University of Reading

Promoting Integrated Pest Management in Arable Fields

Submitted for the Degree of Doctor of Philosophy

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‘Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.’

Han Zhang

May 2017

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Abstract

Integrated pest management (IPM) has gained recognition worldwide as a key tool for sustainable arable farming. Promoting natural pest control, strategic use of insecticides, and farmer participation are three important elements in IPM. However, knowledge gaps exist related to the economic value of natural pest control service, insecticides' efficacies and side effects, and farmers' incentives to adopt natural pest control in arable fields. This thesis addresses these gaps using UK and European arable crop systems. With a natural enemy exclusion experiment and economic surplus method, the annual economic value of predators and parasitoids for the summer grain aphid (*Sitobion avenae*) control in wheat (*Triticum* spp.) in South East England was estimated to be £0-2.3 Million, depending on the aphid infestation levels. Insecticidal sprays based on action thresholds would enhance the value of this ecosystem service. By conducting a UK online survey among experts on insecticide efficacies and side effects in oilseed rape (*Brassica napus*) protection, relatively older chemical groups were perceived to have lower efficacies for target arthropod pests than newer ones. Foliar sprays were perceived to have greater negative impacts than seed treatments on users' health, natural enemies, pollinators, soil and water. Many foliar active ingredients pose potential risks for non-target arthropod species in UK oilseed rape fields. Through an interview of European arable farmers participating in an agri-environmental project, respondents' willingness to encourage natural (animal) pest control was relatively low. In comparison, using insecticides to control pests was the typical practice. Ordinal logistic regression indicated that farmers' decision to promote natural pest control was positively associated with the perceived importance of this ecosystem service on crop production, but negatively associated with the perceived number of important pests in the fields. The implications of these findings and avenues for future research to enhance IPM in arable crops are discussed.

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Chapter 1: General introduction

1.1 Pest control in arable crops

Arable crops – including cereals, pulses, root crops, and oilseed crops – provide the primary source for human food, animal feed, and biofuel consumption worldwide. They are also the most widely cultivated crops in the world, with cereals alone occupying more than half of the harvested area (Fig 1.1; FAO 2013; FAO 2015).

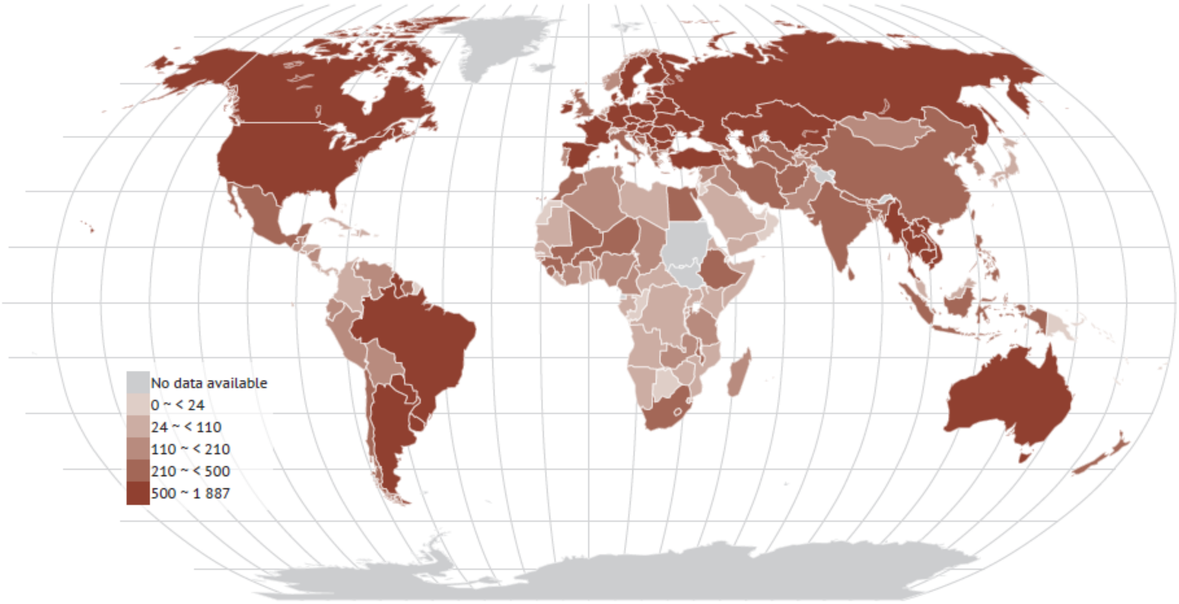

Fig 1.1. Cereal producing countries worldwide in 2013 (kilograms/capita)

This figure is modified from FAO (2015).

Because of the increasing population and rising consumption of meat and biofuel worldwide, arable crops are becoming increasingly important (Ray et al. 2013). In the past 50 years, the increase in harvest has been largely driven by higher yields and more intense crop management (FAO 2013); however, a major challenge to maintain this increase is pest damage problems (animal pests, weeds, pathogens and viruses) (Savary et al. 2012; Parsa et al. 2014). It is estimated that pests are responsible for 20-40% losses in global crop production (Oerke 2006; Savary et al. 2012) .

The most commonly used method to control pests in agriculture is to apply pesticides, including insecticides, herbicides, and fungicides. However, despite a manifold increase in pesticide use over the past 50 years (Fig 1.2), global crop losses to pests have not been significantly decreased, and have even increased in some cases (Pimentel 2005; Oerke 2006). This may be partly related to the problems brought by indiscriminate use of pesticides, including pest resistance, target pest resurgence, and secondary pest outbreaks (Ehler 2006). Alarmingly, this increasing trend may continue due to agricultural intensification, trade globalization, and climate change (Savary et al. 2012; Parsa et al. 2014).

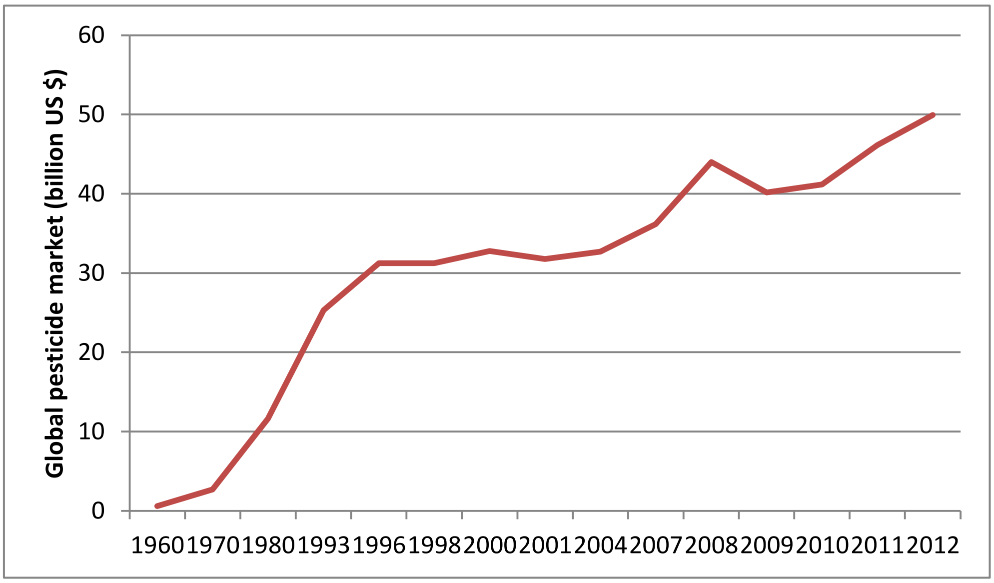

Fig 1.2. Global pesticide market (billion US $) from year 1960 to 2012

This figure is modified from Peshin & Zhang (2014).

Apart from only partially protecting crops from pest damage, the indiscriminate use of pesticides can also cause negative impacts on human health, non-target species, and the wider environment (Gill & Garg 2014). Pimentel (2005) estimated that the total side effects brought by pesticide application in the US could reach to $10 billion per year.

Take pyrethroids – one of the most widely used insecticide chemical groups worldwide – as an example. Although their relative toxicity for mammals is low (Ray & Fry 2006; Casida 2010), and relatively few human poisonings have been reported (Bradberry et al. 2005), sub-lethal influence on human health (e.g., paraesthesia and nausea) have been found (Bradberry et al. 2005).

Pyrethroids have high absorption and low mobility in the soil system (Palmquist et al. 2012), which can cause acute and chronic effects on beneficial species like earthworms (Hartnik et al. 2008; Tripathi et al. 2010; Das Gupta et al. 2011; Song et al. 2015). They also widely exist in water and especially sediments (Amweg et al. 2005; Ng et al. 2008), due to surface runoff and drift (Palmquist et al. 2012). Pyrethroids are highly toxic to invertebrates and fish; however, their bio-accumulate rate is relatively low, due to quick dissipation rates in water and high affinity of sediments (Palmquist et al. 2012).

Pyrethroid residues have also been found in honeybee (*Apis mellifera*) hives (Mullin et al. 2010) and in wild bees (Hladik et al. 2016). Early studies have already shown they have an influence on honeybee's homing behaviours (van dame et al. 1995), and more recent research has found lethal and sub-lethal effects on pollinators (e.g., through laboratory assays, pyrethroids were found to cause locomotor deficit on honeybee; Charreton et al. 2015). As for natural enemies, Theiling & Croft (1988) documented an accelerating trend of increasing toxicity to natural enemies from early inorganic chemicals to the synthetic pyrethroids. Many studies have also provided evidence of pyrethroids' negative impacts on natural enemies (e.g., through laboratory assays, pyrethroids were found to impair the orientation and oviposition behaviours of a parasitic wasp, *Aphidius ervi;* Desneux et al. 2004).

Indeed, there is increasing concern about the potential side effects of pesticides use in agriculture (Damalas 2009), and a more sustainable pest control approach – integrated pest management (IPM) – continues to gain recognition worldwide.

1.2 Concept and development of integrated pest management (IPM)

In 1959, Stern and his team for the first time defined the concept of 'integrated control' as 'applied pest control which combines and integrates biological and chemical control' (Stern et al. 1959). In the 1960s, the concept of 'pest management' was introduced and gained popularity: it included more pest control techniques such as host plant resistance (a plant's ability to resist pest infestations), semiochemicals (organic compounds released by an organism to affect behaviours of other organisms) and cultural control (modifying the growing environment to reduce the build-up of pests) (Geier & Clark 1961). Then, 'integrated control' and 'pest management' gradually converged as a basis for 'integrated pest management', though they still both focused on insect pests. In the early 1970s, the modern integrated pest management (IPM) was born and incorporate all classes of pests (Kogan 1998; Bajwa & Kogan 2002; Ehler 2006).

Currently there are many definitions of IPM depending upon the stakeholder types and their underlying philosophy for pest control (Bajwa & Kogan 2002). However, the core of IPM is a systemic approach which encourages the integration of multiple methods to control pests in a 'safe, cost-effective, and environmentally friendly manner' (Parsa et al. 2014). For the scope of this thesis, I use the IPM concept defined by the European Union (EU; European Union 2009):

> '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.

Following this concept, EU legislation also identified eight principles of IPM (Table 1.1). For more detailed explanations and examples of these principles, please refer to the Annex III of Framework Directive 2009/128/EC and Barzman et al. (2015).

Table 1.1 General principles of integrated pest management

Principles	Explanations
Prevention and suppression	The prevention and/or suppression of harmful organisms should be achieved or supported
Monitoring	Harmful organisms must be monitored by adequate methods and tools, where available
Decision-making	Based on the results of the monitoring the professional user has to decide whether and when to apply plant protection measures
Non-chemical methods	Sustainable biological, physical and other non-chemical methods must be preferred to chemical methods if they provide satisfactory pest control
Pesticide selection	The pesticides applied shall be as specific as possible for the target and shall have the least side effects on human health, non-target organisms and the environment
Reduced pesticide use	The professional user should keep the use of pesticides and other forms of intervention to levels that are necessary
Anti-resistance strategies	Where the risk of resistance against a plant protection measure is known and where the level of harmful organisms requires repeated application of pesticides to the crops, available anti-resistance strategies should be applied to maintain the effectiveness of the products
Evaluation	Based on the records on the use of pesticides and on the monitoring of harmful organisms the professional user should check the success of the applied plant protection measures

Note: this table is modified from the Annex III of Framework Directive 2009/128/EC and Barzman et al. (2015).

Since the introduction of IPM, many studies have shown that IPM can bring long term economic, health, and environmental benefits to farmers and the society under certain conditions (Ehler 2006; Lefebvre et al. 2015; Barzman et al. 2015). Many policymakers and researchers around the world have been actively promoting this approach to sustainable pest management in agricultural production.

Many governments have provided financial support for large IPM research programs, including the ENDURE project in Europe (initially funded by the European Commission from 2007-2010 and now a self-funded research group; http://www.endure-network.eu/), the Regional IPM Centres in the US (sponsored by the National Institute of Food and Agriculture; http://www.ipmcenters.org/), and the National Research Centre for Integrated Pest Management in India (http://www.ncipm.org.in/).

Furthermore, to reduce unnecessary pesticide applications, several countries have also set up extensive monitoring systems for major pests to provide regional pest control decision support for farmers (Barzman et al. 2015). These include the online disease forecasting platform for major crops in Germany (das Informationssystem Integrierte Pflanzenproduktion; www.isip.de), the weekly regional crop protection recommendations for farmers in Switzerland (www.phytopre.ch, www.agrometeo.ch, www.sopra.admin.ch), and the weekly updates on regional aphid activities in the UK (https://cereals.ahdb.org.uk/monitoring/aphid-news.aspx; Fig 1.3).

Fig 1.3. One of 16 suction-traps operated by the Rothamsted Insect Survey in UK

These traps collect aphid data to provide information for the weekly aphid alert in UK. The picture is modified from http://www.rothamsted.ac.uk/insect-survey/networks.

1.3 Key components of IPM and the focus of this thesis

IPM is a complex regime that involves multiple components (e.g., cultivation techniques; crop cultivars; suitable machinery; Barzman et al. 2015), and major knowledge gaps exist in several areas including: the economic values of natural pest control, the efficacies and side effects of pesticides, and the incentives and barriers for farmer participation in IPM. This thesis thus aims to provide better evidence and information for each of these.

Based on the scope of the study, ‘pest’ here refers to animal pests for arable crops (mainly arthropods), ‘natural enemies’ refers to the naturally occurring species that target these pests (mainly arthropods and locally present in/around arable fields), and insecticides are the main pesticide group studied in the thesis.

1.4 IPM: natural pest control

1.4.1 Concept of natural pest control service

The first of eight principles in the EU IPM (prevention and suppression) stresses the importance of protecting and enhancing natural pest control in the croplands (Barzman et al. 2015). Indeed, natural pest control is a key element in the IPM regime and an important regulating ecosystem service for sustainable crop production, where crop pests are suppressed, to some degree, by their natural enemies (predators, parasitoids, pathogens) in the fields (Power 2010; Thies et al. 2011; Crowder & Jabbour 2014; Dicks et al. 2016). It is 'the action of parasites, predators, or pathogens on a host or prey population which produces a lower general equilibrium position than would prevail in the absence of these agents', where the general equilibrium position is 'the average density of a population over a period of time in the absence of permanent environmental change' (Stern et al. 1959). Natural pest control is effective when a target pest population is regulated by natural enemies so that the pest density exceeds the economic-injury level ('the lowest population density that will cause economic damage') at a lower frequency (Stern et al. 1959). The long term pest suppression by natural enemies is achieved when the general equilibrium position of the target pest lies far below the economic-injury level so that the pest species would not cause economic damage to the crop (Stern et al. 1959).

1.4.2 Benefits and risks of natural pest control service in arable crops

The positive contributions of natural pest control service toward arable crop production have been characterised through field experiments, ecological modelling, and economic evaluation.

By conducting natural enemy exclusion experiments in the winter wheat fields in Michigan, Safarzoda et al. (2014) confirmed that natural enemies could effectively control cereal aphids. By developing a novel landscape model for natural pest control of cereal aphids in a Swedish agricultural region, Jonsson et al. (2014) predicted that natural enemies would reduce cereal crop damage by 45-70%. With the avoided cost method (by comparing the relative yield loss and insecticide costs with and without natural enemies in the fields), Landis et al. (2008) estimated that the economic value of natural control of the soybean aphid (*Aphis glycines* Matsumura) in four US states was about $33/ha in 2005/06.

