004). Multiple resistances to ALS inhibiting herbicides and glyphosate are also reported in horseweed (Conyza canadensis)*	Not measured	*N/A*
Owen (a)	2016	Anti resistance management	Herbicide resistance and non chemical control	Combination	Not measured	*The goal of this paper is to address the options available for robust integrated weed management, specifically the management of herbicideresistant (HR) weeds, and assess the benefits and risks of tactics that contribute to more diverse approaches.*	Not measured	*Herbicides will continue to be critical components of future weed management, but it is clear that focusing solely on herbicide solutions to HR weeds will not resolve the problem across the landscape. Importantly, if new mechanisms of herbicide action are not forthcoming in the near future, it is also clear that herbicides will need to be supplemented by other means. Furthermore, although there is a sound knowledge base supporting IWM, the barriers to adopting a more diverse approach to managing HR weeds are formidable and might not be fully understood.*
Paraschivu, Cotuna, and Paraschivu	2014	Non chemical methods	Resistant variety	Combination	Positive	*Growing moderately resistant cultivars and timely application of an effective fungicide has been demonstrated significantly reduce kernel absorption, kernel damage and mycotoxin contamination*	Not measured	*N/A*
Paraschivu, Cotuna, and Paraschivu	2014	Prevention and suppression	Crop rotation	Single	Not measured	*Avoiding short rotation maize-wheat will substantially reduce risks of FHB epidemics especially in areas where climatically conditions are favorable. On the areas where maize is not grown, infested residue of wheat, barley and rice is a more important source of inoculum.*	Not measured	*N/A*

						Thus, rotation schemes with wheat grown after other cereals should generally be avoided. Non-host crops that can be incorporated into rotations include sunflower, beans, canola and forage legumes		
Paraschivu, Cotuna, and Paraschivu	2014	Prevention and suppression	Cultivation technquies- tillage versus non tillage	Single	Negative	*Using reduced or zero-tillage system will increase FHB risks especially if much more residues will be presented on the soil surface.Fernandez et al. (2005) showed that FHB index was highest under minimum tillage and lowest under zero-tillage. Dill-Macky and Jones (2000) observed that disease incidence was lower in mouldboard plowed plots than in either chisel plowed or zero-tillage plots*	Not measured	*N/A*
Paraschivu, Cotuna, and Paraschivu	2014	Prevention and suppression	Cultivation technquies- tillage versus non tillage	Single	No effect	*Several studies have examined the effect of tillage practices on DON levels but no difference among tillage systems was noticed.*	Not measured	*N/A*
Pardoa, Riravololonab and Munier-Jolainb	2010	Prevention and suppression	modified soil tillage, possibly including occasional mouldboard ploughing to bury seeds in deep soil layers, and repeated shallow tillage with such timing as to promote seedling emergence and destruction before crop drilling (the so-called falseseed bed technique, Rasmussen, 2004);	Combination	Positive		Decrease	*A field trial was initiated in 2000 at the INRA experimental farm in Dijon (France) to test the performances of four cropping systems based on the principles of IWM. IWM-based cropping systems were efficient in reducing the reliance on herbicide and the potential environmental impact associated with the herbicide used over the first 6 years of the trial (see Chikowo et al., 2009 for the details). For the most typical IWM cropping system (CS4 in the study), the average amount of herbicide applied annually was reduced by 92% as compared to the reference standard system. One cropping system even completely excluded the use of herbicides for weed management. Despite the reduced reliance on herbicides, the tested IWM systems provided satisfying control of the weed infestations over the 6-year period (Chikowo et al., 2009). The mean pesticide input in the standard cropping system CS1 was about 200 D ha−1 (Fig. 3A). In IWM-based farms, this cost was about 90, 83, 63, 36 D ha−1 in CS2, CS3, CS4 and CS5 respectively, thus saving from 55 to 82% of pesticide costs. Of course herbicide costs were reduced, but the costs of all the other pesticides were also reduced, because the rules aiming at reducing weed infestations also tended to reduce the risk related to other pests, as already stated. In IWM-based virtual farms, the machinery costs*

								were higher than in the standard system (Fig. 3B), because machines were required in greater numbers and/or at greater purchase prices (see Annex 3). The major example is the no-till disc seed drill used in farms of CS2, whichwas7 times as expensive as the equipment used for seeding in reference farms. In CS2, the increased fixed costs were compensated by reduced variable costs (mainly fuel consumption) in relation to reduced tillage, but this was not the case in farms implementing CS3, CS4 and CS5.
Pardoa, Riravololonab and Munier-Jolainb	2010	Prevention and suppression	Autumn sowing timing	Single	Positive	*delayed autumn sowing to escape the emergence peak of a range of autumn-emerging species (Rasmussen, 2004);*	Not measured	*N/A*
Pardoa, Riravololonab and Munier-Jolainb	2010	Prevention and suppression	Competitive cultivars and competitive crop species,	Combination	Positive	*sown at high densities and reduced row distance to maximise the competitive ability of the crop canopy (Didon, 2002; Korres and Froud-Williams, 2002; Lemerle et al., 1996);*	Not measured	*N/A*
Pardoa, Riravololonab and Munier-Jolainb	2010	Prevention and suppression	Inter-row spacing	Single	Positive	*Precision local in-row nitrogen fertilisation in crops with large inter-row spacing*	Not measured	*N/A*
Pardoa, Riravololonab and Munier-Jolainb	2010	Non chemical methods	mechanical weeding	Single	Positive	*mechanical weeding, using weed harrows, simple hoes, rotary hoes, rotary brushes, finger hoes, according to the crop and inter-row distances*	Not measured	*N/A*
Pelzer et al.	2012	Monitoring, Informed decision making, Evaluation	DEXiPM	Single	Positive	*results showed that innovative cropping systems with a limited use of pesticides can have a better overall sustainability, despite the fact that some of the indicators can be negatively impacted.*	Decrease	*tool to evaluate the sustainability of actual cropping systems, to diagnose their strong and weak points and, on this basis, to encourage discussions during the design of innovative cropping systems*
Pesticide Stewardship - https://pesticidestewardship.org/resistance/preventing-resistance/	2020	Pesticide selection	Choose selective pesticides	Single	Positive	*To avoid resistace, when available and appropriate, choose selective pesticides that break down quickly (avoid persistent pesticides).*	No Effect	*N/A*
Pesticide Stewardship - https://pesticidestewardship.org/resistance/preventing-resistance/	2020	Pesticide selection	Spot treatments	Single	Positive	*Where practical, use spot treatments, barrier treatments or banded treatments to better target pest populations or the zone where pest control is required*	Decrease	*Targeted use of pesticides*