Beyond direct pest control, studies on the contributions of natural pest control include: reducing the rate of development of insecticide resistance in pests (Liu et al. 2014; Lefebvre et al. 2015), providing consumers with potentially healthier food containing fewer chemical residues (Baker et al. 2002; Florax et al. 2005), and reducing negative effects of insecticides on users' health and the wider environment (Gill & Garg 2014; Bonmatin et al. 2015).

However, numerous factors may disrupt the pest control efficacies by natural enemies. Foremost, intense arable crop production systems mean that the performance of this ecosystem service at both field and landscape levels can be uncertain across seasons, years, crops and locations (Bommarco et al. 2013; Crowder & Jabbour 2014):

Due to the toxicological characteristics, pesticides (especially insecticides) could affect the natural pest control efficacies through lethal (directly exposed by chemicals or indirectly by toxic preys; Douglas et al., 2015) and sub-lethal impacts (e.g., impaired feeding and oviposition behaviours; Desneux et al., 2007) on natural enemies in the farmed landscape. Conventional soil management (e.g., intense tillage) could also disturb this ecosystem service by directly killing/injuring natural enemies (especially ground dwelling predators), and indirectly reducing surface residues for sheltering and alternative food resources (Holland 2004; Soane et al. 2012; Tamburini et al. 2016). Such intense management leads to more simplified landscape composition, providing less support for the survival/development of natural enemies in terms of the quantities/qualities of habitats and the availability of additional prey (Bianchi et al. 2006; Chaplin-Kramer & Kremen 2012; Rusch et al. 2013).

Apart from the anthropogenic influences, the performance of natural pest control service is also influenced by numerous complex biotic and abiotic factors, including the crop-pest-natural enemy interactions (Coll 2009), soil characteristics (Irmler 2003; Holland & Luff 2000), weather and climate change (Thomson et al. 2010; Ewald et al. 2015).

1.4.3 Methods to promote natural enemies

To mitigate/minimize the negative effects of agricultural intensification on the natural pest regulation in arable fields, many farming practices have been proposed, investigated, and promoted by researchers and policymakers (Dicks et al. 2016).

Reducing the disruption of insecticides on natural pest control in the fields (e.g., selecting more targeted chemicals, minimising application intensities) is among the best studied practices (Dicks et al. 2016), and is also one of the key aims of IPM (Barzman et al. 2015; for detailed strategies see Section 1.5.2). Reduced tillage could be beneficial for the development of vegetation- and ground-dwelling natural enemies and their pest control abilities (Tamburini et al. 2016; Rivers et al. 2016). Some pest-resistant crop cultivars were also linked with enhanced predation/parasitism by natural enemies (Cai et al. 2009).

As an important tool to conserve biodiversity, agri-environment schemes (AES) have provided financial support for EU farmers to establish/manage semi-natural habitats on their farmland (Batáry et al. 2015). These measures have shown positive effects on conserving natural enemies and promoting natural pest regulation in arable fields (Holland et al. 2016): e.g., cover crops (Tillman et al. 2004), beetle banks (Collins et al. 2002), and wildflower strips (Tschumi et al. 2016).

1.4.4 Knowledge gaps in economic valuation of natural pest control service

Apart from searching for effective methods to enhance natural pest control service for agricultural production, estimating the economic benefits of this ecosystem service is an important way to quantify its contribution to human welfare, encourage farmers to implement a more sustainable pest management approach, and guide policymakers in supporting relevant initiatives (Braat & de Groot 2012; Schaefer et al. 2015).

However, few studies have estimated the economic value of natural pest control service (Bengtsson 2015; Naranjo et al. 2015). To the best of our knowledge (Table 1 in Naranjo et al. 2015), there are only 11 peer-reviewed studies involving a total of four arable crops (wheat, barley, soybean, and cotton), 15 related pests, and six countries (US, Canada, Benin, Sweden, Denmark, and New Zealand). It is also difficult to compare the values among the few existing economic studies, because of the often significant differences in study locations, trophic relationships, input costs, data used, and modelling techniques. Thus the accumulated evidence base is insufficient to provide useful information/guidance for arable farmers and policymakers to promote this ecosystem service based on its economic contribution alone.

1.5 IPM: insecticides

1.5.1 Benefits of insecticides

As shown in Section 1.4, the efficacies of natural pest regulation in arable fields could be negatively influenced by numerous factors other than human intervention (e.g., climate change; Ewald et al. 2015). Thus insecticide application may be necessary when natural enemies fail to control pests. Indeed, selective insecticide use is one of the widely used tactics in IPM (Naranjo et al. 2015).

Insecticides are considered as an economic, labour-saving, and efficient tool for crop protection (Damalas & Eleftherohorinos 2011). They help to maintain/improve the quantity, quality, nutritional value, and cosmetic appeal of the agricultural produce (Cooper & Dobson 2007; Waterfield & Zilberman 2012; Popp et al. 2013). Consequently, insecticides can have numerous benefits, including the maintenance/improvement of food security, enhanced farmer income and income stability, consumers' health, and national agricultural productivity (Cooper & Dobson 2007; Damalas 2009; Bennett et al. 2010).

1.5.2 Strategic use of insecticides in IPM

However, IPM also recognizes the risks of using insecticides (e.g., side effects on natural enemies and other non-target species; Section 1.1). Indeed, one of the crucial aims in IPM is to use insecticides rationally and carefully to optimize their efficacies of pest control and minimize their side effects (Cooper & Dobson 2007; Barzman et al. 2015).

First of all, insecticides that are suitable to use in IPM are the ones with high selectivity and efficacy, low toxicity and side effects, and which support profits for farmers (Damalas & Eleftherohorinos 2011). Because of ongoing scientific progress in related disciplines (e.g., chemistry and molecular biology), more targeted and environmental friendly agrochemicals are becoming available (e.g., Pymetrozine, a pyridine azomethine compound, acts as a feeding inhibitor against homopteran insects; Harrewijn & Kayser 1997; Damalas & Eleftherohorinos 2011; Gill & Garg 2014; Barzman et al. 2015). Stricter legislations on insecticide registrations also help provide a better guarantee that the products available in the market fulfil these criteria (e.g., from 1993 to 2008, about 704 active substances were banned in the EU, among which 26% were insecticides; Karabelas et al. 2009; Fig 1.4).

Since the first launch in the 1990s, neonicotinoids have become the fastest expanding insecticidal chemical group for crop protection, owing to their high selectivity towards insect pests (targeting the insect nicotinic acetylcholine receptor), systemic and translaminar action (meaning the chemicals can be distributed in the plant tissues from roots/leaf lamina), and versatile application methods (e.g., foliar sprays, seed treatments) (Jeschke et al. 2010). However, over the past decade, increasing evidence has shown neonicotinoids can have lethal and sub-lethal impacts on both managed and wild pollinators (e.g., through field-realistic exposure, thiamethoxam was found to impair bumblebees' (*Bombus* spp.) learning and memory; Stanley et al. 2015; EASAC 2015; IPBES 2016). European Food Safety Authority ruled in 2012 that neonicotinoids posed an "unacceptable" danger to bees which led to a temporary restriction on the three active ingredients (clothianidin, imidacloprid and thiamethoxam) on flowering crops by the European Commission in December 2013 (EC 2013) and which is likely to be extended (PAN 2017).

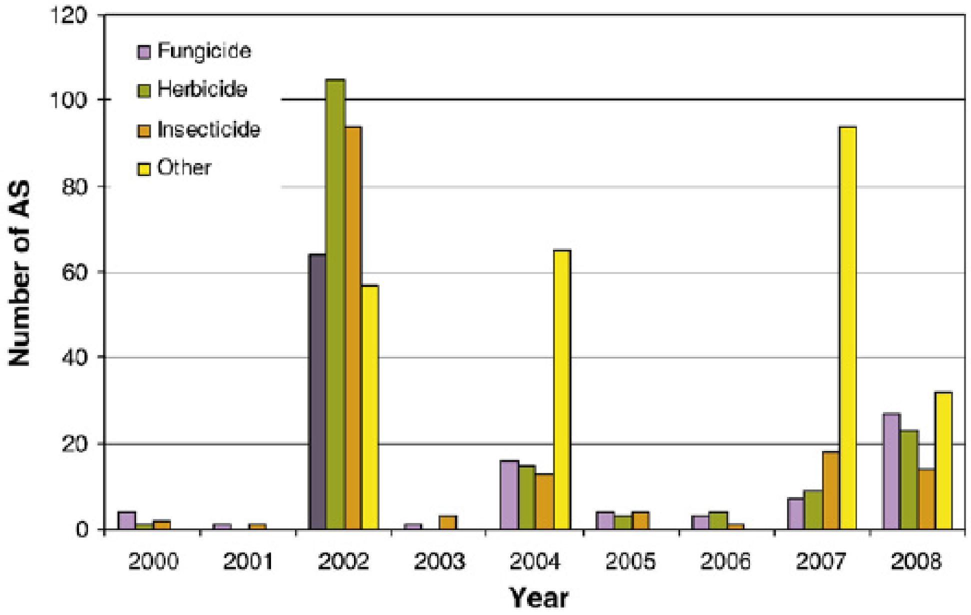

Fig 1.4. Number and type of existing active substances (AS) withdrawn from Annex I of EU Directive 91/414

This figure is modified from Karabelas et al. (2009).

Whether to apply insecticides to a crop field should be based on the potential risks of pest damage toward that crop. As shown in Section 1.2, some countries have built up extensive pest monitoring systems to support local farmers for their pest control decision-makings; this has been shown to reduce the pesticide frequencies in arable crops (Kudsk &

Jensen 2014). Action thresholds (applying insecticides when the threshold level of pest infestation is reached so as to prevent subsequent crop damage) are also under development to provide guidance for farmers/advisors to decide the necessity of chemical treatments in arable fields (Nault & Anthony 2010; Hallett et al. 2014; Barzman et al. 2015).

Timing of insecticide applications is also an important consideration. Researchers have identified the need to consider the phenology of beneficial species (natural enemies, pollinators) to reduce the disruption of applications toward their development and activities (Gill & Garg 2014; Roubos et al. 2014). Weather conditions may also influence the effectiveness of insecticidal treatments (e.g., high wind speeds may deposit chemicals off the target crops and cause more drifting problems; Gill & Garg 2014).

To preserve the efficacies of existing insecticides, it is also of vital importance to reduce the development rates of insecticide resistance in pests; indeed, this is one of the main initial drivers for the development of IPM (Fig 1.5; Barzman et al. 2015). Besides reducing the unnecessary doses and frequencies of applications, alternating insecticides with different mode of actions is also highly recommended to reduce the development of resistance (Bass et al. 2015). The Mode of Action classification scheme developed by the Insecticide Resistance Action Committee provides a platform to identify potential alternation options (Sparks & Nauen 2015).

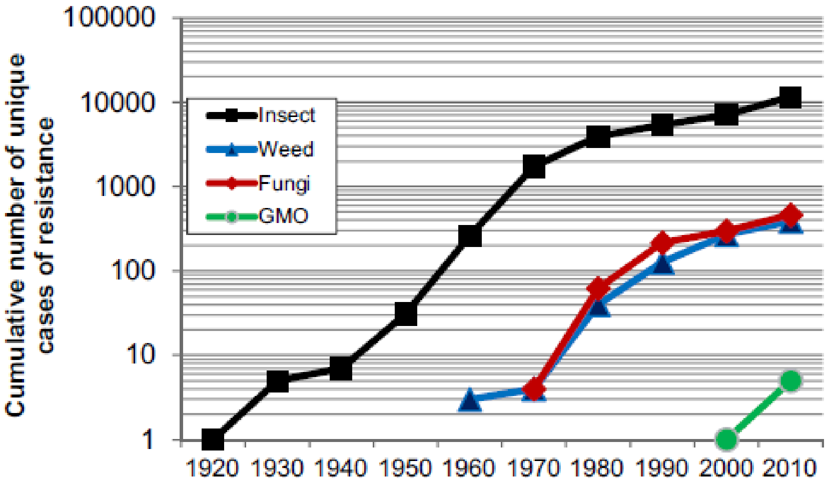

Fig 1.5. Cumulative increase in the number of individual cases of resistance for insecticides, herbicides and fungicides

This figure is modified from Sparks & Nauen (2015).

1.5.3 Knowledge gaps in insecticides efficacies and side effects

The key criteria for the use of insecticides in IPM are to maximise/maintain their pest control efficacies, and to minimise their negative impacts on the environment and non-target species. However, despite ongoing efforts from researchers and policymakers, fundamental knowledge gaps regarding the efficacies and side effects of available insecticidal formula still exist, which brings uncertainties and risks when selecting chemicals for crop protection in IPM.

For example, for aphid control in UK oilseed rape in 2014, seven active ingredients were authorised (five belong to the chemical group pyrethroids, and one each from carbamates and neonicotinoids) (BCPC 2014; IRAC 2017). However, although pest control efficacies differ among chemical groups, and even among active ingredients within the same chemical group (Šmatas et al. 2012), there is little publicly available information concerning their relative up-to-date efficacies (taking into account resistance development) for pest control (Elbert et al. 2008; Godfray et al. 2015), and even less about their relative impacts toward oilseed rape yields and farmer profits (Budge et al. 2015).

Similarly, little is known about which formula cause more overall side effects toward non-target species and the wider environment. A few reviews have summarized the updated negative impacts of some widely used chemical groups (e.g., for neonicotinoids see EASAC 2015; van der Sluijs et al. 2015; Bonmatin et al. 2015; IPBES 2016); however, to our knowledge, none have managed to compare the overall side effects among different chemical groups or active ingredients.

1.6 IPM: farmer participation

1.6.1 Importance of farmer participation in IPM

Despite the efforts of researchers and policymakers to promote IPM in the agricultural production, and the number of studies showing that IPM could bring long-term economic, health, and environmental benefits to farmers and the society (Ehler 2006; Lefebvre et al. 2015; Barzman et al. 2015), the worldwide adoption rate by farmers is hard to quantify but is thought to remain low (Ehler 2006; Peshin 2013; Parsa et al. 2014)Researchers have highlighted a lack of consideration of farmers’ perception and behaviours towards IPM practices when designing and promoting this approach (Meir & Williamson 2005), and asked: 'Why should farmers follow an agenda which has been created by scientists for scientists?' (Morse & Buhler 1997). Indeed, like other agricultural-related policies, the wider adoption of IPM in arable farming depends on strong farmer motivation and participation, which is also an important element in the IPM regime (Lefebvre et al. 2015; Barzman et al. 2015).

1.6.2 What influence farmers' pest management decision-making

When considering which pest management strategies to use, farmers' decision-making is influenced by a set of complex factors.

First of all, they usually consider how much they will benefit from adopting a certain pest management technique, based on implications for input costs (e.g., machineries, agrochemicals), management costs (e.g., time spent on pest control depending on the complexity of techniques), and influence on the final products (e.g., crop yields and qualities) (Lefebvre et al. 2015). Indeed, farmers tend to adopt new farming strategies only if they work better than current practices (Hillocks 2012). IPM related techniques were found to be more complex to adopt than traditional insecticide application (Shojaei et al. 2013), and there is still a lack of quantitative data regarding their contribution to farm profits (Lefebvre et al. 2015).

Farmers' perception of risk greatly influences their behaviour in pest management, especially the risk of pest damage and subsequent financial losses (Park et al. 1997; Milne et al. 2016). Farmers tend to be more risk adverse toward new and unfamiliar techniques such as IPM (Lefebvre et al. 2015), but those with more income may have more financial flexibility to invest in alternative pest management (Cullen & Warner 2008; Waterfield & Zilberman 2012). Past experiences with pest damage in the field (especially when heavy losses occurred) can also influence farmers' risk perspectives and pest control behaviour in the current growing season (Meir & Williamson 2005).

Farmers' risk perspectives also include potential health hazards and environmental pollutions from insecticide exposure (Cuyno et al. 2001; Khan & Damalas 2015). Personal experience of health problems from agrochemicals can lead to more careful and less intense applications (Meir & Williamson 2005). Studies have also found that farmers with greater income and higher education tend to have more environmental awareness and may be willing to learn and use more ecologically benign techniques like IPM (Rahman 2003; Poppenborg & Koellner 2013).

Individual knowledge level is also an important factor. Studies show that by gaining more awareness and knowledge of the existence and role of natural enemies in the fields, farmers become more likely to adopt alternative pest control techniques (Segura et al. 2004; Wyckhuys & O'Neil 2007). See Table 1.2 for other potential influences on farmers' pest control decision-making.

Table 1.2 Factors affecting farmers' pest control decision-making

Factors	Examples
Expectations, needs and desires	Ability and need to minimize risk; desire to keep fields 'clean'; need to conform to specifications laid down by external agents
Experience and perception of biophysical conditions	Past experience and current expectations of climatic conditions; past experience of losses associated with pest problems
Knowledge, belief and experience of pest management strategies	Knowledge of pest causing the perceived problem; experience of efficacy and cost of pest control methods
Perception of pesticides	Perception of the efficacy and necessity for pesticides; personal exposure to the consequences of pesticide misuse
Availability of resources	Timely availability of and access to pest control inputs; comparative and opportunity cost of labour; availability of and perceived trustworthiness of advice
Market related factors	Potential market prices; market demands in terms of quality or specifications
Opinions and information from others	Opinions and information from family and friends; neighbours' pest management strategies and their perceived success; influence of pesticide advertising

Note: this table is modified from Meir & Williamson (2005).

1.6.3 Knowledge gaps in farmers' incentives to use IPM in arable crops

As shown in Section 1.6.2, the low adoption rate of IPM by farmers could be due to the uncertainties of cost effectiveness, lack of knowledge, complexity of techniques, and intensity of management. However, it is only recently that farmers' perceptions and participation has become an important part of IPM research, and few studies have systematically analysed the potential drivers of IPM adoption by farmers (Meir & Williamson 2005; Lefebvre et al. 2015). Because IPM is a complex regime involving multiple approaches, arable farmers may only be able to adopt new pest control practices piecemeal over time (Lamine 2011; Barzman et al. 2015). It is thus important to first understand the incentives for adopting key IPM principles and elements in arable fields.

For example, promoting natural pest control service in the fields is a fundamental principle in the IPM regime, and this ecosystem service could positively contribute to arable crop production (Section 1.4); however, little research has assessed whether this ecosystem service is important from arable farmers' perspectives (Segura et al. 2004). To our knowledge, no studies have analysed the influence of farmers' perceptions of natural pest control on their decision-making in promoting this ecosystem service.

1.7 Aim and objectives

The overall aim of this thesis is to provide better evidence and information to help promote integrated pest management in arable crop production. Specifically, it focuses on three objectives based on the knowledge gaps addressed in this chapter:

1) Estimating the economic values of natural pest control service in arable crops;

2) Comparing experts' perceptions of the pest control efficacies and side effects of available insecticides for major pests in arable crops;

3) Analysing the potential factors which influence farmers' incentives to adopt key components in IPM for arable crop protection.

Each of the above objectives is addressed by a case study, forming the three main chapters of this thesis, with the structure of each chapter as follows:

Chapter 2 presents the work which estimates the economic values of predators and parasitoids to control summer grain aphid (*Sitobion avenae* Fabricius) in wheat (*Triticum* spp.) in South East England, based on a natural enemy exclusion experiment and economic surplus model. It takes into account the influences of different pest infestation levels on the efficacies of natural pest regulation. By incorporating different levels of insecticidal application intensity, the analyses of the potential contribution of using action threshold-based method towards the economic values of this ecosystem service are also presented. By conducting a set of sensitivity analyses, it explores how the changes in insecticidal input costs and wheat price elasticities of supply and demand could affect the values.

Chapter 3 presents the work which compares the perceived insecticide efficacies, side effects and alternatives for the arthropod pest control in UK oilseed rape (*Brassica napus*), based on a UK-wide online survey among relevant agronomists and entomologists. Based on expert opinions, the perceived pest control efficacies for key pests among available chemical groups for the 2013/14 growing season are compared. It also compares the perceived negative impacts of two application methods (seed treatments and foliar sprays) on users' health, natural enemies, pollinators, soil and water. Using the Hazard Quotient method, the analyses of the potential risks of common foliar active ingredients used for UK oilseed rape protection on non-target arthropod species are also given. This chapter then presents the analyses that look at whether the experts in the survey support or oppose to the current neonicotinoid restriction, and the perceived influence of the restriction on oilseed rape production. This chapter also provides respondents' suggestions on the alternative pest management strategies for future oilseed rape production in UK.

Chapter 4 presents the work which looks into European farmers' incentives to promote natural pest control service in arable crop fields, based on face-to-face interviews among arable farmers involved in an EU funded agri-environmental project across seven Member States. It presents the analyses of the perceived importance of natural enemies (species that target animal pests) for crop production. Respondents' relative preferences toward available habitat management options which could promote this ecosystem service are also given. With ordinal logistic regressions, the assessment of the potential factors influencing farmers' decisions on whether to promote natural pest control in their fields is provided. In particular, the focus is on how farmers' perceptions of natural pest control service influence their conservation actions. In parallel, the potential factors influencing farmers' decisions on using insecticides are analysed.

Then, focusing on the three objectives of the thesis, Chapter 5 summarises the key findings of Chapter 2-4 in the wider context, on which recommendations are based for further promoting integrated pest management in arable crop production. Finally, a critical evaluation of the methods used in the case studies is developed and potential opportunities for future work are highlighted.

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Chapter 2: Economic valuation of natural pest control of the summer grain aphid in wheat in South East England[*]

Abstract

Wheat (*Triticum* spp.) is the most important arable crop grown in the UK, and the grain aphid, *Sitobion avenae* Fabricius (Hemiptera: Aphididae), is one of the key pests of this crop, reducing yields through virus transmission in the autumn and feeding damage in the summer. Pyrethroid sprays are the dominant insecticides used to control the summer grain aphid, but resistance has been detected in the UK. Natural enemies could help suppress grain aphid and reduce the need for insecticide sprays, but no studies have evaluated the economic benefits provided by this natural pest control service within the UK context, which could help inform effective integrated pest management strategies. Based on a natural enemy exclusion experiment carried out in South East England, this study used an economic surplus model to estimate the values of predators and parasitoids to control summer grain aphid in wheat in this region. Incorporating three levels of spray intensity and three levels of pest infestation, the results of this model indicate that the annual economic value of natural pest control service was between £0 and £2.3 Million (2010-2014). These values are considered to be conservative due to the assumptions used in the model. Under the medium level of pest infestation, a 10% increase in the proportion of wheat fields that use the action threshold-based spray method would increase the value of natural pest control by 23% (£0.4 Million). 71% of the benefit would go to wheat farmers. However, the uncertainties in the price elasticities of supply and demand for wheat in South East England may influence this distribution. A potential increase in insecticide costs due to the development of resistance would also increase the value of natural pest control. These findings support growing efforts from policy-makers to promote this ecosystem service in agricultural landscapes.

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2.1 Introduction

Wheat (*Triticum* spp.) is the most widely cultivated crop in the UK, with ~2 million ha planted annually from 2010 to 2014, representing 42% of the total national arable cropping area and generating £2 billion in sales annually (DEFRA 2014; DEFRA 2015a). The grain aphid, *Sitobion avenae* Fabricius (Hemiptera: Aphididae), is one of the main insect pests in UK wheat production (Foster et al. 2014), acting as a potential vector of the barley yellow dwarf virus to the young seedlings sown during the autumn period and causing direct feeding damage through leaves and ears in the summer (Dewar et al. 2016). Indirect crop damage caused by the summer grain aphid is the secretion of honeydew during feeding, which provides a medium for sooty moulds that reduce the photosynthetic rate (Larsson 2005).

The dominant insecticides applied in wheat to control summer grain aphid are pyrethroid sprays. From 2010 to 2014, an average of 1.6 million ha of UK wheat was treated with pyrethroids annually, representing 92% of total insecticidal spray area for this crop (Garthwaite et al. 2010, 2012, 2014). However, since 2011, pyrethroid resistance has developed in the UK grain aphid (Foster et al. 2014; AHDB 2015). An alternative spray for aphid control has been pirimicarb (1.5% of total insecticidal spray area for wheat) (Garthwaite et al. 2010, 2012, 2014), however, its authorisations are set to end in July 2017 (Dewar et al. 2016; AHDB 2016a). These factors have caused concerns for the future of effective grain aphid control in UK wheat.

An alternative control mechanism for grain aphid infestation is provided by natural enemies present in the wheat fields, including predators (e.g., Carabidae), parasitoids (e.g., Aphidiinae), and pathogens (e.g., Entomophthorales). Many studies have demonstrated their importance for suppressing grain aphid damage in wheat production (Plantegenest et al. 2001; Schmidt et al. 2003; Thies et al. 2011; Safarzoda et al. 2014). Beyond direct pest control, the contributions of natural pest control include: reducing the rate of development of insecticide resistance in pests (Liu et al. 2014; Lefebvre et al. 2015), providing consumers with potentially healthier food containing fewer chemical residues (Baker et al. 2002; Florax et al. 2005), and reducing negative effects of insecticides on other ecosystem services (e.g., pollination, see Potts et al. 2016).

The effectiveness of natural pest control is influenced by various factors, many of which remain poorly understood and unquantified. Foremost, numerous studies have demonstrated that insecticides negatively affect the development and pest control abilities of natural enemies in croplands by killing or weakening non-target species (Geiger et al. 2010; Roubos et al. 2014). Subsequently, there have been recent policy and research interests in encouraging a reduction in the intensity of insecticide application, particularly by using the action threshold method (applying insecticides when the threshold level of pest infestation is reached so as to prevent subsequent crop damage) to control pests (Nault & Anthony 2010; Hallett et al. 2014; Barzman et al. 2015). While encouraging the natural pest control mechanism, this method recognizes the limits and risks of pest suppression by natural enemies alone, especially under heavy pest infestations (Collins et al. 2002; Kobayashi et al. 2011; Gupta et al. 2012). However, there remains little information on the extent of benefits that this method can have in enhancing natural pest control service in agriculture.

Estimating the economic benefits of an ecosystem service has been suggested as a method to quantify its contribution to human welfare, encourage farmers to implement a more sustainable pest management approach, and guide policy makers in supporting relevant conservation programs (Braat & de Groot 2012; Schaefer et al. 2015). Some attempts have been made to estimate the monetary values of natural pest control service (see Table 1 in Naranjo et al. 2015 as a summary). It is difficult to compare the values among economic studies, because of the often significant differences in study locations, trophic relationships, input costs, data used, and modelling techniques. However, few evaluations have been conducted on the wheat-grain aphid system (Porter et al. 2009), and to our knowledge, none on any crop-pest system within the UK context.

By expanding upon the economic surplus model developed by Letourneau et al. (2015), this study estimates the economic value of natural pest control of the summer grain aphid damage in UK wheat, while accounting for the influence of different intensities of insecticide input and levels of pest infestation. In particular, the potential contribution of the action threshold-based method towards the value of natural pest control is analysed. By conducting a set of sensitivity analyses, this study also quantifies the potential variation in the value from the uncertainties in the price elasticities of supply and demand, and the insecticide input costs. This study focuses on the summer grain aphid control by the related predators and parasitoids in the South East England. However, the model could potentially be used for other regions and crop-pest systems. This study focuses on the summer grain aphid control by the related predators and parasitoids in the South East England (including London; Fig 2.1). However, the model could potentially be used for other regions and crop-pest systems. The study region has a surface area of ~21,000 km^2, representing ~9% of the total area of UK. The annual wheat growing area in this region (2011-2014) is 233,000 ha, with 8t/ha of yields, and £306 million of production values (Table 2.2).

Fig 2.1. A map of England with South East region (including London) in red.

This figure is modified from https://commons.wikimedia.org/wiki/File:South_East_England_in_England.svg

2.2 Methods

2.2.1 Overview of economic surplus method

The economic surplus method is commonly used in economics to estimate the change in benefits and costs brought by a change in technology in a market setting (Alston et al. 1998). It is measured as the sum of consumer surplus (ΔCS, benefits that consumers would receive when the market price that they pay for a product is lower than the highest price they are willing to pay) and producer surplus (ΔPS, benefits that producers receive when they sell a product at a higher price than the cost of producing it). Assume Fig 2.2 represents the wheat market in South East England. The demand curve (*Demand*) denotes the relationship between wheat price and quantity that consumers are willing and able to purchase. The supply curve (*Supply 1*) is the relationship between product price and quantity that farmers are willing to produce. The intercept between the two curves represents an equilibrium point where the market price is set (P_0), with related wheat quantities produced (Q_0). Consumer surplus is represented by the area (A+B+C), and producer surplus (D+E).

Hypothetically, if there is a lack of natural enemies of the summer grain aphid in the wheat fields in South East England (i.e., natural pest control is at the minimum level), crop damage from grain aphid would be likely to occur (Östman et al. 2003), resulting in lower yields or increased insecticide input. Either of these two changes would increase the incremental cost of crop production, leading to a leftward shift of the supply curve (*Supply 2*), and a higher market price (P_1). Thus the economic surplus will fall (A+B+D) and the difference in economic surplus with and without natural pest control can be identified (C+E), capturing the value of this ecosystem service (Alston et al. 1998; Letourneau et al. 2015).

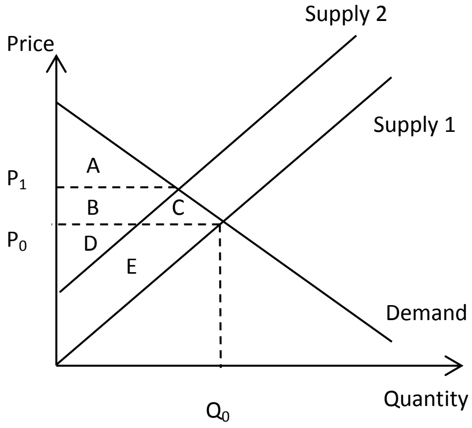

Fig 2.2. Framework of wheat market in South East England and the related measurement of economic surplus

2.2.2 Insecticide intensity and pest infestation levels

This study incorporated three levels of insecticidal application intensity of foliar sprays in the model: i) **no-spray**, where no foliar sprays are used to control grain aphid in the summer; ii) **action threshold-based spray** (AT), where insecticides are applied according to the action threshold of grain aphid in the fields (in the UK the action threshold is five aphids/tiller) (George & Gair 1979; Dewar et al. 2016); and, iii) **preventive spray**, where foliar sprays are always applied in the summer to prevent crop damage from grain aphid.

It is assumed that AT and preventive sprays can successfully control grain aphid damage to the extent that yield will not be influenced (Song & Swinton 2009; Letourneau et al. 2015). Thus, a lack of natural enemies could result in a yield reduction in no-spray fields, and insecticide increase in AT fields, but would not influence preventive spray fields. The potential influence on the supply shift (From *Supply 1* to *Supply 2* in Fig 2.2, denoted as *K*) by exclusion of natural pest control in the wheat fields can therefore be derived as follows (Eq. 1). It is estimated as a weighted average influence from the potential yield reduction in the no-spray fields, and insecticide increase in the AT fields. For a detailed model refer to Letourneau et al., 2015 (p217, Eq. 3).

$$K = \sigma_{no-spray} I_{no-spray} + \sigma_{AT} I_{AT} \qquad \text{(Eq. 1)}$$

where K denotes the supply shift parameter, $\sigma_{\text{no-spray}}$ and σ_{AT} denote the percentage of wheat fields that use no-spray and AT methods respectively, and $I_{\text{no-spray}}$ and I_{AT} denote the influence on the supply shift by an exclusion of natural pest control in the no-spray and AT fields respectively.