Philippot et al.	2013	Non chemical methods	Reduction in soil tillage, mechanical vs chemical weeding	Combination	Not measured	*Over 7 months, the system with integrated weed management emitted significantly more N2O with cumulated measured emissions of 240 and 544 g N-N2O ha− 1 for conventional and integrated systems, respectively. Abundances of microbial guilds varied slightly between systems, although ammoniaoxidising bacteria were more abundant in the reference system (1.7 106 gene copies g−1 dry weight soil) compared to the integrated system (1.0 106 gene copies g−1 dry weight soil). These differences revealed both the long-term modification of soil biogeochemical background and the functioning of microbial processes due to 11 years of alternative field management, and the short-term impacts of the agricultural practices introduced as part of weed management during the cropping year.*	Not measured	*The abundances of the different microbial communities involved in N cycling and the intensity of N2O emissions were not related, punctual high N2O emissions being more dependent on favourable soil conditions for nitrifying and denitrifying activities. Future studies will be performed to check these findings for other pedoclimatic conditions and to examine the impact of such cropping systems.*
Popp et al.	2013	Prevention and suppression, Non chemical methods	Tillage	Combination	Positive	*This project (supported by EU Life+) demonstrated that conservation tillage consistently reduced runoff, soil erosion and soil nutrient losses. In addition, numbers of earthworms, beetles and other soil fauna increased, as did microbial biomass activity. But there were also benefits for farmers because profitability was maintained. Crop establishment costs were reduced by 15–20 % in conservation tillage. However, crop yields were slightly lower, as commonly found during the conversion to conservation tillage. Nevertheless, they were higher in dry years, since water availability increased due to reduced runoff from conservation tillage (Syngenta 2010).*	Decrease	*During the past two decades, IPM programmes have reduced pest control costs and pesticide applications in fruit, vegetable and field crops. Reductions in pest control costs and pesticide use in IPM programmes can be achieved by introducing or increasing populations of natural enemies, variety selection, cultural controls, applying alternative pesticides and improving timing of pest suppression treatments. For farmers, very often the main benefit of IPM is the avoidance of uneconomical pesticide use. However, a large part of the benefits are reduction of externalities and therefore occur to other groups. This poses considerable measurement and valuation problems. Although the IPM programmes did reduce pesticide use, most of the programmes still relied heavily on pesticides.*
Pujari, Bhattacharyya and Das	2013	Prevention and suppression	Crop Rotation	Single	Not measured	*Crop rotation or sequence is designed to present a nonhost crop to insect pests. Crop isolation/rotation strategies are most effective against pests that do not disperse over great distance and/or that overwinter in or near host crop field. Some of the serious insect pests viz., brinjal shoot and fruit borer, Leucinodes orbonalis, carrot rust fly, Pistia rosae, Colorado potato beetle, Leptinotarsa decemlineata and onion maggot, Delia antique were managed by following crop rotation techniques (Weisz et al., 1994; Walters and Eckenrode, 1996; Collier and Finch, 2000; Rath and Dash, 2006). However, this agro-technique was found much less*	Not measured	*N/A*

						effective in managing cabbage maggot, Delia radicum because of their abilities to move to a great distance (Collier et al., 2001). Similarly, the isolation of susceptible crops from surrounding host crops can be an effective management strategy for aphidborne viral plant diseases, although distances of up to 25 km may be necessary to prevent the spread of virus (Schellhorn and Sork, 1997). Rotation with glucosinolate-containing crops belonging to Brassicaceae family was found to be through biofumigation effects against some soil borne pests and diseases (Kirkegaard et al., 1998).		
Pujari, Bhattacharyya and Das	2013	Prevention and suppression	Crop diversification/polyculture	Single	Not measured	*Crop diversification can help to realise the potential of resource-limited natural enemies by satisfying their requirements for food and shelter. Increased plant diversity can benefit natural enemies by providing them with favourable microclimate to act (Rao et al., 2002), a source of alternative hosts or prey or a supply of plant-based foods (i.e., nectar and pollen) (Wackers et al., 2007). Polyculture is an agricultural practice in which multiple plants are grown in the same space. In contrast to monoculture, polyculture imitates the diversity of natural ecosystems, which has a significant impact on the insect populations (Shrivastava et al., 2010). The population density of arthropod herbivores in polyculture was found to be lower than in monoculture (Andow, 1991).*	Not measured	*N/A*
Pujari, Bhattacharyya and Das	2013	Prevention and suppression	Trap crops	Single	Not measured	*Growing trap crops in organic farming can reduce pest pressure on the main crop by being more attractive to insect pests than main crops. In recent years, efforts in trap cropping has been increased considerably and become a vital component in IPM Package. Inherent characteristics of a trap crop may include not only differential attractiveness for feeding but also other attributes that enable the trap crops to serve as a sink for insects. Raising tomato with marigold in 3:1 combination gave maximum reduction in fruit damage caused by Helicoverpa armigera in tomato (Hussain and Bilal, 2007). Different species of plants may vary in their ability in serving as a trap crop. However, the effectiveness of trap cropping depends on the proper timing of planting, adequate spacing and size of the trap crop (Hokkanen, 1991).*	Not measured	*N/A*
Pujari, Bhattacharyya and Das	2013	Prevention and suppression	Preventative strategies	Combination	Positive	*The preventive strategies are attempted through cultural practices, increasing overall crop biodiversity and conservation of potential habitats for beneficial organisms (Zehnder et al., 2007 and Lotter, 2003). The main logic behind this strategy is to stop pest*	Not measured	*N/A*

						outbreak/suppress pest infestation by encouraging Good Agricultural Practices (GAPs) and other measures.		
Pujari, Bhattacharyya and Das	2013	Non chemical methods	Conservation of natural enemies	Single	Not measured	*Conservation biological control involves habitat manipulation to increase populations of predators and parasitoids, that can help keep pest populations below the economic injury levels. Cultivation of flowering insectary strips to provide pollen and nectar as a means of conservational biological control can enhance the survivability and performance of natural enemies by directly providing energy-rich sugars to beneficial insects (Altier et al., 2005). Adult encyrtid wasps (Copidosoma koehleri) lived twice as long as control when provided nectar from buckwheat, faba beans, phacelia and nasturtium (Baggen et al., 1999). Other habitat management strategies to conserve beneficial insects are providing overwintering habitat as experienced by the adoption of 'beetle banks' in England. Beetle bank is a strip planted with grasses and/or perennial plants at the centres of cereal fields in order to provide temperature-moderating overwintering habitats for predaceous ground beetles. These grasses also provide refugia for predatory carabid and staphylinid beetles and spiders as well as for birds and small mammals. In the winter, beetle bank harbour more than 1000 predatory invertebrate individual per square meter (Zehnder et al., 2007). Likewise, the predatory spider fauna in rice ecosystem can be successfully augmented by placing straw bundles alone or in combination with other border crops (Tanwari et al., 2011).*	Not measured	*N/A*
Pujari, Bhattacharyya and Das	2013	Monitoring	Trap Technology	Single	Not measured	*Uses of sticky traps, physical barriers and pheromone lures to suppress insect pests have more relevance in organic farming with a view to monitor their population and management as well. When paired with traps, pheromone and scent lures utilise both chemical and visual attractants (Foster and Harris, 1997). Yellow sticky traps can be used as an efficient tool to monitor the population of leaf miners, aphids, thrips and whiteflies as these insect pests are attracted to the yellow colour. This control method when used at proper time, can suppress specific insect pests. Yellow sticky traps have been used as a practical control measures for Liriomyza flies as well as for whiteflies in vinyl houses producing vegetables (Wu et al., 1998). Physical traps or barriers can also be used to manage snails to determine if they continue to spread. Exploration of pheromone trap is another important approach to monitor and*	Not measured	*N/A*