The influence on the supply shift also depends upon the level of pest infestation in the fields, which will fluctuate naturally. Therefore, expanding upon Letourneau et al. (2015), three pest infestation levels were used to capture this uncertainty (Fig 2.3):

1. **Low infestation level**: under this level, grain aphid density would be lower than the action threshold (five aphids/tiller) even with a lack of natural enemies in the fields. Thus, no subsequent yield reduction would occur in the no-spray fields, and no related increase of insecticidal sprays would be needed for AT fields. In this case K=0.

2. **Medium infestation level**: under this level, grain aphid density would be lower than the action threshold if natural enemies are present in the fields, but would be higher if natural enemies are lacking. Thus, without natural enemies, related yield reduction would occur in the no-spray fields, and insecticide costs would be increased in AT fields. In this case $K=\sigma_{\text{no-spray}}I_{\text{no-spray}}+\sigma_{\text{AT}}I_{\text{AT}}$.

3. **High infestation level**: under this level, grain aphid density would exceed the action threshold even with natural enemies in the fields. However, compared with the no-spray fields where natural enemies are present, those without such pest control mechanism would harvest less wheat. As for the potential insecticide input change in the AT fields, because the average annual number of insecticidal spray rounds applied to UK wheat (2010 to 2014) was one (Garthwaite et al. 2010, 2012, 2014), we assumed that when aphid density exceeds the action threshold, one spray round at the recommended dose would be sufficient to control the pest. Thus, under this level, insecticide input would remain the same (one spray round) regardless of the level of natural pest control in the wheat fields. $K=\sigma_{\text{no-spray}}I_{\text{no-spray}}$.

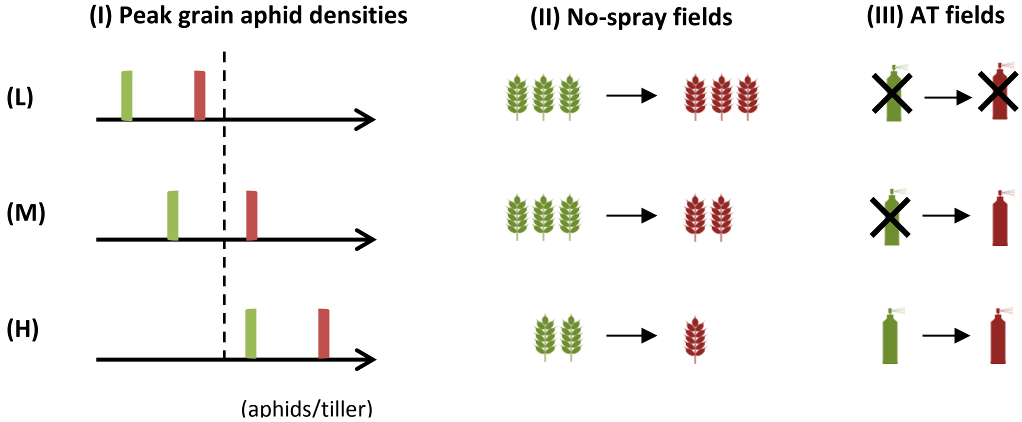

Fig 2.3. Conceptual model of (I) peak grain aphid densities (aphids/tiller), (II) the related levels of crop yields in the no-spray wheat fields, and (III) the related levels of insecticidal spray inputs in the action threshold-based (AT) wheat fields, under the (L) low, (M) medium, and (H) high pest infestation levels in South East England.

Colour green and red denote the presence and absence of related natural enemies respectively. In the column I: the dotted line denotes the action threshold of grain aphid control; the coloured solid lines denote the amount of peak grain aphid densities; the distance between the green and red lines represents the difference of the peak grain aphid densities with and without natural pest control in the wheat fields. In the columns II and III, the amount of wheat grain and spray symbols represent a rough measure of the level of crop yields and spray inputs respectively. In column III, the black cross symbol denotes that no spray is required.

Economic surplus (ΔES) is estimated as follows (Eq. 2-5) (Letourneau et al. 2015):

$$Z = K\varepsilon/(\varepsilon + \eta) \quad \text{(Eq. 2)}$$

$$\Delta CS = ZQ_0P_0(1 + 0.5Z\eta) \quad \text{(Eq. 3)}$$

$$\Delta PS = Q_0P_0(K - Z)(1 + 0.5Z\eta) \quad \text{(Eq. 4)}$$

$$\Delta ES = \Delta CS + \Delta PS \quad \text{(Eq. 5)}$$

where η denotes the absolute value of the price elasticity of demand for wheat in the South East England, and ε the price elasticity of supply. ΔCS consumer surplus, and ΔPS producer surplus. The price elasticity of demand is a measure of the responsiveness of the quantity demanded by consumers of that good to changes in its price. It is defined as the percentage change in quantity demanded that results from a one percent change in the price. The demand for a good is elastic relative to the price if the absolute value of demand elasticity is greater than one, and inelastic if less than one. The price elasticity of supply is the analogous measure on the producers' side.

2.2.3 Modelling of $I_{\text{no-spray}}$

Data for the analyses of yield response changes with and without natural enemies in no-spray fields ($I_{\text{no-spray}}$ in Eq. 1) was derived from a field experiment conducted as part of the European Union (EU) funded LIBERATION (Linking farmland biodiversity to ecosystem services for effective eco-functional intensification, www.fp7liberation.eu) project. 16 conventional winter wheat fields (minimum distance of 1 km apart) were selected in Oxfordshire and Berkshire, in South East England. At the edge of each field site, an experimental treatment plot of 15 × 14 m was established. All plots were managed conventionally with application of plant protection products as normal except that they received no foliar application of insecticide.

Levels of aphid control by natural enemies in each of the plots were measured using cage experiments, using a methodology adapted from Rusch et al. (2013). At around GS50 BBCH, approximately 50-100 grain aphids were introduced to two experimental areas within each plot. The aphid population was left to establish for 10 days before one was randomly selected for an open treatment and one had a field cage placed over the aphid population to exclude both aerial and ground dwelling natural enemies. Cages with 5 × 5 mm plastic mesh net (30 cm diameter and 100 cm high) and a solid metal cylinder base were dug 10 cm into the soil to prevent ground-dwelling predators from entering the cages. To prevent flying predators, cages were sprayed with sticky glue. An initial count of aphids in the open and caged area was made at cage establishment. After 5 days the plots were again visited and a second aphid count was carried out.

Expected wheat yield loss response due to grain aphid damage was taken from a Swedish study (Larsson 2005):

$$Y = 4.5\ ln(A) - 5.5\ (R^2 = 0.97) \qquad \text{(Eq. 6)}$$

where A is the number of peak grain aphids per tiller, and Y is the percentage yield loss (%) due to aphid damage in winter wheat. Eq. 6 was used for this study because the estimated economic injury level (lowest number of insects that causes economic damage) is similar to the action threshold suggested to control summer grain aphid in the UK wheat (four and five aphids/tiller respectively). Also, this yield damage represents the summer grain aphid damage (direct feeding and indirect honeydew).

To use Eq. 6 to estimate the relative yield response with and without the contribution of natural enemies in the fields ($I_{\text{no-spray}}$ in Eq. 1), the relationship between the peak aphid densities with and without natural enemies was needed. Data collected from the cage experiments were used to estimate this relationship. It was assumed that the relationship at the second aphid count in the cage experiments represented the situation at the peak aphid dates. It was also assumed that this experiment represents a normal level of natural pest control in South East England, and that pest densities can always be reduced by natural enemies:

$$A_{without} = 1.96A_{with} + 1.65\ (R^2 = 0.58) \qquad \text{(Eq. 7)}$$

where A_{with} denotes the peak aphid density (aphids/tiller) with natural enemies in the fields, $A_{without}$ denotes the peak aphid density with a lack of natural enemies.

From Eq. 6 and Eq. 7, the estimated peak aphid densities (A) and percentage yield loss (Y) in relation to a change in natural enemies were displayed (Table 2.1). It showed that with a normal level of natural pest control in the wheat fields: low pest infestation level is when the peak aphid/tiller is zero or one, medium level is when peak aphid/tiller reached two to four, and high level is when peak aphid/tiller is five or higher. Because grain aphid density in England normally lies below five (Holland & Oakley 2007; Dewar et al. 2016), we only included five and six aphids/tiller in the high infestation scenario.

Table 2.1. Estimated peak aphid densities and yield reductions in relation to a change in natural enemies in the wheat fields in South East England.

Peak grain aphid densities (number/tiller)		Percentage yield losses (%)	
Without NE[1]	With NE	Without NE	With NE
2	0	0	0
4	1	0	0
6	2	2	0
8	3	4	0
9	4	5	0[2]
11	5	6	2
13	6	6	3

Note: 1. NE = natural enemies; 2. this value amounts to <1% so is treated as no damage.

2.2.4 Derivation of indicator values

For each pest infestation level, we estimated an average annual economic surplus value of natural pest control of the summer grain aphid in South East England for the years 2010 to 2014 using a number of indictors (see Table 2.2). Wheat crop prices (£/ha) were inflated according to the Consumer Price Index (CPI), taking 2014 as a base year (ONS 2016). For the related insecticide increase (I_{AT} in Eq. 1), data from Nix (2010-2014) and ABC (2010-2014) were combined to take into account price changes in chemical, labour, machinery and fuel costs. To estimate the proportion of no-spray wheat fields in South East England ($\sigma_{no\text{-}spray}$ in Eq. 1), the average percentage of organic wheat fields in England for the past five years (2010 to 2014) was used as an estimation (DEFRA 2016a). To estimate the proportion of AT fields (σ_{AT} in Eq. 1), we assumed that the average percentage of wheat fields without insecticide sprays from 2010 to 2014 represented the sum of no-spray and AT fields, thus achieving estimates for the proportion of AT fields (Garthwaite et al. 2010, 2012, 2014). Because little regional or national price elasticity (ε and η in Eq. 2) information was available for UK wheat production, estimations for the EU15 (the 15 member countries, including UK, in the European Union prior to the accession of ten candidate countries on 1 May 2004) were used (Haile et al. 2015; FAPRI 2016).

Table 2.2. Indicators of economic surplus model

Region: South East England	2010	2011	2012	2013	2014
Wheat areas (1000 ha)^1	240	243	248	197	237
Wheat yields (t/ha)^1	8	8	7	7	9
Wheat quantities (Million t)^1	1.9	2.0	1.7	1.4	2.1
Wheat prices (£/t)^2	169	173	209	164	133
Wheat production value (Million £)	321	346	355	230	279
Insecticide input (£/ha)^3	20	21	16	16	18
Proportion of no-spray fields (%)^4	0.8	0.8	0.8	0.8	0.8
Proportion of AT fields (%)^5	37	37	37	37	37
Absolute value of demand elasticity^6	0.3	0.3	0.3	0.3	0.3
Supply elasticity^6	0.12	0.12	0.12	0.12	0.12

Note: 1. From DEFRA (2015b); 2. Average ex-farm prices between milling and feeding wheat in the South East England (AHDB 2016b), inflated using 2014 as base year (ONS 2016); 3. Estimated from Nix (2010-2014) and ABC (2010-2014), inflated using 2014 as base year (ONS 2016); 4. Estimated from DEFRA (2016a); 5. Estimated from Garthwaite et al. (2010, 2012, 2014), and AT = action threshold-based spray; 6. Estimated from Haile et al. (2015) and FAPRI (2016).

2.3 Results

The annual average economic benefits provided by the natural pest control of summer grain aphid in wheat in South East England (2010-2014, with 2014 as base year) were: £0 under the low pest infestation level, £2.3 Million (standard deviation £0.4 Million) under the medium level, and £0.8 Million (standard deviation £0.1 Million) under the high level (Fig 2.4).

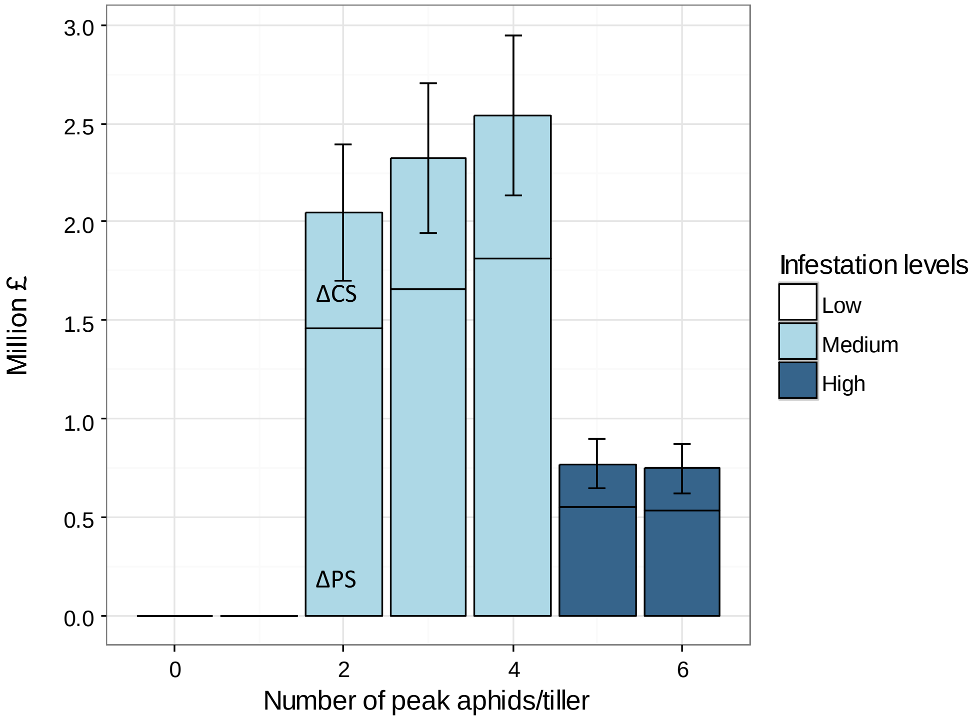

Fig 2.4. Economic surplus values of natural pest control for summer grain aphid in wheat in South East England.

The blue bars denote average economic surplus (Million £) from 2010 to 2014 (2014 as base year), and the error bars denote related standard deviations. For each bar, the section above the horizontal line denotes consumer surplus (ΔCS), and below producer surplus (ΔPS). There were no values for the low infestation level (where pest densities were 0-1 aphids/tiller).

Focusing on the medium pest infestation level and keeping the proportion of no-spray fields constant (0.8%), with a 10% increase in the proportion of AT fields in South East England (σ_{AT} in Eq. 1), the economic surplus value of natural pest control (ΔES) would increase by ~£0.4 Million (average annual value of the peak aphid densities of 2-4 aphids/tiller from 2010 to 2014, with base year 2014) in the region. This equates to an average value increase of 23.4% (standard deviation 15.6%) (Fig 2.4). This shows that using the AT strategy to control summer grain aphid can positively contribute to the economic benefits provided by natural enemies. To interpret it more easily, we defined an 'AT contribution ratio' $\alpha = P_{ES}/P_{AT}$ (where P_{AT} denotes the percentage increase in the σ_{AT}, i.e., 10%, and P_{ES} denotes the subsequent average percentage change in the economic surplus). Thus the AT contribution ratio is 2.3, meaning that with a 10% increase in the proportion of AT wheat fields in South East England, there would be an average 23% increase in the economic surplus value of natural pest control of the summer grain aphid in this region.