						manage key destructive insect pest species which are really difficult to manage in organic system of cultivation. Mass trapping of males of squash vine borer (Melittia cucurbitae) by using pheromone deprived the females from successful mating and oviposition.		
Pujari, Bhattacharyya and Das	2013	Non chemical methods	Use of attractants	Single		*Among the various alternate strategies available for the management of fruit flies, use of methyl eugenol traps stands as the most outstanding alternative. Methyl eugenol has both olfactory as well as phagostimulatory action and is known to attract fruit flies from a distance of 800 meter (Roomi et al., 1993). Methyl eugenol, when used together with an insecticide impregnated into a suitable substrate, forms the basis of male annihilation technique. This technique has been successfully used for the eradication and control of several Bactrocera species in India (Ravikumar and Viraktamath, 2007 and Dhillonet al., 2005)). In Taiwan the use of McPhail trap to attract female oriental fruit flies as well as melon fruit flies (Bactrocera dorsalis) was found to be effective. The trap is fruit-like in shape and consists of a yellow plastic reservoir containing protein hydrolysis solution as an odour attractant for female oriental fruit flies (Wu et al., 1998). The melon fruit fly can successfully be managed over a local area by cue-lure traps. The application of molasses + malathion and water in the ratio of 1: 0.1: 100 provides good control of melon fly (Dhillon et al., 2005).*	Not measured	*N/A*
Pujari, Bhattacharyya and Das	2013	Prevention and suppression	Fruit bagging	Single	Not measured	*Fruit bagging has been used to protect the infestation of fruit by insects. Individual fruits are bagged when they were young and remain bagged until harvest. No additional pesticidal sprays are needed once the bags are placed on the fruits. Bagging has been considered as a traditional practice adopted by farmers for controlling insects, especially melon flies, fruit flies and banana leaf and fruit scarring beetles. (Wu et al., 1998). Bagging of fruits on the tree (3 to 4 cm long) with 2 layers of paper bags at 2 to 3 day intervals minimises fruit fly infestation and increases the net returns by 40 to 58 per cent (Fang, 1989; Jaiswal et al., 1997). Akhtaruzzaman et al. (1999) suggested that cucumber fruits should be bagged at 3 days after anthesis, and the bags should be retained for 5 days to achieve effective control.*	Decrease	*No additional pesticidal sprays are needed once the bags are placed on the fruits.*
Ramsden et al.	2017	Non chemical methods	Conservation Biological Control	Single	Positive	*The results of the present study show that the number of natural enemies trapped correlated with the subsequent change in cereal aphid abundance. We found that, in this respect, an increase in the abundance of natural enemies recorded led to a reduction in the rate of change of aphids caught. The relationship between natural enemies and the subsequent abundance of aphids caught in cereal fields was*	Not measured	*N/A*

						unaffected by location, either at 10 or 100m from the field boundary. *The results of the present study show that, on average, where no Syrphinae larvae or Aphidiinae were trapped, the subsequent number of aphids collected increased. The presence of either natural enemies reduced the rate of increase.*		
Reddy	2011	Pesticide selection	DiPel biological insecticide	Combination	Positive	*An IPM regime consisting of commercially available products* *(neem and DiPel), applied alternately, was cost competitive for* *management of the pest complex attacking cabbage crops*	Decrease	*The IPM components neem and DiPel are suitable for use in an IPM program for managing insect pests on* *cabbage*
Ritchie et al.	2018	Informed decision making	Decision support system	Single	Positive	*Decision support systems (DSS) integrate information for disease control decisions. This could include information on the pathogen lifecycle, weather, cultivar resistance, fungicides and their mode of action/characteristics, as well as crop growth stage and current disease pressure. A range of DSS have been developed across Europe, all using different criteria for calculating risk. They run on different platforms. Examples include Simphyt (Germany), PLANT-Plus (Netherlands), NegFry and Blight Management (Denmark), ProPhy (Netherlands), Mileos (France), PhytoPre (Switzerland) and Irish rules (Ireland). A range of tools to support risk forecasting and also more complex DSS for late blight are available in the UK (Table 2). These range from simple weather-based risk forecasts at postcode level to more complex systems that are designed for use on individual farms. It has been estimated that around 8% of the UK area uses commercial DSS, in contrast to Nordic countries where it is estimated that nearly 40% of growers use recommendations based on commercial DSS (Cooke et al., 2011). DSS can reduce the amount of fungicide applied by between 8 to 62% and sub-models used by different countries can be tested using the EuroBlight platform (Hansen et al., 2010).*	Not measured	*N/A*
SAI Platform WATER CONSERVATION TECHNICAL BRIEFS- TB 4 - Integrated Pest Management: A guide to protecting water quality	2010	Prevention and suppression	Soil cultivation and tillage	Single	Positive	*physically kills some pests, buries them, or exposes them to drying conditions on the soil surface or as food for birds or other predators. Soil cultivation also buries and kills weed seedlings, and buries potential food sources for insect pests.*	Not measured	*N/A*

SAI Platform WATER CONSERVATION TECHNICAL BRIEFS- TB 4 - Integrated Pest Management: A guide to protecting water quality	2010	Non chemical methods	Use of natural enemies	Single	Positive	*Some predators like ladybirds, spiders, lacewings and birds are the most commonly observed natural enemies, but parasites as parasitic wasps and flies often have the greater control effect*	Not measured	*N/A*
Sharma et al.	2011	Non chemical methods	Technology	Single	Not measured	*technology can be considered an eco-friendly, biosafe and green technology. Effectiveness still to be determined*	Decrease	*the entire development of RNAi technology will create a new biological science offering massive economic and social spin-offs.*
Sharma et al. (a)	2013	Non chemical methods	Mychorrhizae	Single	Positive	*Multi-dimensional protective role of mycorrhizae against diseases and pests and improving feriliser use efficiency*	Decrease	*with multiple benefits, mycorrhiza incorporation can be considered as one of the important component of integrated disease management strategies particularly for organic production systems*
Sharma, Bailey, and Fraser	2011	Informed decision making	Review of practices	Combination	Positive	*In general our nonparametric results indicate that full-time, younger or less experienced arable farmers located primarily in the southern and eastern parts of the UK employ the largest number of PM technologies. Our nonparametric results find no evidence of an influence of educational level or level of profitability on the number of technologies adopted, contrary to our prior expectations, however, the Poisson Model does highlight that farmers possessing only secondary level education are likely to adopt fewer technologies. Perhaps more surprisingly, our results suggest that organic farmers, whom we would expect would need to rely heavily on some of the technologies considered in the survey, do not appear to adopt a larger number of PM methods than do their conventional peers. Adoption of PM technologies appears to be driven primarily by agronomic and climatic factors, with the warmer and more intensively cropped areas showing the highest the rate of adoption. We find some evidence that farm size has a positive and significant impact on the number of techniques adopted.*	Not measured	*N/A*
Slater et al.	2016	Non chemical methods	Plant-plant signalling	Single		*"A plant's induced defence response changes the emission of volatile organic compounds (VOCs), which can repel insect herbivores and attract the herbivore's natural enemies (Du et al. 1998; Bruce et al. 2008; Babikova et al. 2013), helping to regulate pest populations and reduce crop damage. " "recent exciting research has shown that mycorrhizal fungi can also carry defence signals between different plants. This means that plants are warned of aphid presence and*	Not measured	*N/A*