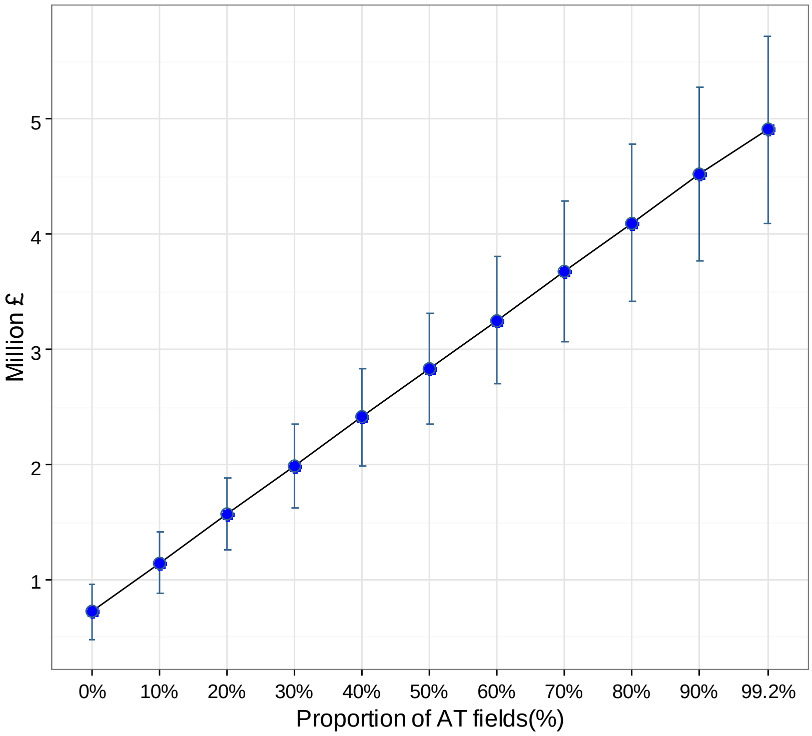

Fig 2.5. Economic surplus values of natural pest control of summer grain aphid in wheat in South East England with a change in the proportion of action threshold-based (AT) fields while keeping other indicators constant, under the medium pest infestation level.

The blue dots denote average values (Million £) of peak aphid densities of 2-4 aphids/tiller, from 2010 to 2014 (2014 as base year), and the error bars denote related standard deviations.

The share of benefits that producers (i.e., wheat farmers) would achieve from natural pest control service in their fields is an important consideration in encouraging them to adopt the AT method (Östman et al. 2003). This could be reflected in the proportion of producer surplus (%PS), which is determined by the price elasticities of supply and demand (ε and η respectively):

$$\%PS = \frac{\Delta PS}{\Delta ES} = \frac{\eta}{\varepsilon+\eta} \qquad \text{(Eq. 7)}$$

As for consumers (i.e., wheat processing companies that purchase wheat from farmers), because the proportion of surplus they would achieve from natural pest control service is determined by price elasticities (1-%PS; Eq. 7), their benefits would be enhanced with the increasing percentage of AT wheat fields in South East England (Fig 2.4 & 2.5). Thus consumers would generally benefit from farmers adopting the AT strategy in the fields, unless their share of benefits becomes close to zero (when the absolute value of demand elasticity is close to infinite, i.e., perfect elastic; or supply elasticity is close to zero, perfect inelastic).

Because little information is available on the wheat price elasticities of supply or demand within the UK context, their variations can potentially influence the economic surplus, proportion of producer surplus, and AT contribution ratio. Under the AT method, variation in the insecticide input costs (reflected in the I_{AT} in Eq. 1) could also influence these values. Thus, for the above mentioned indicators, we conducted a set of sensitivity analyses to compare their influence on the outputs, by decreasing and increasing their current values (see Table 2.2) by 10% respectively, while keeping other indicators constant (Table 2.3).

Table 2.3. Sensitivity analyses of the influence of the price elasticity of supply (ε), absolute value of price elasticity of demand (η), and insecticide costs on the economic surplus (ΔES), proportion of producer surplus (%PS), and AT contribution ratio (α).

ε	η	ΔES (Million £)	%PS (%)	α
-10%	--	2.4 (0.4)	73.5	2.2 (1.4)
0.12	0.3	2.3 (0.4)	71.4	2.3 (1.6)
+10%	--	2.2 (0.4)	69.4	2.5 (1.7)
--	-10%	2.3 (0.4)	69.2	2.3 (1.6)
0.12	0.3	2.3 (0.4)	71.4	2.3 (1.6)
--	+10%	2.3 (0.4)	73.3	2.3 (1.6)
Insecticide input (£/ha)		ΔES (Million £)	%PS (%)	α
-10%		2.1 (0.4)	71.4	2.2 (1.4)
Baseline		2.3 (0.4)	71.4	2.3 (1.6)
+10%		2.5 (0.4)	71.4	2.5 (1.7)

Note: α= P_{ES}/P_{AT} (where P_{AT} denotes the percentage increase in the proportion of action threshold-based (AT) wheat fields, i.e., 10%, and P_{ES} denotes the subsequent average percentage change in the economic surplus (ΔES) of natural pest control of summer grain aphid in wheat in South East England); ΔES and α are average values of peak aphid densities of 2-4 aphids/tiller, from 2010 to 2014 (2014 as base year), and the numbers in the brackets denote related standard deviations; for insecticide input, 'Baseline' denotes the respective values from Table 2.2.

Keeping other indicators constant, with a 10% increase in the supply elasticity (from 0.11 to 0.12, and from 0.12 to 0.13), the economic surplus value of natural pest control of summer grain aphid in wheat in South East England would decrease by an average of 4% (from £2.4 to 2.3 Million, and from £2.3 to 2.2 Million). The proportion of producer surplus would decrease by 3%, and the AT contribution ratio would increase by 7%. On the other hand, a 10% increase in the absolute value of demand elasticity (from 0.27 to 0.3, and from 0.3 to 0.33) has little influence on the economic surplus or the AT contribution ratio, but it would increase the benefit share to producers by 3%. A 10% increase in the insecticide costs would not influence the proportion of producer surplus, but it would increase the surplus value and the AT contribution ratio by 9% and 7% respectively.

2.4 Discussion

By using an economic surplus approach, this study estimated the annual value of natural pest control of the summer grain aphid in wheat in South East England to be £0-2.3 Million, depending on the levels of pest infestation (base year 2014). To our knowledge, this is one of the first attempts to conduct economic evaluation on this ecosystem service within a UK context (Naranjo et al. 2015). It is also among the first studies to estimate the economic contribution of natural pest control on wheat, one of the most widely grown crops in the UK and many other countries (Sandhu et al. 2015). This research only focused on the control of summer grain aphid damage by natural enemies present in the wheat fields. However, the same natural enemies could potentially provide further crop protection by consuming other related pests (e.g., rose – grain aphid, *Metopolophium dirhodum*) (Holland & Oakley 2007; Dewar et al. 2016). Thus the economic benefits provided by these natural enemies could potentially by higher.

The lowered monetary value of natural pest control under high pest densities reflected that the economic contribution of this ecosystem service could be limited by the level of pest infestation (Fig 2.4). This resulted because, under the high pest infestation level, natural enemies would not be capable of maintaining grain aphid populations below the action threshold (Fig 2.3; Collins et al. 2002; Kobayashi et al. 2011; Gupta et al. 2012). Following a similar hypothesis, Zhang & Swinton (2012) also estimated that the economic value of natural enemies to control the soybean aphid, *Aphis glycines* Matsumura, in five Midwestern US states would be lower in years with greater pest densities. This model assumed a linear relationship between the peak grain aphid densities with natural enemies in the wheat fields and those without (Eq. 7). However, higher pest densities could potentially increase the probabilities of natural enemies encountering their prey, thus increase the efficacy of natural pest control. Indeed, by conducting field cage experiments, Safarzoda et al. (2014) found that grain aphid in the closed plots (i.e., excluding natural enemies) reached 1-5 aphids/tiller, while in the open plots they remained <=0.03 aphids/tiller (as compared to Table 2.1). Thus our study could have adopted a conservative estimate of the crop protection ability of natural enemies, hence a conservative economic surplus value of this ecosystem service.

Under the current UK situation, it could be expected that low and medium grain aphid infestation levels are more common than high level (Holland & Oakley 2007; Dewar et al. 2016). However, future climate change may increase the inter-annual variation in grain aphid abundance and its related natural enemies, and the predator-prey relationships. Increasing average temperature could have a positive effect on the population growth of grain aphid (Ciss et al. 2014); however, it may also increase the predation rate by related natural enemies (Sentis et al. 2012; Khan et al. 2016). On the other hand, higher precipitation/temperature seasonality may inhibit aphid activities and facilitate natural pest control in the fields (Diehl et al. 2013).

This study illustrated that using an action-threshold (AT) spraying strategy to control grain aphid could enhance the economic benefits provided by natural enemies in wheat fields, which is one of the main aims of integrated pest management (IPM) promoted by the EU (EU 2009). The model assumed a near-linear relationship between the proportion of AT wheat fields and value of natural enemies (Fig 2.4). However, in a real situation, the increase in the AT fields could potentially enhance the efficiency of natural pest control, due to the reduced disturbance from insecticides in neighbouring fields (Furlong et al. 2004; Dasgupta et al. 2007). Thus the contribution of the AT method towards the value of natural pest control could potentially be higher.

Little data is available on the adoption rate of AT method for a certain crop-pest system (but see Song & Swinton 2009). The LEAF (Linking Environment and Farming) Marque is an environmental assurance system recognising sustainably farmed produce, where the certified farm businesses are required to follow a set of nine management principles, including IPM (LEAF 2016). Similar to 2013, ~5% wheat fields in UK were managed by this system in 2014 (LEAF 2015). However, from 2013 to 2014, a 10% increase has been achieved for the total UK croplands grown by these businesses. It is thus reasonable to assume that the proportion of wheat fields using AT strategy to control summer grain aphid has grown beyond 5% in the UK, and that it has potential to increase.

Under the AT method, the contribution of natural pest control service is also reflected by the related reduction of insecticide input. If insecticide costs become more expensive to control the same level of pest infestation, the economic value of this ecosystem service will increase accordingly (Table 2.3). Increasing insecticide costs are possible due to the development of insecticide resistance in grain aphid in the UK (Foster et al. 2014), which might require additional spray rounds or higher application rates in the future (Wilson & Tisdell 2001; Dewar 2014). This may lead to further increase in the input costs because of the ‘pesticide treadmill’ (Nicholls & Altieri 1997). It has been estimated that at least 10% of pesticides in the US were applied to deal with increasing resistance problems (Pimentel 2005). The estimated insecticide costs in this study were a broad estimation (Table 2.2) and are considered to be conservative. This is because the potential side effects of insecticides toward health, non-target species, and the wider environment have not been fully taken into account (Zhang et al. 2017): Pimentel (2005) estimated that the total externality costs from pesticides was similar to the investment in pesticide control in the US (about $10 billion annually). Rising chemical costs and the resulting increase in the economic value of natural enemies could justify the growing efforts worldwide to encourage IPM (Böcker & Finger 2016; Jones et al. 2016; Rasche et al. 2016).

Because the price elasticities of supply and demand for wheat could also influence the amount and distribution of economic benefits provided by natural pest control (Table 2.3; Alston et al. 1998), they should be properly measured for effective decision-making process

(Griffith et al. 2001). However, there is little information about these indicators for the UK and its regional markets.

The price elasticity of supply in this study was assumed to be inelastic (Table 2.2), which was also reflected in previous research (Griffith et al. 2001; Zhuang & Abbott 2007). As wheat is the most widely grown arable crop in South East England (0.2 million ha, 20.4% of total farmed area in this region, average from 2010 to 2014) (DEFRA 2016b; DEFRA 2016c), farmers would have limited land to increase the percentage of production if wheat price increases (Jansson & Heckelei 2011). Thus, it is reasonable to assume that supply elasticity in this region is inelastic. As for the price elasticity of demand, because wheat is a staple food, consumers' demand is relatively unresponsive to the change in price (Angus et al. 2009). However, since consumers in this context are wheat processing companies and wheat is widely grown in other UK regions, it is potentially easy for consumers to purchase wheat from other UK regions. Thus the demand elasticity could be higher than the one used in this study (Table 2.2). The sensitivity analyses showed that a more elastic measure in the demand elasticity would mean more benefits derived from natural pest control service would go to farmers (Table 2.3).

By using an economic surplus approach, this study not only estimated the economic contribution of natural enemies to wheat protection, but also indicates that there is a financial incentive for farmers to use the action threshold strategy for pest management. However, this factor alone may not be enough to persuade more farmers to adopt this method. Indeed, farmers' decisions on pest control are influenced by a set of complex factors: e.g., complexity of the related techniques (Shojaei et al. 2013), farmers' perception of risk (Park et al. 1997; Milne et al. 2016), and their environmental awareness (Lefebvre et al. 2015). In order to secure wider adoption of IPM in agricultural production, more studies need to be conducted on farmers' incentives to use these techniques in their fields (Lefebvre et al. 2015). Also, this study only incorporated one aspect of IPM in the evaluation process (i.e., action threshold). To provide a more comprehensive analysis of the contribution of IPM towards the enhancement of natural pest control service in the croplands, future research should be done to incorporate other related techniques (e.g., providing semi-natural habitats for natural enemies, such as beetle banks). This would require the researchers to measure the monetary inputs and outputs in the field experiments, an area where little data exists (Letourneau et al. 2015).

2.5 Conclusion

With an ecological-economic model, this study assigned monetary values of natural pest control of the summer grain aphid in wheat in South East England. It addressed the limits of natural pest control under the high pest infestation level, and positive contribution of using action threshold-based spraying method on the values of this ecosystem service. Because of the development of insecticide resistance in UK grain aphid, the potential subsequent increase in insecticide application costs would increase the economic value of natural pest control, and thus the justification of promoting natural enemies in the fields. The price elasticities of supply and demand for wheat could also influence the amount and distribution of the benefits brought by this ecosystem service. Due to various assumptions used in the model, the values derived from this study should be interpreted as conservative estimates. Although this study showed that farmers would benefit from incorporating natural enemies in their pest management decision-makings, more studies need to be conducted on their attitudes and concerns of adopting related conservation techniques in the fields. To have a more comprehensive analysis on the economic value of natural pest control or other ecosystem services in the agricultural sector, more monetary data should be collected from field studies looking at the effectiveness of these measures.

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Chapter 3: Arthropod pest control for UK oilseed rape – comparing insecticide efficacies, side effects and alternatives[†]

Abstract

Oilseed rape (*Brassica napus*) is an important combinable break crop in the UK, which is largely protected from arthropod pests by insecticidal chemicals. Despite ongoing debate regarding the use of neonicotinoids, the dominant seed treatment ingredients used for this crop, there is little publicly available data comparing the efficacy of insecticides in controlling key arthropod pests or comparing the impacts on non-target species and the wider environment. To provide an insight into these matters, a UK-wide expert survey targeting agronomists and entomologists was conducted from March to June 2015. Based on the opinions of 90 respondents, an average of 20% yield loss caused by the key arthropod pests was expected to have occurred in the absence of insecticide treatments. Relatively older chemical groups were perceived to have lower efficacy for target pests than newer ones, partly due to the development of insecticide resistance. Without neonicotinoid seed treatments, a lack of good control for cabbage stem flea beetle was perceived. Wide spectrum foliar insecticide sprays were perceived to have significantly greater negative impacts than seed treatments on users' health, natural enemies, pollinators, soil and water, and many foliar active ingredients have had potential risks for non-target arthropod species in UK oilseed rape fields for the past 25 years. Overall, 72% of respondents opposed the neonicotinoid restriction, while 10% supported it. Opposition and support of the restriction were largely based on concerns for pollinators and the wider environment, highlighting the uncertainty over the side effects of neonicotinoid use. More people from the government and research institutes leaned towards neutrality over the issue, compared to those directly involved in growing the crop. Neonicotinoid restriction was expected to result in greater effort and expenditure on pest control and lower production (0-1 t/ha less). Alternatives for future oilseed rape protection were then discussed.

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3.1 Introduction

Oilseed rape (*Brassica napus*) production has increased in many European Union (EU) countries since 2005 when the EU set a target for 20% of its energy to be from renewable sources by 2020 (EREC 2008). In the UK, oilseed rape production reached 652,000 hectares in 2015 (DEFRA 2015a), increasing annually by an average 2% over the past ten years. UK oilseed rape is grown for vegetable oil, animal feed and biodiesel. It serves as a break crop with wheat production and accounts for about 80% of the UK combinable break crops (Twining & Clarke 2009; DEFRA 2015b).

Oilseed rape has many arthropod pest and disease problems, prompting widespread use of chemical insecticides (AHDB 2015). Pesticide usage survey data collected by the UK's Fera Science Ltd. (Fera 2015; methods and figures see Appendix 3A) indicate that, between 1974 and 1988, pest control in oilseed rape in Great Britain was dominated by the use of organophosphate sprays and organochlorines as both foliar sprays and seed treatments. After 1990, pyrethroids quickly replaced these chemicals as foliar sprays, because of their higher efficacy in pest control and lower toxicity to humans, becoming the major insecticide group used from 1995 onwards. On average, pyrethroids represented 80% of total insecticidal weights, and 95% of total area treated for all foliar sprays used in oilseed rape in Great Britain for the past 25 years. Since the ban on organochlorines in 1999 (due to their high toxicity to users, and persistence and bioaccumulation in the environment), neonicotinoids have become the main seed treatments for oilseed rape in Great Britain, with 1,930 kg weight increase every two years. Three neonicotinoid active ingredients, clothianidin, thiacloprid and thiamethoxam, have been restricted in Europe since the end of 2013 (European Commission 2013), and the 2014/15 season was the first without these seed treatments being available.

The neonicotinoid restriction primarily resulted from the perceived negative lethal and sublethal impacts on both managed and wild pollinators (European Commission 2013). Since the start of the restriction, the evidence base has been strengthened around the effects of neonicotinoids on crop production, human health, pollinators and the wider environment (Godfray et al. 2015; van der Sluijs et al. 2015; EASAC 2015; IPBES 2016). However, major gaps remain (e.g., concentration and toxicity of neonicotinoid metabolites in the environment, see (Bonmatin et al. 2015)). Strongly contrasting views about the risks of using this chemical group in agriculture exist, and little consensus has been reached (EASAC 2015;

IPBES 2016), with an ongoing argument in UK between the National Farmers Union (NFU) and government regarding the lifting of the restriction (Case 2016). The neonicotinoid debate has resulted in uncertainties for the future of oilseed rape production and management for UK farmers, in terms of cropping areas, insecticide choices and impact on profits (Scott & Bilsborrow 2015; Budge et al. 2015).

Two new chemical groups have recently been adopted by UK growers (azomethines and oxadiazines, from around 2012), which could potentially act as alternatives to neonicotinoids. However, as with all currently available chemical groups, there is little publicly available information concerning their relative efficacy in controlling key pests (Godfray et al. 2015), or their side effects on non-target species and the wider environment. Thus it is difficult to assess the overall impact of using a specific insecticide chemical on oilseed rape.

In this study, based on experts' opinions, we provide an insight into these matters by comparing the relative efficacies and side effects of insecticide chemical groups used in UK oilseed rape production. Experts' opinions on the neonicotinoid restriction are also analysed. Because the survey finished in June 2015, the perceived inputs and yields are compared between 2013/14 and 2014/15 season. For future sustainable oilseed rape production in the UK, the potential alternative crop management options are thus discussed.

3.2 Materials and Methods

3.2.1 Survey Structure

An online survey by Qualtrics (Qualtrics 2015) was conducted to collect UK experts' opinions. The online survey has been approved by the ethics committee of the School of Agriculture, Policy and Development, University of Reading. As stated in the ethical approval (B165) and cover letter, the data can only be shared in summary forms, where no individual will be identified, and raw data will be destroyed in March 2018.

The survey had 28 questions (see Appendix 3B. Survey questionnaire) divided into four parts: (i) general section (6 questions including occupations, experience of giving farmer advice, and knowledge of crops), (ii) wheat section (7 questions, including yields, main pests and damage, insecticide efficacy, and importance of arthropod natural enemies), (iii) oilseed rape section (7 questions, as in the wheat section) and (iv) neonicotinoid section (8 questions, including opinions and reasons for the restriction, expected yields and inputs, and alternative pest management strategies). This paper refers only to the oilseed rape and neonicotinoid sections.

Respondents were also asked to give the regions they refer to when providing the information. To capture the degree of certainty, respondents were asked to give certainty scores on a 1-5 scale (5 being most certain) following several of the questions.

3.2.2 Survey distribution

The potential participants of this survey are related agronomists and entomologists that have worked for UK organizations in the last five years (2009/10-2013/14), and are familiar with some aspects about arthropod pests and related control methods (insecticides and natural enemies) for UK oilseed rape production (Appendix 3B). In January 2015, a pilot study using 15 experts, mainly from universities, was conducted. Because only minor changes to the wording of a small number of questions were made based on their feedback, these responses were included in the analyses. The main nationwide survey was carried out between March and June 2015. Potential respondents were contacted by searching through directories of universities, research institutes, NGOs (non-government organizations), government sectors, consulting firms, and agri-chemical companies. Universities were filtered via the Guardian league table 2015 by subjects of ‘Agriculture, forestry & food’ and ‘Biosciences’, and then relevant researchers were selected by scanning through the related department staff pages. Independent consultants were contacted through the Association of Independent Crop Consultants (AICC). Most experts were contacted by email and some through general enquiry web pages. Snowball sampling methods (where a respondent may pass the survey to other related experts) were also utilized to gain more respondents. A reminder with a link to the survey was sent to individuals two weeks after the initial request, and one more reminder two weeks later if no reply was received.

3.2.3 Statistical analyses

Main arthropod pests and related damages in oilseed rape

Respondents were asked to rank the relative importance of the three most widespread arthropod pests (one being most important of the three) in oilseed rape in the past five years (2009/10 to 2014/15). These scales were used as weights (i.e., weights for the 1st, 2nd and 3rd most important pest were 0.5, 0.33 and 0.17 respectively, with a collective weight of 1) to produce a weighted average response for each pest. Answers were further categorised into different regions and the weighted average for each pest for each region was estimated. See Appendix 3C for the regional distribution.

Respondents were also asked to estimate, without insecticides, the direct feeding damage from each selected arthropod pest and the damage that Turnip yellows virus (TuYV; caused by *Myzus persicae*, peach—potato aphid) would have caused in the past five years, in terms of percentage yield loss (%), followed by the certainty scale (1-5, 5 being most certain). Average damage levels, standard deviations and certainty levels of the three most important pests were estimated.

Efficacy of insecticides and arthropod natural enemies

Information about the perceived efficacy of both chemical and natural pest control methods was requested in the survey.

The perceived efficacy of each available insecticide chemical group in the 2013/14 season was requested for each of the main pests selected from the previous question, following a 0-6 efficacy scale as below:

Table 3.1. Insecticide efficacy scale

0	1	2	3	4	5	6
Not sure	0% pest control	1-20% control	21-50% control	51-80% control	81-90% control	91-100% control

Pairwise efficacy comparisons among the available chemical groups were conducted by the Skillings–Mack (Skillings & Mack 1981; Srisuradetchai 2015) and related post hoc tests (Pohlert 2014), using the software R 3.2.5 (R Core Team 2016). Responses were omitted if a respondent answered for only one chemical group for a specific pest. Due to the asymmetrical distribution and the non-parametric analyses for these ordinal data, medians and interquartile ranges were used to summarize the efficacy level.

The same efficacy and certainty scales were used to estimate the importance of arthropod natural enemies on pest control (without insecticides). Qualitative opinions on its importance for oilseed rape production were gathered by selecting from the following options: ‘Strongly agree’, `Agree’, `Neutral’,` Disagree’, `Strongly disagree’ and `Not sure’.

Side effects of insecticides on human health, environment and non-target arthropods

Perceived negative influences on users’ health, natural enemies, pollinators, water and soil were compared between the two application methods for UK oilseed rape(seed treatments and foliar sprays), using a 0-5 scale (0 being no influence, and 5 being greatest influence). Sign tests (Millard 2013) were used to compare the perceived median differences between seed treatments and foliar sprays on these aspects. Responses were omitted if the respondent only answered for one of the two treatment types. Due to the asymmetrical distribution and the non-parametric analyses for these ordinal data, medians and interquartile ranges were used to summarize the side effect level.

Potential risks of common foliar active ingredients to the non-target arthropods for UK oilseed rape were also analysed by the in-field Hazard Quotient approach ((ESCORT 2000); see Appendix 3D for details). Hazard Quotient is the required assessment for pesticide registration in the European Union. The method combines the laboratory acute test (EFSA 2015) of two sensitive species (cereal aphid parasitoid *Aphidius rhopalosiphi* and predatory mite *Typhlodromus pyri*) and field application rate of the related foliar active ingredient (Fera 2015) to produce a Hazard Quotient. If the quotient of either species exceeds two, the threshold level, it indicates a potential hazard of the active ingredient towards non-target arthropods. Due to the limited publicly available test results, only one representative active ingredient (the one that was used most often in UK oilseed rape and had test results available) was chosen from each available chemical group. For the same reason, and also that *Typhlodromus pyri* would normally be applicable in orchard fruit crops, only *Aphidius rhopalosiphi* was used as the test species.

Opinions on neonicotinoid seed treatment restrictions

A five-point Likert scale was used to measure expert opinions on the current neonicotinoid restrictions (‘Strongly favour’ to ‘Strongly oppose’ including a ‘Not sure’ option). Different possible reasons for holding favourable and unfavourable opinions were displayed for respondents to select. Fisher's exact test was used (with Monte Carlo simulated p value, 100,000 replicates) (R Core Team 2016) to explore whether or not experiences in farming services and the nature of the employing organization had an impact on respondents' opinions.

3.3 Results

3.3.1 Response rates and information about respondents

In total, 455 online surveys were sent out, and 146 responses were received (43% effective response rate accounting for incorrect emails and declines), with 101 completed (70% of total responses). 90 people participated in the oilseed rape and neonicotinoid sections. The following analyses focused on these two sections.

From 2010 to 2014, 43% of respondents (39 out of 90) had worked for independent consultants/ consulting organizations (Fig 3E.1 in Appendix 3E). University staff accounted for 27%, government 17% and agri-chemical companies 16%. 65% of respondents had provided advice services to farmers.

3.3.2 Main arthropod pests and related damage in oilseed rape (2009/10-2013/14)

Based on a weighted average of expert ranking, the three main arthropod pests in oilseed rape in the past five years were perceived to be cabbage stem flea beetle (*Psylliodes chrysocephalus*) (weighted average response = 28), pollen beetle (*Meligethes aeneus*) (18), and peach—potato aphid (*Myzus persicae*) (8). Different regions varied slightly (e.g., for the North West region, the second most important pest was cabbage seed weevil, and the equal third were aphids and brassica pod midge) (Fig 3.1; Table 3E.1 in Appendix 3E).

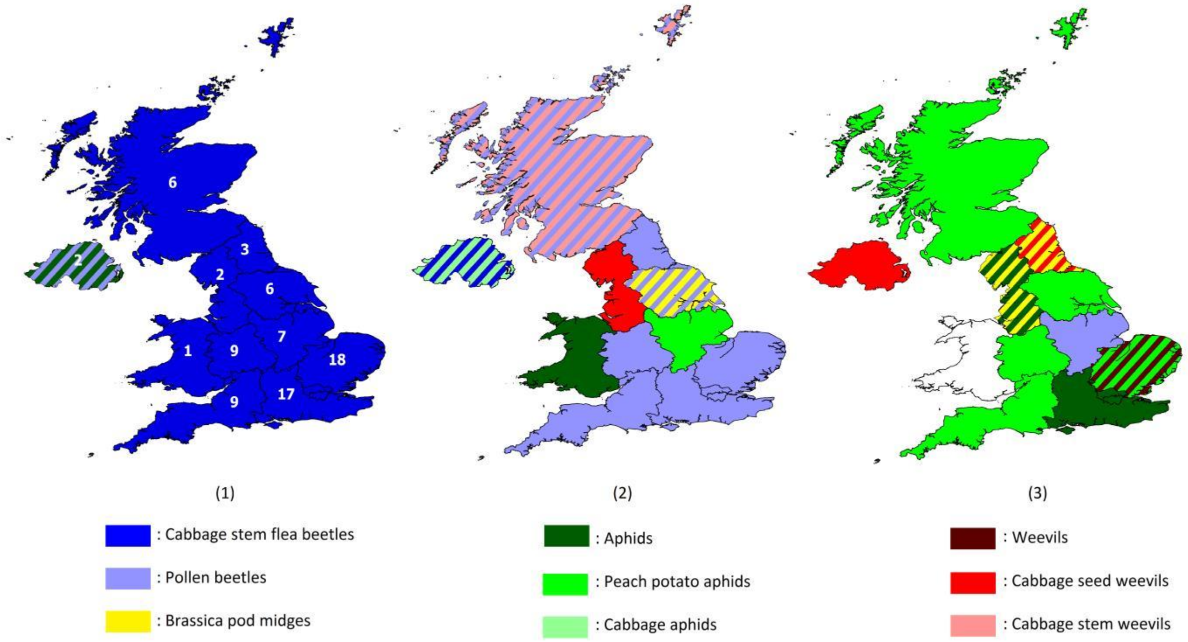

Fig 3.1. Perceived top three important arthropod pests of oilseed rape for each UK region.

(1) Most important arthropod pests; (2) 2nd most important arthropod pests; (3) 3rd most important arthropod pests. Note that different regions are not directly comparable, due to different numbers of respondents for each region (see number in the first graph). The white area for Wales in the third graph denotes no data, since respondents only mentioned two pests. Stripes indicate two pests of equal importance. For the data see Table 3E.1 in Appendix 3E. Map shapefiles are from the GADM database of Global Administrative Areas and the Office for National Statistics (GADM 2015; ONS 2016), and software is QGIS (QGIS Development Team 2016).

Due to the limited number of respondents, and the fact that some respondents represented several regions (up to four, Appendix 3C), Fig 3.1 represents a broad visualization. The following analyses were conducted without categorising into regions.

Without insecticide applications, the perception was that cabbage stem flea beetle would have caused the greatest direct damage, with a mean yield loss of 24% (certainty level 3). However, expert opinion on this also had the largest variation, with a standard deviation of 26%. Second was pollen beetle damage, with a mean value of 19%, and standard deviation of 20% (certainty level 3). Perceived peach—potato aphid direct damage averaged 13%, with a standard deviation of 10% (certainty level 3). TuYV loss without insecticides was perceived to be 15%, with a standard deviation 11%, and a certainty level of 2 (Table 3.2).

Table 3.2. The number of respondents, perceived mean crop yield loss (%) and certainty levels of the main arthropod pests (direct damage), and the turnip yellows virus in UK oilseed rape from 2009/10 to 2013/14 (without insecticides).

	Cabbage stem flea beetles	Pollen beetles	Peach potato aphids	TuYV
Number of respondents	56	41	19	66
Mean damage (s.d.)	24.2 (26.3)	18.9 (20.5)	13.2 (9.9)	15.0 (11.0)
Mean certainty levels (s.d.)	2.8 (1.1)	2.8 (1.0)	2.6 (1.3)	2.3 (1.2)

Note: Numbers in the brackets are the related standard deviations (s.d.). Certainty levels: 1-5, 5 being most certain.

3.3.3 Efficacy of insecticides in oilseed rape (2013/14)

In terms of efficacy of the insecticide groups for oilseed rape protection, because of the potential complex annual variation in efficacy, only the available chemical groups used for the 2013/14 season were studied (Table 3.3).

Table 3.3. The perceived median insecticide efficacies (number of missing values; number of 'Not sure' responses; interquartile ranges) for the three main arthropod pests in UK oilseed rape in 2013/14.

Pests (number of respondents)	Carbamates	Pyrethroids	Neonicotinoid seed treatments	Neonicotinoid sprays	Oxadiazines	Azomethines
Peach–potato aphid (16)	2 (1; 1; 1-2) a	2 (0; 1; 1-3) a	5 (0; 0; 4-5.25) b	5 (2; 1; 5-6) bc	4 (6; 3; 4-4) c	4 (0; 1; 4-5.5) b
Pollen beetle (26)	1 (8; 4; 1-2.5) a	3 (2; 0; 2.75-4) a	1 (7; 3; 1-3) ab	4 (2; 2; 4-5) bd	4.5 (5; 8; 4-5) c	4 (5; 3; 3.5-5) d
Cabbage stem flea beetle (44)	1 (16; 4; 1-1.25) a	3 (1; 0; 3-3.5) b	5 (0; 0; 4-5) c	4 (8; 5; 2-5) c	3 (17; 13; 2-4) d	2 (17; 9; 1-3.75) d

Note: efficacy levels: 0 (Not sure), 1 (0% pest control), 2 (1-20%), 3 (21-50%), 4 (51-80%), 5 (81-90%), 6 (91-100%); 'Not sure' answers are omitted; different letters mean significant differences (α =0.05) between two chemical groups (based on Skillings–Mack and related ad-hoc tests).