						thus can produce VOCs (Volatile Organic Compounds) to repel aphids and avoid an imminent attack (Babikova et al. 2013) "		
Stetkiewicz	2018	Monitoring, Informed decision making, Evaluation	Resistance		Positive	*The majority of spring barley trials (65%) did not show a statistically significant impact of fungicide treatment on yield. the difference between treated and untreated yields could be explained by disease resistance, average seasonal rainfall (whereby wetter seasons saw an increased impact of fungicide use on yield), and high combined disease severity. Stakeholders were broadly open to taking up IPM measures on farm; sowing of disease resistant varieties was most frequently selected as the best technique in terms of both practicality and cost, though individual preference varied. However, a disparity was seen between farmer perception of their uptake of IPM and actual, selfreported uptake for both varietal disease resistance and rotation.*	Decrease	*there is scope for IPM uptake to be improved upon and fungicide use to be reduced while maintaining high levels of yield in Scottish spring barley production.*
Stetkiewicz et al. (a)	2019	Pesticide selection	Review treated v untreated fungicide plots	Single	Not measured	*Fungicide treatment impacted yield levels significantly in just over one third of the trials assessed from 2011 to 2014, though disease levels were significantly reduced in many cases. The lack of a constant influence on yield, and the minimal cost benefit from fungicide treatment, estimated at less than 5% on average, suggests there may be an opportunity to reduce fungicide use in this sector with little negative impact on yield or profit. In addition, the yield differences seen in these field trials (on average: 0.62 t/ha for commercially relevant varieties grown from 2011 to 2014 and 0.74 t/ha for all trials in the 1996–2014 database) were well below those expected by Scottish spring barley farmers and agronomists (Stetkiewicz et al., 2018). Stetkiewicz et al. (2018) report 71.8% of surveyed farmers and 75% of agronomists estimating the impact of fungicide application to spring barley to be between 1 and 2 tonnes per hectare – well above the impacts reported here. Farmers and agronomists therefore appear to be substantially over estimating the impact of fungicide use on yield.*	Not measured	*N/A*
Stewart and Cromey	2011	Prevention and Suppression	Microbial Bioinoculants	Single	Positive	*"Microbial bioinoculants can be used for pasture and arable crops, such as perennial ryegrass, oilseed rape and maize, which are sown directly into the field. For example, a soil application of granules containing a mix of four strains of Trichoderma atroviride gave a 20% increase in seedling emergence in ryegrass pastures with a resulting 10–20% increase in yield (kg DM/ha). This yield benefit was attributed to a combination of direct plant growth enhancement through root stimulation and control of soil-borne pathogens that*	Not measured	*N/A*

						cause pre/post-emergence damping-off and root rot diseases (e.g., Rhizoctonia, Fusarium, Pythium spp.)"		
Stewart and Cromey	2011	Prevention and Suppression	Genotype mixtures	Single	Positive	*"Growth of poplars in short-rotation coppice for biofuel production has led to an increase in rust outbreaks caused by Melampsora spp. The use of three genotype mixtures in willow plantations significantly reduced the impact of rust outbreak" "Rust can be controlled by intensive use of fungicides, but this is not a viable option for use on a low value crop being grown as a source of renewable energy. The use of willow genotype mixtures as an alternative low cost and effective strategy could significantly reduce the impact of rust in the plantation by delaying disease onset, retarding inoculum build-up and reducing disease levels at the end of the season"*	Not measured	*N/A*
Stewart and Cromey	2011	Prevention and Suppression	Biochar application	Single	Positive	*"Biochar application has positive effects on the plant root zone through increased populations of beneficial microbes and arbuscular mycorrhiza colonisation. Pores within the biochar particles provide a refuge for the mycorrhizal fungi, promoting their growth. Thus, biochar might also provide a delivery system for plant growth-promoting microorganisms and those with potential for biocontrol."*	Not measured	*N/A*
Suckling et al.	2014	Non chemical methods	Mass trapping	Single	Not measured	*Mass trapping involves trapping and removing a large number of individuals using attractive volatile compounds,53 and like the related tactic of lure and kill,54 has good potential to suppress or eradicate low-density, isolated pest populations.*	Not measured	*N/A*
Suckling et al.	2014	Non chemical methods	Sterile Insect Technique	Single	Not measured	*Sterile insects released into the environment in large numbers compete with wild conspecifics for mates. Successful mating results in no offspring being produced, and thus the number of wild insects declines*	Not measured	*N/A*
Suckling et al.	2014	Non chemical methods	Biological control	Single	Not measured	*The goal of biological control is to reduce the population of the pest to the point where additional control measures are not needed. Biological control is extremely unlikely to achieve eradication by itself; there is only one known instance of population extinction with biological control,79 and this was of a nontarget insect.*	Not measured	*N/A*
Suckling et al.	2014	Non chemical methods	Host destruction	Single	Not measured	*Removal of host plant material can be a useful approach to pest suppression along with other tactics during an eradication attempt, especially for host-specific pests.*	Not measured	*N/A*
Suckling et al.	2014	Non chemical methods	Physical and mechanical methods	Single	Not measured	*If the infested area is well known from successful delimitation surveys, sometimes it is possible to use physical barriers to ensure that theorganismis contained*	Not measured	*N/A*