It should be noted that some chemical groups are not applied against some pests due to certain phenological and pharmacological factors. For example, neonicotinoid seed treatments are not normally used against pollen beetles, because they are primarily applied to autumn sown crops, whereas pollen beetles pose a threat in spring. Neonicotinoid sprays and oxadiazines are mainly used for this pest. Carbamates (mostly pirimicarb) are used mainly for aphid control, and azomethines are applied mainly against aphids and pollen beetles. This information was reflected in Table 3.3 by the perceived relatively low efficacy levels for the non-targeted pests.

Based on the pairwise comparisons among different chemical groups, neonicotinoids and the two newly introduced chemical groups (oxadiazines and azomethines) were perceived to have higher efficacy than carbamates and pyrethroids for peach–potato aphid (81-90% and 1-20% respectively) and pollen beetle control (51-80% and 21-50% respectively). Neonicotinoid seed treatments were perceived to have more efficacy than pyrethroids against cabbage stem flea beetle (81-90% and 21-50% respectively).

3.3.4 Side effects of insecticides in oilseed rape

Comparing the two main insecticide application methods for UK oilseed rape, foliar sprays were thought to have significantly more negative impacts than seed treatments on users' health, natural enemies, pollinators, water and soil (Table 3.4). The median influence levels (from 0, no influence, to 5, greatest influence) across all categories were perceived to be 3 for sprays and 1 for seed treatments.

Table 3.4. Number of pairs, medians (interquartile ranges) of the influence scale (0-5) of the general seed treatments and foliar sprays, and the sign tests of the perceived median differences in side effects between seed treatments and foliar sprays.

Categories	Number of pairs	Seed treatments	Sprays	Sign tests (α=0.05)
Health	63	1 (0-1)	2 (1.5-3)	<0.00001
Natural enemies	64	1 (1-2)	4 (3-5)	<0.00001
Pollinators	61	1 (1-2)	4 (3-4)	<0.00001
Water	59	1 (1-2)	3 (2-4)	<0.00001
Soil	55	1 (1-2)	2 (1-3)	0.02

Note: influence scale: 0-5, 0 being no influence, 5 being greatest influence.

Focusing on the Hazard Quotients for foliar sprays, different active ingredients have large differences in terms of the potential risks to non-target arthropods. Dimethoate has much higher potential hazard levels, with lambda-cyhalothrin and thiacloprid following. In comparison, pymetrozine, indoxacarb and pirimicarb pose lower potential risks towards non-target arthropods (Fig 3.2).

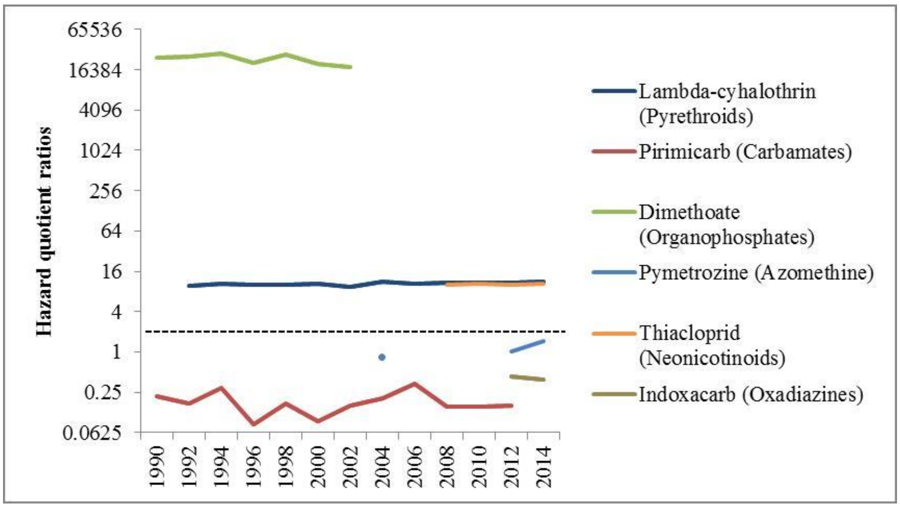

Fig 3.2. Hazard Quotient ratios of insecticide active ingredients used in oilseed rape in Great Britain (1990-2014).

The test species is the aphid parasitoid *Aphidius rhopalosiphi*. Trigger value is 2 (marked with the black dashed horizontal line), above which indicates potential hazard of an active ingredient on non-target arthropod species. Y axis is the log scaled with base 4.

3.3.5 Uncertain future – neonicotinoid debates

From the information gathered, 72% (65 of 90) participants either opposed or strongly opposed the neonicotinoid restrictions in the UK while only 10% (9 of 90) supported or strongly supported this policy. 13 respondents took a neutral stance, and three respondents were not sure about this proposition (Fig 3E.2 in Appendix 3E).

In terms of organizations (NGOs and food industries were omitted, due to low respondent numbers), an average of 51% respondents from the government, universities, and private research institutes (Group A) opposed the neonicotinoid restriction, compared with 90% of respondents from the agri-chemical companies, commercial/independent consultants, and growers (Group B) (Fig 3.3). This difference was driven less by respondents who supported the restriction (an average of 20% from Group A compared with 7% from Group B), but more by those who held ‘Neutral’ and ‘Not sure’ opinions (30% compared with 3%). To compare this more quantitatively, we regrouped the six options in two ways: one was *oppose* (including ‘Oppose’ and ‘Strongly oppose’) versus *favour* (including ‘Favour’ and ‘Strongly favour’); the other was having an opinion (*oppose*/ *favour*) versus ‘Neutral’/ ‘Not sure’. Fisher’s exact test was used to test differences among organizations regarding their opinions on this issue. Results showed that there was no clear difference among organizations for whether to favour or oppose neonicotinoid restriction, but more people from Group A than Group B had a neutral/ not sure proposition (Table 3E.2 in Appendix 3E).

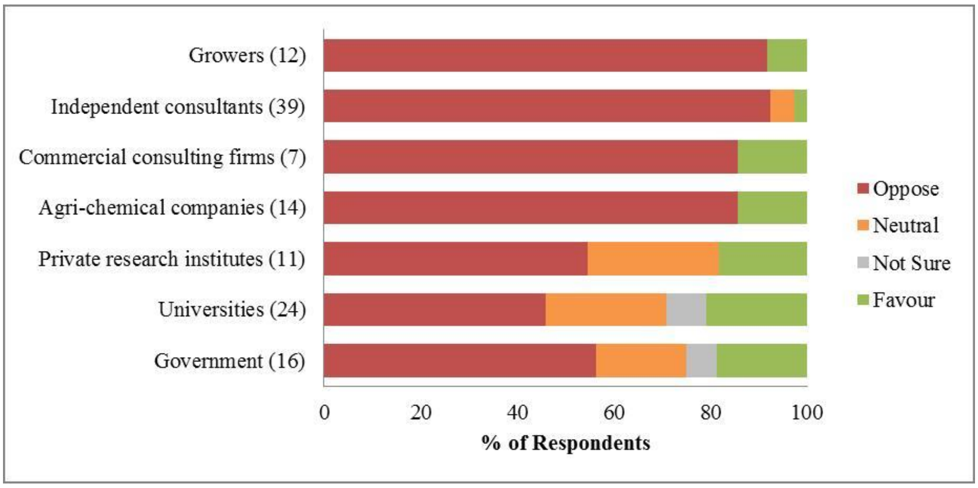

Fig 3.3. Percentage of respondents’ opinions on neonicotinoid restriction by organization type. *Oppose* includes ‘Strongly oppose’ and ‘Oppose’ options, *favour* includes ‘Strongly favour’ and ‘Favour’ options. Numbers in the brackets are the number of respondents from that organization type who answered the question.

Fisher’s exact test also showed a clear division between Group A and B regarding whether a respondent had provided advice services to farmers in the past five years (Table 3E.3 in Appendix 3E). An average of 41% from Group A and 85% from Group B had done so (Fig 3.4).

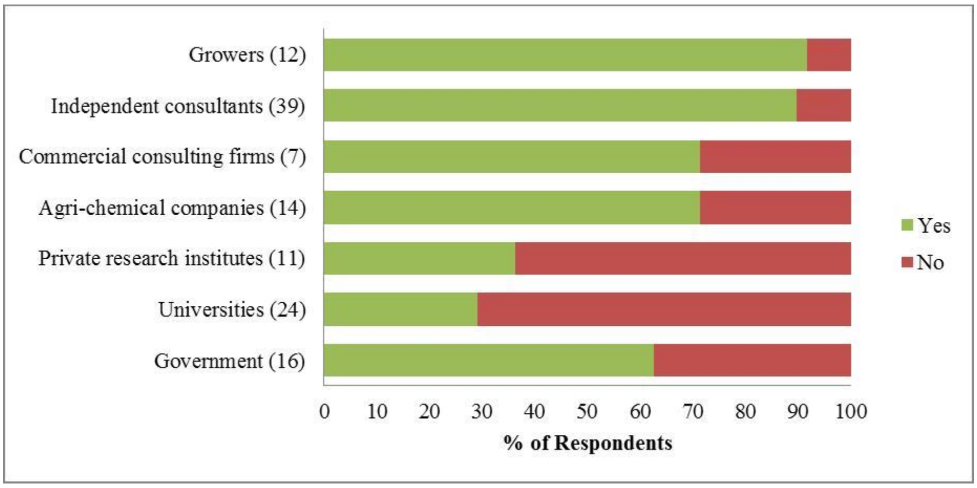

Fig 3.4. Percentages of respondents who have provided advice services to farmers by organization type (2009/10-2013/14).

Numbers in brackets are the number of respondents from that organization type who answered the question.

Although only 10% (9) of respondents favoured the neonicotinoid restriction in the UK, all of them expressed concerns about the negative impacts neonicotinoids could have on pollinators and the wider environment. Four respondents believed that farmers can adjust to the management accordingly, and two suggested that the arthropod pest problems were not severe (Fig 3.5). Of the 65 respondents that opposed the restriction, the two most widespread reasons were also around environment and pollinators (95% and 89% respectively). 71% of respondents worried that other products are not as efficient as neonicotinoids, and 60% thought that oilseed rape production will be greatly reduced (Fig 3.6).

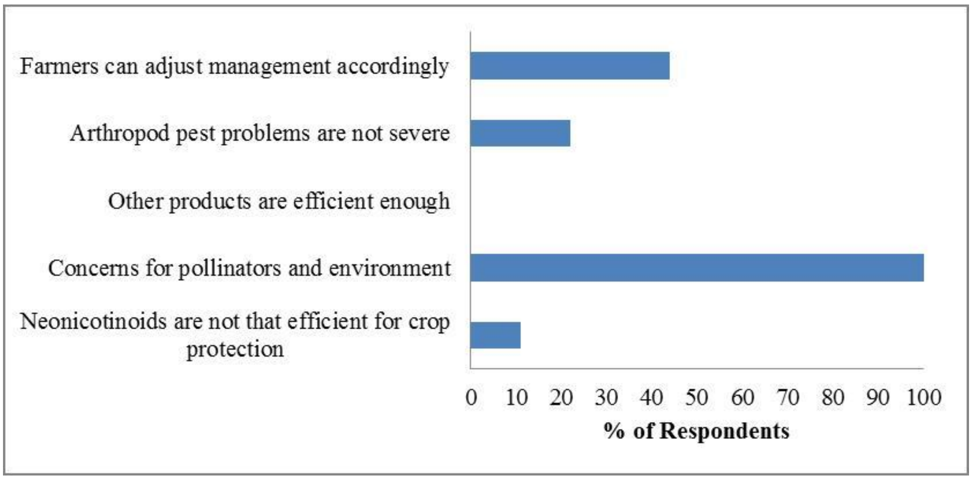

Fig 3.5. Reasons for favouring neonicotinoid restriction

Total number of respondents is 9.

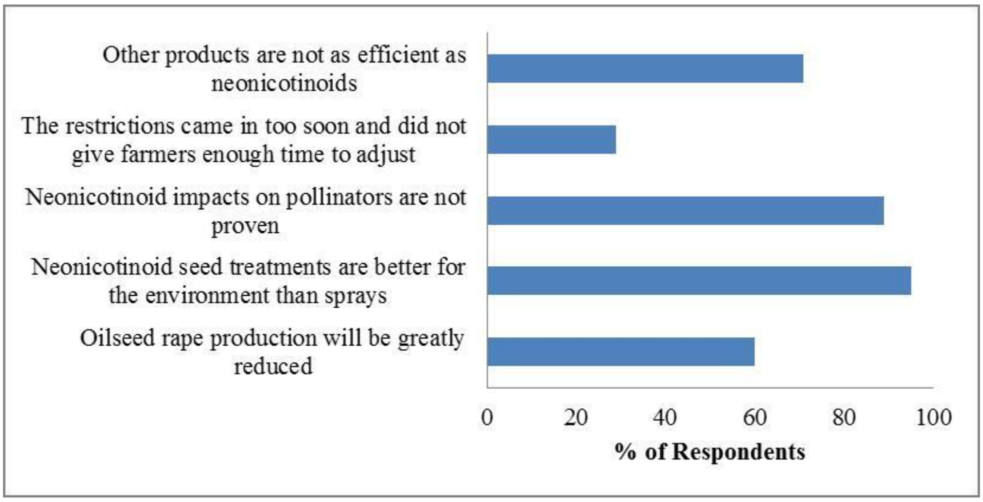

Fig 3.6. Reasons for opposing neonicotinoid restriction

Total number of respondents is 65.

3.3.6 2014/15 VS 2013/14 oilseed rape growing season

For the 2014/15 season (compared with 2013/14), 64% of respondents (48 out of 75) felt that more time had been spent by agronomists inspecting crops since the restrictions (Fig 3.7). 70% of respondents (54 out of 78) indicated that oilseed rape farmers spent more money on insecticide products during the 2014/15 season, but 37% (29 out of 78) thought that just a bit more had been spent (Fig 3.8). Only one respondent thought that farmers spent a bit less than 2013/14, while 15 were unsure. Most of the 76 respondents expected that the winter oilseed rape harvest in 2014/15 season would be between 0-1 t/ha less or about the same as the previous year (36% and 24% respectively). 22% of respondents were not sure about the answer, which was to be expected since yield changes are influenced by many factors in addition to pesticide use. Similar patterns occurred regarding the spring oilseed rape harvest. As the survey finished in June, yields for the year 2014/15 were estimated by the respondents directly (Fig 3.9).

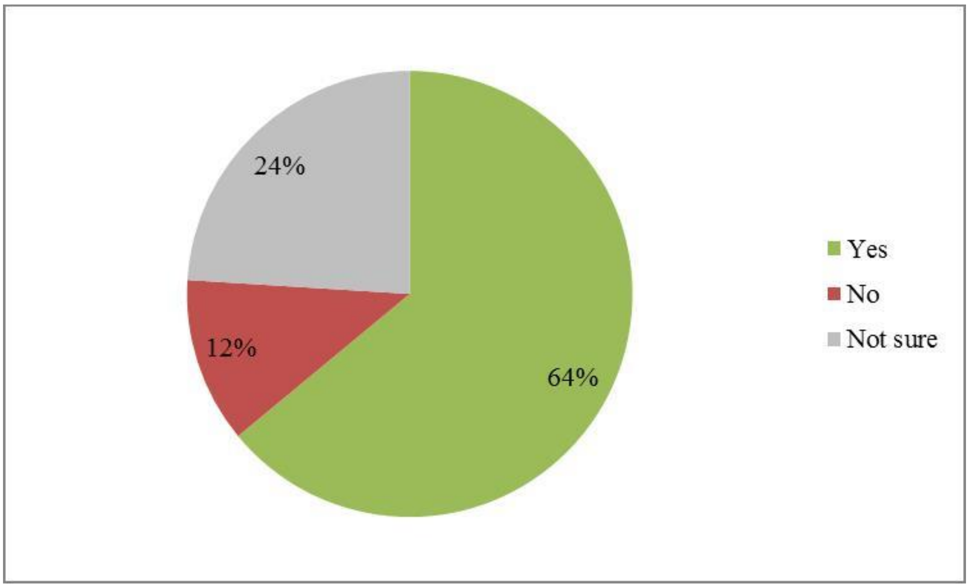

Fig 3.7. Whether more time was spent by agronomists inspecting oilseed rape fields for arthropod pest abundance.