Suckling et al.	2014	Non chemical methods	New technology	Single	Not measured	*New technologies are under development for the suppression of insect pests. Unfortunately, many are not widely applicable for eradication. The most valuable tools are likely to offer generic solutions that might be readily adapted to multiple targets. Anti aggregation chemicals have been used to disrupt the response of scolytids to their aggregation pheromones, causing the pest to disperse, which, although protecting valuable hosts, potentially counters the aim of containing an outbreak. The concept of cross-species behavioural disruption uses insects as agents against another species. Despite successful use of parapheromones to attract male fruit flies of one species to chase and physically interact with another species during the day, tests were unsuccessful at disrupting fruit fly mating behaviour at dusk.*	Not measured	*N/A*
Swiergiel et al.	2019	Non chemical methods	Biocontrol	Single	Not measured	*Development of pest management strategies in organic apple production in collaboration with farmers utilising complementary biological control strategies*	Not measured	*N/A*
Swiergiel et al.	2019	Non chemical methods	Biological controls	Single	Not measured	*Study of the control exerted by natural enemies over aphids and scales in apple orchards and the management factors affecting the natural regulation of pests they provide*	Not measured	*N/A*
Swiergiel et al.	2019	Non chemical methods	Semiochemicals	Combination	Not measured	*Enhancement of pest management resiliency in apple orchards through a synergy between semiochemicals and conservation biological control*	Not measured	*N/A*
Tang et al.	2010	Informed decision making, Reduced pesticide use, Non chemical methods	Modelling	Combination	Positive	*Modelling can reduce pesticide use but needs more work*	Decrease	*Modelling rates of pesticide application and natural enemy release to get optimum timing of each*
Thomas	1999	Prevention and suppression	Biological Control and Host Plant Resistance for Control of Insect Pests	Combination	Positive	*"It was found that partial resistance and partially effective biocontrol can be combined to give additive or synergistic reductions in pest density." "Although neither strategy acting in isolation may be completely successful, opportunities exist for improving control through their combined, integrated use. However, the study also revealed that plant resistance and biocontrol can interact negatively with, under some conditions, plant resistance causing complete disruption of natural enemy activity. The exact nature of the interaction depends on the specific relationship between natural enemy and herbivore and the mode of action of the host plant resistance and its effects on herbivore life history."*	Not measured	*N/A*

Thomas	1999	Non chemical methods	Pathogens for use in biological control, particularly as biorational pesticides	Single	Positive	*"Studies after spray applications have identified that under certain conditions hosts infected by the biopesticide can go on to produce new spores and infect further hosts through horizontal transmission (11, 15, 16). The dynamics of this process are governed by the factors that regulate natural host-pathogen interactions because infections result from natural pathogen delivery mechanisms. These include a number of biotic factors relating to the specific life history and behavioral traits of the host and the pathogen, as well as a range of abiotic factors that have a fundamental influence on the physical and biochemical processes involved in the host-pathogen interaction (refs. 11, 15, and 16; S. Blanford and M.B.T., unpublished work).*	Not measured	*N/A*
Toma et al.	2018	Informed Decision Making	Informed Decision Making	Single	Positive	*access to technological information and trust in/perceived usefulness of the different information sources will have an impact on technological uptake and lead to improved IPM*	Decrease	*transfer of technological information on the uptake of innovative crop technologies*
Tuovinen	2015	Non chemical methods	Biological control	Single	Not measured	*Active biological control: spreading of entomo-pathogenic fungi, bacteria and viruses, parasitic nematodes, parasitoid insects, predaceous insects and mites. Methods of introduction of predatory mites - Slow release sachets, used in greenhouses*	Not measured	*N/A*
Tuovinen	2015	Monitoring	Precise and targeted control actions	Combination	Not measured	*Timing of sprayings based on monitoring results, Timing of introduction of biocontrol agents, Development stage of target pests, Local, focused sprayings, hot spots, Outdoor: avoiding windy weather conditions, use of wind-safe nozzles*	Not measured	*N/A*
Tuovinen	2015	Pesticide selection	Minimised use of pesticides	Combination	Not measured	*Good spraying equipments for each crop, Right nozzle type for each target, Lowest effective dose (notice the risk of resistance development), Adjusted amount of solution according to plant size, Use of surface tension adjuvants when appropriate, Focused sprayings*	Not measured	*N/A*
Tuovinen	2015	Evaluation	Documentation Evaluation Learning	Combination	Not measured	*Active notebook, updated data: monitoring results, actions taken, observations etc. Evaluation of the effectiveness of plant protection actions*	Not measured	*N/A*
University of Warwick, ADAS UK Ltd	2011	Non chemical methods	Bacillus thuringiensis (Bt) Microbial Biopesticide	*Single*	Not measured	*"In some highly susceptible hosts, ingestion is followed by a general paralysis leading to death within an hour. In the majority of insects, only the gut is paralysed and death occurs in about 48 h depending on dose."*	Decrease	"At present, microbial Bt is used mainly on fruit, vegetable and ornamental crops where its selectivity and safety are considered desirable and where there are problems with resistance to conventional insecticides."
University of Warwick, ADAS UK Ltd	2011	Non chemical methods	Entomopathogenic viruses: Baculoviruses	Single	Not measured	*"Death occurs in 5 – 8 days depending on the dose, but it can be longer."*	Not measured	*N/A*

University of Warwick, ADAS UK Ltd	2011	Non chemical methods	Entomopathogenic fungi.	Single	Not measured	*"Entomopathogenic fungi cause infection in all the major taxonomic groups of insects and mites" "Death occurs within 4 – 7 days of infection, followed by the production of large numbers of spores on the cadaver. Thousands or millions of spores may be produced on large insects. The spores of many species of Entomophthorales are actively discharged from the cadaver in order to transmit the fungus to new hosts. They also show a range of other adaptations to increase transmission including timing the release of spores to periods of the day that are most favourable to infection, and manipulating host behaviour so that diseased insects die in exposed positions (Roy et al., 2006)." "When mass produced Metarhizium spores are sprayed in an oil-based formulation they cause up to 90% locust and grasshopper control in 14 – 20 days"*	Decrease	*These pests are usually treated with conventional insecticides sprayed over very large areas, particularly organophosphates, and hence there are genuine concerns about environmental and human safety.*
University of Warwick, ADAS UK Ltd	2011	Non chemical methods	Entomopathogenic nematodes.	Single	Not measured	*"Subsequent multiplication of the bacteria contributes to host death due to the action of bacterial toxins, which can occur within as little as 48 h of infection. The bacterium also acts as a source of food: the nematode can kill its host without its associated bacterium but is unable to reproduce without it. After the host has died, the dauer juvenile nematodes mature into adults and the infection cycle terminates with the production of large numbers of progeny juveniles. If adequate moisture is present, the next generation dauer juveniles leave their hosts through the cuticle."*	Not measured	*N/A*
University of Warwick, ADAS UK Ltd	2011	Non chemical methods	Combination of M. anisopliae [entomopathogenic fungi] and the pyrethroid permethrin for the control of the deer tick (Ixodes scapularis)	Combination	Not measured	*"While M. anisopliae was moderately pathogenic to tick larvae the addition of permethrin did not significantly affect larval mortality. Results from a second study combining M. anisopliae with a pyrethroid were more positive"*	No Effect	*N/A*
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	Kpindou et al. (2001) combined the entomopathogen with lambda-cyhalothrin	Combination	Not measured	*"Here the chemical pesticide gave rapid knockdown with mortality due to the M. anisopliae beginning two days after application."*	No Effect	*N/A*
University of Warwick, ADAS UK Ltd	2011	Non chemical methods	Koppenhöfer et al. (2003) investigated the potential of combining entomopathogenic nematodes with imidacloprid for control of white grubs (Scarabaeidae)	Combination	Not measured	*"Here, imidacloprid had little effect on SID 5 (Rev. 07/10) Page 14 of 27 survival or pathogenicity of Heterorhabditis bacteriophora. Similarly, other neonicotinoids (thiamethoxam and acetamiprid) were found to be compatible with entomopathogenic nematode species, although high rates of acetamiprid did affect Steinernema feltiae behaviour. Where combinations of a nematode and a neonicotinoid led to higher levels of insect mortality the nematode*	No Effect	*N/A*

						populations in the soil were also found to be higher. It was suggested that these higher nematode populations could provide extended control of the pest, however, this will depend in part of the remaining pest population and the ability of the nematode to survive in the soil."		
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	biopesticides with the botanical insecticide neem	Combination	Not measured	*"Shah et al. (2008) found both M. anisopliae and neem cake (a by-product of neem oil production) to be effective against early instars of the black vine weevil when incorporated into compost and that the addition of neem cake enhanced the efficacy of M. anisopliae. It was suggested that the neem cake caused greater movement of the larvae by acting as a repellent or antifeedant leading to increased acquisition of fungal spores. The apparent antifeedant properties of the neem cake also resulted in reduced larval growth. Reduced feeding may in turn have weakened the larvae making them more susceptible to the entomopathogen. Similarly, Mohan et al. (2007) found most isolates of B. bassiana tested to be compatible with neem oil and that a combination was more effective against tobacco budworm. This improved efficacy was seen both by increased mortality and faster speed of kill. Barčić et al. (2006) investigated the efficacy of Bt, neem and pyrethrins for the control of the Colorado potato beetle (Leptinotarsa decemlineata). Here the combinations were found to have greater efficacy and persistence compared to the individual components."*	No Effect	*N/A*
University of Warwick, ADAS UK Ltd	2011	Non chemical methods	James (2003) combined azadirachtin (from neem) with the entomopathogenic fungus Paecilomyces fumosoroseus	Combination	Not measured	*"James (2003) combined azadirachtin (from neem) with the entomopathogenic fungus Paecilomyces fumosoroseus for control of the same pest. Again higher levels of mortality were recorded when the azardirachtin and the entomopathogenic fungus were combined in sequential sprays separated either by two hours or three days"*	No Effect	*N/A*
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	synthetic insecticides with the entomopathogenic fungus	Combination	Not measured	*"Er & Gökçe (2004) investigated the compatibility of synthetic insecticides with the entomopathogenic fungus Isaria fumosorosea (= Paecilomyces fumosoroseus) for control the glasshouse whitefly Trialeurodes vaporariorum in laboratory experiments. The results suggested potential for combining the fungus with a range of different insecticides. Positive results have also been recorded when M. anisopliae or B. bassiana were combined with oils (Malsam et al. 2002) or neem extract (Islam et al. 2010) against whitefly. In contrast, work by James and Elzen (2001) recorded a decrease in the expected level of pest control of B. tabaci when B. bassiana was combined with imidacloprid. There is no clear explanation for this result other than a possible behavioural effect caused either by the imidacloprid or the B. bassiana" "Gatarayiha et*	No Effect	*N/A*

						al. (2010) found that potassium silicate may enhance the efficacy of Beauveria bassiana in controlling two-spotted spider mite (T. urticae). Here the potassium silicate was applied as SID 5 (Rev. 07/10) Page 16 of 27 a plant nutrient and the B. bassiana applied to leaves conventionally. It was hypothesised by the authors that the potassium silicate increased plant resistance, which resulted by reduced feeding by the mites and increased their vulnerability to the fungus." "For example, Jung & Kim (2007) investigated using X. nematophila (the bacterial symbiotic mutualist of the entomopathogenic nematode Steinernema carpocapsae) in combination with microbial Bt against Bt-resistant diamondback moth larvae, Plutella xylostella. A co-application of X. nematophila and microbial Bt resulted in greater mortality than when X. nematophila was fed to larvae on its own. In addition, X. nematophila cells were only recovered from larval haemocoel when used in combination with microbial Bt, suggesting that Bt facilitated entry for X. nematophila by causing damage to gut epithelial cells."		
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	microbial biopesticides and potentiating chemicals	Combination	Not measured	*"application of the alarm pheromone E β farnesene increased the movement of aphids on leaf discs of pepper in a laboratory bioassay, which caused them to pick up more spores of the entomopathogenic fungus Lecanicillium longisporum (= Verticillium lecanii) leading to an increase in fungus induced mortality (Roditakis et al., 2000). Elsewhere, a phagostimulant based on flour and ground maize cob applied with multiple nucleopolyhedrovirus (SfMNPV) increased the virus induced mortality of fall armyworm Spodoptera frugiperda in field experiments by causing the insect to ingest more virus particles from foliage (Castillejos et al., 2002)." "Stilbene optical brighteners are known to potentiate the pathogenicity of NPVs to lepidopteran larvae (Thorpe et al., 1999; Ibargutxi et al., 2008). It is hypothesised that the optical brightener causes degradation of the insect peritrophic membrane and thereby facilitates entry of virus into midgut cells. However the effect may vary with insect species (Shapiro & Farrar, 2003). Optical brighteners can also act as protectants for virus particles from u.v. radiation damage (Shapiro & Farrar, 2003) so this needs to be taken into account when studying their role as potentiators in the field."*	No Effect	*N/A*
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	microbial biopesticides and potentiating chemicals	Combination	Not measured	*"a combined application of a sublethal dose of imidacloprid and B. bassiana caused an increase in the mortality of leaf-cutting ants Atta sexdens compared to the fungus on its own, and it was found that the insecticide reduced the movement of ants at this dose*	No Effect	*N/A*

						(Santos et al., 2007) (see above). In contrast, Roditakis et al. (2000) observed that imidacloprid applied at 1% of the recommended dose caused an increase in the movement of aphids leading to enhanced secondary pick up of spores of L. longisporum (see above). Furlong & Groden (2001) reported that applying sublethal concentrations of imidacloprid together with spores of B. bassiana resulted in increased mortality of larvae of Colorado potato beetle Leptinotarsa decemlineata in laboratory tests. This occurred when imidacloprid was applied at the same time as the fungus or when it was applied 24h before the fungus, but not when the insecticide was applied 24h after the fungus. It was found that the imidacloprid inhibited larval feeding and it was proposed therefore that starvation-induced stress factors made the larvae more susceptible to the fungus. In this case, the possibility that fungal infection made the insect susceptible to normally sublethal concentrations of imidacloprid can be ruled out as there was no increase in mortality when the insecticide was applied after the fungus"		
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	Biopesticides	Combination	Not measured	*"Ansari et al. (2004) observed that a co-infection of M. anisopliae and Heterorhabditis megidis in the scarab Hoplia philanthus resulted in a reduction in the production of progeny nematodes. Reducing the amount of within-host reproduction will also reduce the degree of self-perpetuating control by a biopesticide, so from this perspective it is not a good strategy unless the combination results in a very strong synergistic effect." "Liu et al. (2006) observed that co-infection of H. armigera with HaNPV and Bt Cry1Ac resulted in a lower than expected amount of insect mortality."*	Not measured	*N/A*
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	Biopesticides	Combination	Not measured	*"A tank mix of L. muscarium (Mycotal) and teflubenzuron (Nemolt) has been considered to give improved control of glasshouse whitefly, Trialeurodes vaporariorum" "A tank mix of B. bassiana (Naturalis-L) and abamectin (Dynamec) has been considered to give improved control of two-spotted spider mite, T. urticae" "A tank mix of B. bassiana (Naturalis-L) and spinosad (Conserve) has been considered to give good control of sciarid fly (Bradysia spp.) and shore fly (Scatella spp.) in glasshouses used for ornamental bedding plant propagation" "A tank mix of pyrethrum (Pyrethrum 5 EC) and B. bassiana (Naturalis-L) has been considered to give improved control of sciarid and shore flies" "Using a tank mix of two biopesticides, B. bassiana (Naturalis-L) and entomopathogenic nematodes has been considered to give improved control of the ground-dwelling life stages of thrips, sciarid and shore flies in protected herb production." "Using biopesticides in*	Not measured	*N/A*

						combination with chemical pesticides in a sequential programme, rather than as a tank mix, is used by many growers."		
University of Warwick, ADAS UK Ltd	2011	Pesticide selection	combining entomopathogens and chemical insecticides (EPF Metarhizium brunneum, EPN Steinernema feltiae)	Combination	Not measured	*"We found that combining the biopesticides M. brunneum and S. feltiae together could give significant control of CRF, whereas these agents did not control CRF when used on their own" "However, the effect was only observed in two out of three experiments, and it is likely that the outcome of the interaction between M. brunneum and S. feltiae was affected by external factors such as compost type. The combination of M. brunneum and S. feltiae was much less effective than using the chemical insecticide spinosad"*	No Effect	*N/A*
Van der Meulen and Chauhan	2017	Prevention and suppression	Competitive cultivars	Combination	Positive	*Research has demonstrated convincingly that the suppression of weeds by cereal crops can be increased greatly without reducing yield, through a combination of increased crop density and increased crop spatial uniformity.*	Decrease	*While sowing cereals at a higher density would require some increased expenditures (i.e., more seed for sowing), there would be a corresponding reduction in other weed control costs (chemicals, fuel, machinery, and labour).*
Vasileiadis et al.	2013	Informed decision making	DEXiPM	Combination	Positive	*We found DEXiPM® to be a useful tool for supporting users to integrate their overall knowledge through multi-criteria assessment, to identify ex-ante the indicators/criteria that strongly affect the sustainability of cropping systems, which require a lengthy time and resources to be tested in the field, and to compare current MBCSs and innovative IPM-based proposals. This comparative study shows that only the rotated ISs of the northern and south-western regions could be classed as sustainable for all three dimensions of the sustainability. This suggests that their implementation could be considered to demonstrate the interest of these strategies for farmers. However, all innovative rotated systems proposed could maintain the same economic sustainability and were more environmentally sustainable than the current rotated systems, so are also acceptable for testing under "real" field*	Not measured	*N/A*
Velicka et al.	2018	Prevention and suppression	Sowing date	Single	Positive	*The aim of the investigation was to evaluate the response of weed density in spring oilseed crop to the sowing date. In 2015, the first sowing date was 15 April. Afterwards the sowing was performed every 5 days until 20 May. In 2016, the first sowing date was 10 April. Afterwards the sowing was performed every 5 days until 25 May (except for the 7th and 8th sowing date, the interval between which was 10 days because of the adverse weather conditions). The number of weed seedlings and the number of weeds before harvesting differed between the experimental years. In 2015, with a delay in spring oilseed sowing until 5 May, the number of weed seedlings decreased. The highest number of weed seedlings was recorded in the plots sown on 10*	Not measured	*N/A*

						May, and later it declined. In 2016, a 10–15 day delay in sowing resulted in significantly the highest number of emerged weeds, and in the plots sown at later dates the number of weeds inconsistently decreased.		
Wallace et al.	2019	Prevention and suppression	Cover crop	Single	Positive	*Averaged across study years and fertility regimes, cover crop treatments resulted in a 56% to 82% decrease in emerged E. canadensis density relative to the control just before a preplant burndown application*	Not measured	*These results demonstrate that cover crops can significantly reduce selection pressure intensity imposed by preplant burndown applications on E. canadensis in no-till systems.*
Wallace, Curran, and Mortensen	2019	Prevention and suppression	Cover cropping	Combination	Positive	*First, recent studies have consistently demonstrated that integrating cover crops into annual grain crop rotations can improve suppression of current glyphosate-resistant weeds, including horseweed (Erigeron canadensis L.; Cholette et al. 2018) and Amaranthus spp. (Loux et al. 2017; Montgomery et al. 2018; Wiggins et al. 2016). And second, cover crops are increasingly integrated into annual grain crop rotations to provide multiple ecosystemservices, including improved soil quality, maintenance of nutrient and water cycling, and enhanced biotic pest regulation (Wayman et al. 2016). These broad trends signal a unique opportunity to design complementary cover-cropping tactics that are guided by an understanding of the processes that select for herbicide resistance in no-till production systems.* *Based on the magnitude of treatment responses, it is reasonable to conclude that interannual variation in growing conditions (study year) and intra-annual variation in residual soil fertility (low vs. high N) are more important drivers of resource acquisition, and therefore weed-suppression potential, than use of cover crop monocultures or mixtures with particular functional traits (N function, phenology). In general, however, observed trends between taxonomic groups (grasses, brassicas, legumes) and fall biomass production are consistent with previous studies that have demonstrated the benefits of using fall-sown grass and brassica cover crops, which have comparatively higher relative growth rates and more efficient N uptake compared with legumes in the fall growing season (Björkman et al. 2015; Brainard et al. 2011; Finney et al. 2015).* *Averaged across study years and fertility regimes, cover crop treatments resulted in a 56% to 82% decrease in emerged E. canadensis density relative to the control just before a preplant burndown application (Figure 4). Mean reduction in E. canadensis density was highest and variance was lowest in cereal rye monocultures, but cover crop mixtures that included forage radish also*	Decrease	*First, cover-cropping tactics could decrease population-level survival rates to herbicides by dampening the herbicide dilution effect that provides a fitness advantage to large individuals. Second, by constraining populations to smaller individuals and producing physical interference of herbicide deposition through the canopy, cover-cropping tactics could further reduce herbicide exposure to emerged populations beyond the demographic effects on population size. As a result, cover-cropping tactics could increase or decrease weed control efficacy of herbicides but could also decrease the selection intensity for herbicide resistance.* *Erigeron canadensis size at the time of herbicide exposure has been shown to directly influence selection intensity for glyphosate resistance. Dinelli et al. (2006) reported that ED50 values were approximately the same for susceptible (S) and resistant (R) populations following glyphosate applications at the 2-leaf stage, but R biotypes were approximately three times more resistant to glyphosate compared with S biotypes when applications were made at the rosette stage. Reduced or altered translocation of herbicides is likely the primary mechanism that confers a size-based fitness advantage in glyphosate-resistant E. canadensis (Dinelli et al. 2006). There is currently widespread concern over the increasing prevalence of weed species that evolve such non–target site resistance mechanisms (Powles and Yu 2010). Notably, altered transport mechanisms of resistance are considered the most likely to develop in response to increased use of synthetic auxin herbicides (SAH) in SAH-*

						resulted in a greater than 75% decrease in E. canadensis density relative to the control. These results demonstrate that cover crops can significantly reduce selection pressure intensity imposed by preplant burndown applications on E. canadensis in no-till systems.		*tolerant crop production systems (Busi et al. 2017). Our results suggest that integration of cover crops could potentially reduce selection intensity for SAH resistance in E. canadensis or other winter annual species by reducing the potential of a size-dependent fitness advantage for biotypes that develop non–target site resistance mechanisms.*
Waller et al.	1998	Prevention and suppression	Crop rotation	Single		*Crop rotation has been an important IPM technique for CPB (Ferro and Boiteau, 1993). Spring colonisation of a new ®eld by CPB can be delayed with the use of crop rotations (Wright, 1984; Lashomb and Ng, 1984).*	Decrease	*By slowing the movement of overwintered CPB adults into new ®elds, rotations reduce the need for insecticide applications and selection for insecticide resistance, especially when the ®elds are more isolated from the previous year's ®elds (Roush et al., 1990; Weisz et al., 1994). Land availability, however, can limit the use of crop rotation for many farmers.*
Waller et al.	1998	Prevention and suppression	Crop Rotation	Single	Positive	*The non-chemical control used most to manage the CPB was crop rotation, which 24 survey respondents have used. Two growers who were interviewed said that crop rotations seem to be the one non-chemical practice that helps to control the CPB the most.*	Not measured	*N/A*
Waters	2015	Monitoring	Sticky traps	Single	Not measured	*The sticky traps were an effective means of measuring psyllid emigration into the plot areas, but do not seem to be an effective metric for measuring efficacy of treatments. It is my opinion based on this trials and others conducted (data not included) that yellow sticky cards will be helpful in determining when infestations of psyllids begin, but are probably not an effective measure of success of insecticide applications as psyllids seem to continually infest fields*	Not measured	*The sticky traps were an effective means of measuring psyllid emigration into the plot areas, but do not seem to be an effective metric for measuring efficacy of treatments. It is my opinion based on this trials and others conducted (data not included) that yellow sticky cards will be helpful in determining when infestations of psyllids begin, but are probably not an effective measure of success of insecticide applications as psyllids seem to continually infest fields*
Waters et al	2012	Non chemical methods, reduced pesticide use	Mapping resistance	Combination	Positive	*Advances have been made in genetic mapping of resistance (R) genes and in identifying novel sources of genes in wild barley populations and land races. Marker assisted selection techniques are being used to pyramid R genes to increase the durability of resistance. Elicitors to induce host resistance used in combination with fungicides can provide effective disease control in the field and could delay the evolution of fungicide insensitivity. Traits that may contribute to disease tolerance and escape have been identified and the extent of genetic variation within barley germplasm is being determined.*	Not measured	*N/A*
Way and van Emden	1999	Informed decision making	Decision support system		Not measured	*Computer generated farmer support systems have been greatly aided by temperature driven computerised systems especially in control of key insect species such as codling moth (T. Alway, 1999, pers. comm.; R. Prokopy, 1999, pers. comm.; Solomon, 1995). Second level IPM, involving multiple management of biologically based tactics for all pests (Prokopy et al.,*	Not measured	*N/A*

						1996), has a positive image for growers and the public (Prokopy et al., 1995), but so far in practice has been too complex, even for advisers. Instead, apart from codling moth control, growers and many advisers seem to use experience-based relatively qualitative estimates of thresholds, for example, they may just relate percentage leaves with spider mite and percentage with predatory mites as a basis for assessing need for a acaricide		
Way and van Emden	1999	Informed decision making	Modelling	Single	Not measured	*The object is usually to mimic relationships already examined in the field in the hope that the model will add novel insights or will be developed as a predictive tactical model. It is implicit in these models, however, that the output can only reflect the input, and therefore the model cannot provide any insight which is non-deductable from simple additivity or other prescribed function of these inputs. Although strategic models can be a shortcut in suggesting outcomes for testing by experiment, they cannot be a substitute for empiricism. Models unfortunately cannot predict the unpredictable, whereas experiments can for example reveal important and often unexpected synergism or compatibility between control methods as shown by our case histories*	Not measured	*N/A*
Way and van Emden	1999	Anti resistance management	Host plant resistance	Single	Not measured	*Host plant resistance is the theoretically ideal control method (van Emden and Peakall, 1996), so in the past has often been given paramount priority, for example by the CGIAR international research institutes, with emphasis on seed based technology including crop protection requirements. The implementation of this approach, however, has been limited by the inability to develop adequate stand-alone host plant resistance in most key crops and against many pests, coupled with the lack of interest by plant breeders in releasing cultivars with partial resistance. Where stand-alone resistance has succeeded initially, the development of virulent strains of a pest has jeopardised its value, especially because it has only been belatedly realised that host plant resistance must be used as just one component of an IPM mix.*	Not measured	*N/A*
Witkowska et al.	2018	Non chemical methods	Physical control - netting over crop	Single	Positive	*With radish production, in this particular situation, it appears that the net covers reduce, but do not completely eliminate, damage by Phyllotreta spp., so that an additional method of control might have to be used (e.g. insecticide applications) whereas, despite the initial concerns, the use of the net did not increase the incidence of lesions believed to be caused by P. parasitica.*	No Effect	*For radish, a single insecticide treatment, involving a post-sowing field spray of chlorpyrifos, has been available until recently, but this has not always been completely effective and use of chlorpyrifos in this way is no longer approved.* *With radish production, in this particular situation, it appears that the net covers reduce, but do not completely eliminate, damage by*

								Phyllotreta spp., so that an additional method of control might have to be used (e.g. insecticide applications) whereas, despite the initial concerns, the use of the net did not increase the incidence of lesions believed to be caused by P. parasitica.
Woodcock et al.	2016	Non chemical methods	Increased natural predators (through diverse margin)	Single	Positive	*Our results suggests that for a typical arable field (c. 12 ha) surrounded by species rich field margins, 50% of the total area could benefit from enhanced pest control services. Increased yields of oilseed rape due to insect pollinators of c. 0.4 t ha1 were identified. We demonstrate that pest control services decline with distance from the crop edge so that their benefit would be limited in the middle of crop fields. There was strong evidence that predatory invertebrates contributed to natural pest control, with the predator exclusion treatment (EXCL) represented within the AICcDi< 2 subset for both aphid colony survival times and the rate of changes in per capita growth rates (Table 2). When aphid colonies were exposed to predation from both canopy and soil active predators they survived on average less than 15 days, while the exclusion of all predators allowed colonies to survive on average 35 days*	Not measured	*N/A*