This is a 2014/15 compared with 2013/14 season. Total number of respondents is 75.

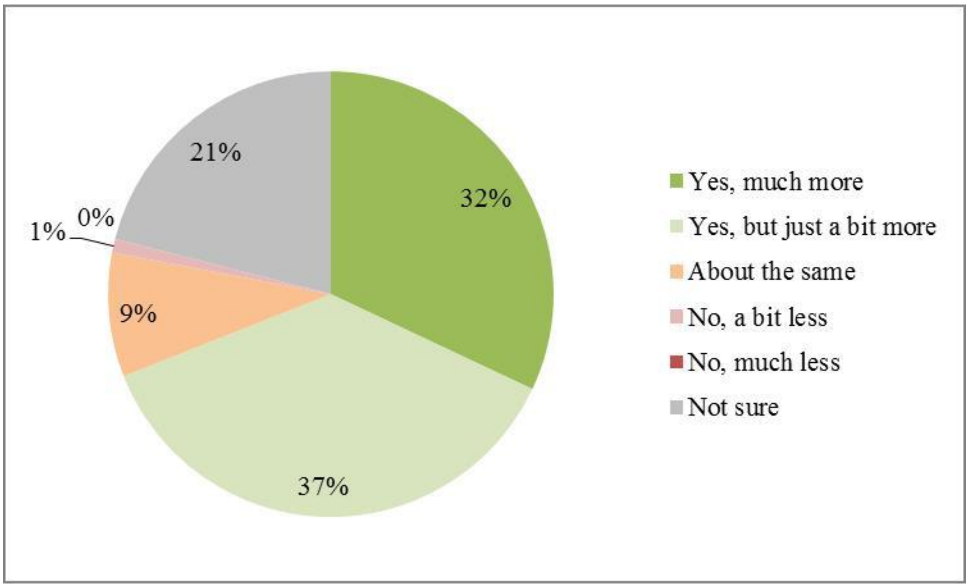

Fig 3.8. Percentage of respondents regarding whether they thought more money was spent on insecticide products

This is a 2014/15 compared with 2013/14 season. Total number of respondents is 78.

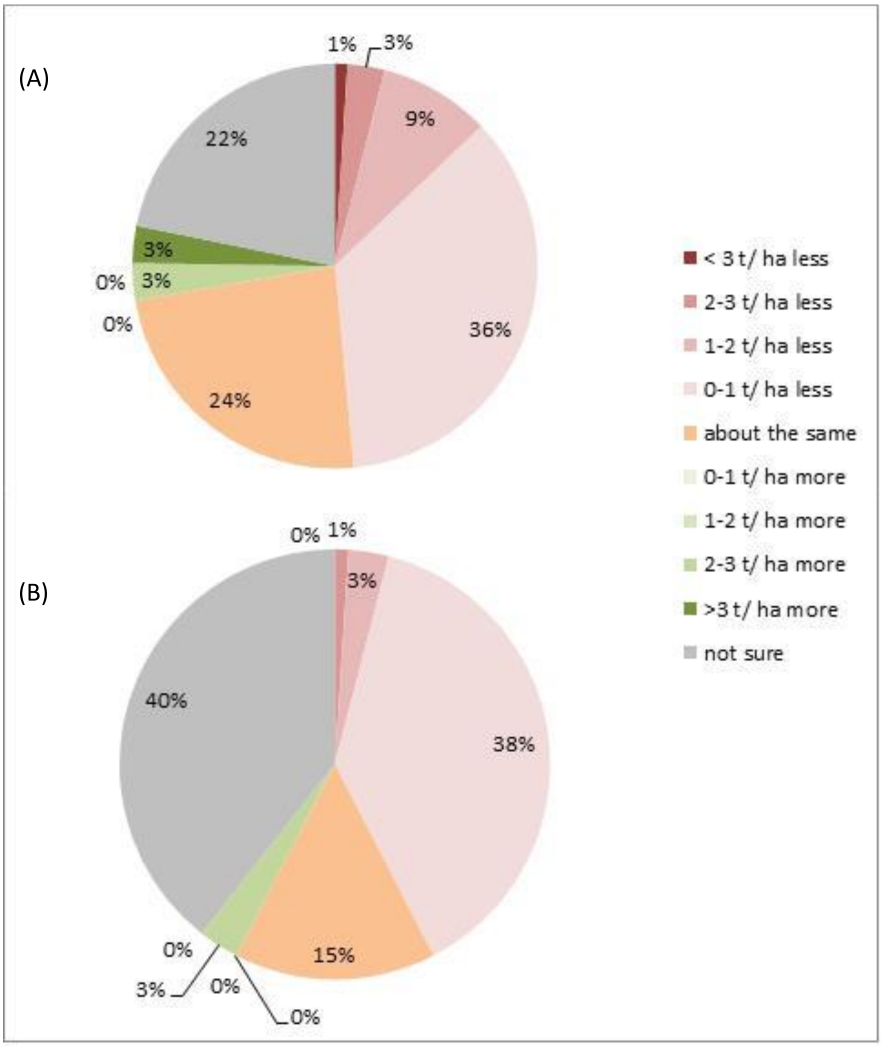

Fig 3.9. (A) Expected winter and (B) spring oilseed rape yield in 2014/15 compared with 2013/14.

Total number of respondents is 76 and 71 respectively.

3.3.7 Alternative pest control options

In a hypothetical situation where neonicotinoids would be permanently banned in the UK, respondents' suggestions towards alternative pest management strategies differed: 76% respondents (66 out of 87) would choose to use new insecticides if available. Other options such as 'Grow oilseed rape less often', 'Use new oilseed rape varieties', and 'Grow a smaller area of oilseed rape' were similar in terms of support (46%, 45% and 43% respectively). The use of currently available insecticides was mentioned by 30% of respondents. For the 'Others' option, 65% (13 out of 20) respondents mentioned the use of biocontrol/ IPM (integrated pest management) as an alternative approach (Fig 3.10). Focusing on natural pest control, 67% (56 out of 83) of respondents agreed that natural enemies are important for oilseed rape production (Fig 3.11). Without insecticide treatments, 57% of respondents thought that natural enemies could exert 1-20% control on oilseed rape pests, and 32% suggested 21-50% control (Fig 3.12).

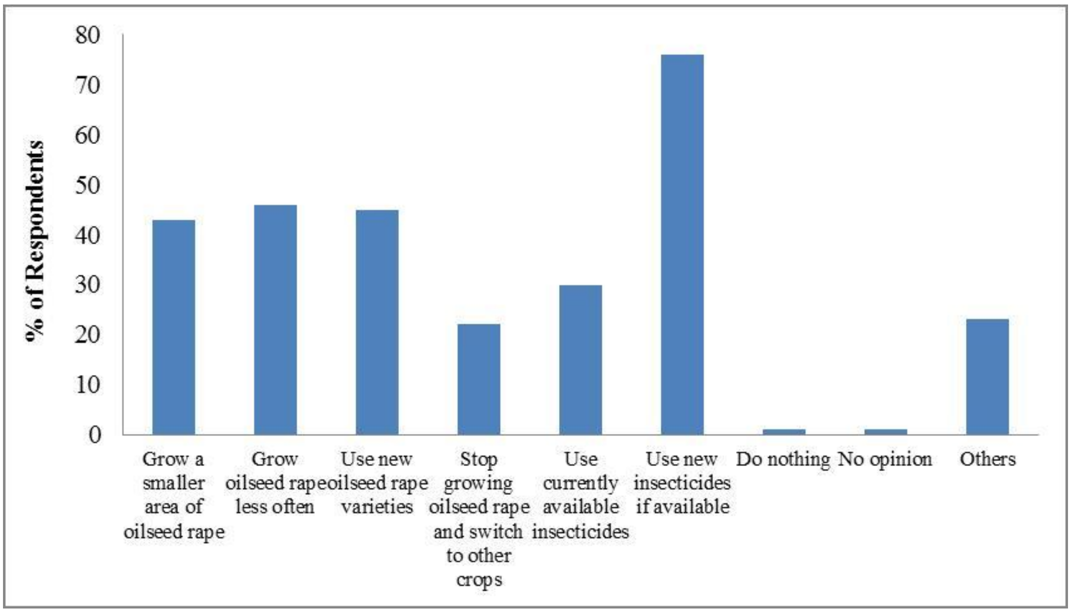

Fig 3.10. Perceived future management options if neonicotinoid seed treatments were withdrawn completely.

Total number of respondents is 87.

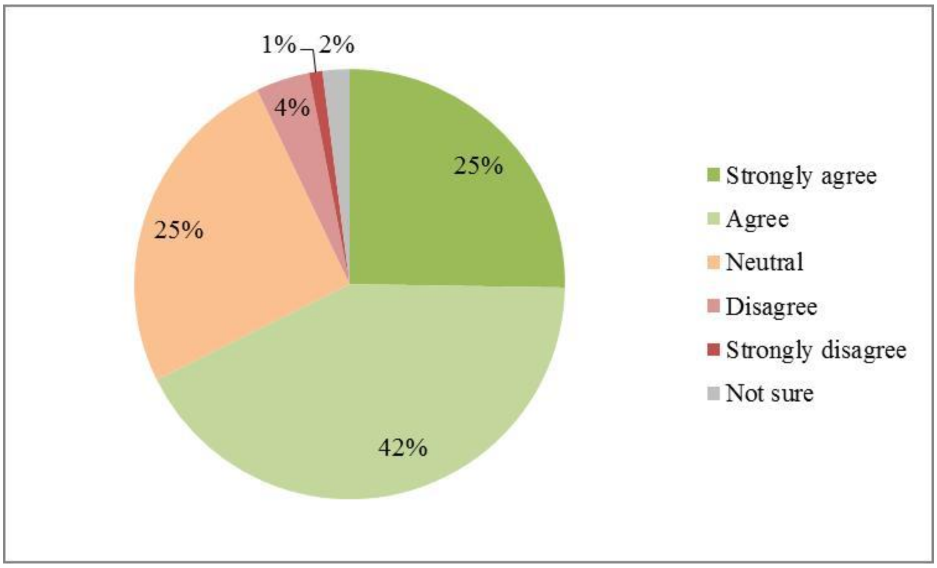

Fig 3.11. Perceived importance of arthropod natural enemies to oilseed rape production in UK

Total number of respondents is 83.

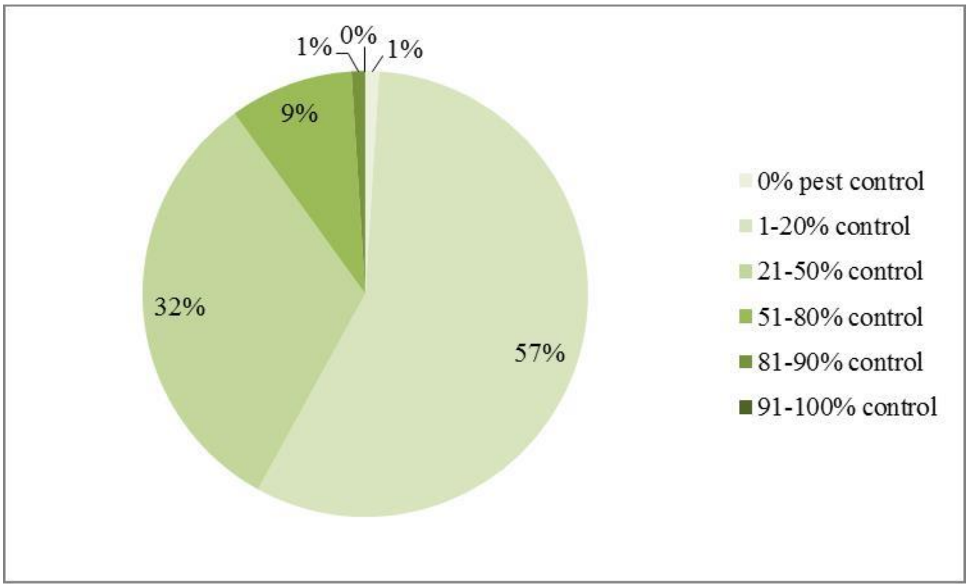

Fig 3.12. Without insecticides, perceived efficacy of arthropod natural enemies to control key pests in oilseed rape.

Total number of respondents is 81.

3.4 Discussion

3.4.1 Main arthropod pests and related damage in oilseed rape (2009/10-2013/14)

The most important arthropod pests in UK oilseed rape based on perceptions from the survey (cabbage stem flea beetle, pollen beetle, and peach—potato aphid) were also indicated by (Williams 2010) on a European scale, except for the peach—potato aphid, which was considered a minor pest in Europe. However, peach—potato aphid is an important pest in the UK, especially as a vector of TuYV ((Nicholls 2013) showed an average 15% yield loss by this virus in untreated crops).

The large variation in levels of perceived pest damage suggests that pest damage is likely to vary greatly under different contexts. (Clarke et al. 2009) suggested a 1% untreated yield loss for cabbage stem flea beetle, 0.5% for pollen beetle, and 3% for aphids carrying TuYV. In 2010, (Ellis & Berry 2012) found varied pollen beetle damage on different study sites in England (0-6% yield loss). The low certainty levels provided by experts (an average of 3 out of 5) suggest that uncertainties and research gaps remain in this area. One way to better comprehend the damage status of a pest species is to have long term regional/national survey of the pest population density, which, combined with a well-established action threshold system, may help analyse the frequencies and intensities of pest outbreaks.

Southern Sweden has monitored the larval abundance of cabbage stem flea beetle (number of larvae/plant) in winter oilseed rape since 1969 and revealed that outbreaks would occur every 7th year (Nilsson 2002). This has convinced the local farmers to apply chemical treatments according to this cyclic pattern (Nilsson 2002). UK has also monitored the larval abundance of cabbage stem flea beetle in winter oilseed rape for more than 10 years (Collins 2017). However, the dataset alone is not enough to advice the damage status of this pest to UK oilseed rape production, because the local action threshold system also includes the adult beetle feeding damage in autumn (% of eaten leaf area between Growth Stage 10-14; AHDB 2016a). UK has surveyed this indicator for three years (Wynn et al. 2017), and more data are needed to potentially connect the abundance of larvae in spring to the damage levels of adult beetles in the following autumn.

3.4.2 Efficacy of insecticides in oilseed rape (2013/14)

Due to the commercial confidentiality and expensive trials (Godfray et al. 2015), it is difficult to obtain data on insecticide efficacy which can differ among active ingredients within one chemical group (Šmatas et al. 2012). Efficacy levels are also difficult to evaluate and compare because many factors can affect them both temporally and spatially, including insecticide resistance (Table 3E.4 in Appendix 3E), application methods, plant growth stages, etc. (Nault & Anthony 2010; Slater et al. 2011).

The perceived high efficacy of neonicotinoids against insect pests and related diseases has been demonstrated in several studies (Maienfisch et al. 2001: cabbage stem flea beetle; Zimmer & Nauen 2011: pollen beetle; Elbert et al. 2008: peach—potato aphid), although others have shown limited efficacy (Panini et al. 2014: peach—potato aphid). For the relatively new groups, oxadiazines and azomethines, the perceived relatively high efficacy against pollen beetle was illustrated in a recent German study (Kupfer & Schroeder 2015). However, limited efficacy by these two groups was also found (Vaitelyte et al. 2011; Jansen & Gomez 2014). It should be noted that without careful management (e.g., rotating insecticides with different available modes of action; Sparks & Nauen 2015, Bass et al. 2015), resistance to the above insecticides could occur for pests in UK oilseed rape, thus reducing the efficacy. Neonicotinoid resistance has already been detected in the peach—potato aphid in Southern Europe (Slater et al. 2012).

Pyrethroids and carbamates had the lowest expected efficacy against the peach—potato aphid (1-20%), which could be partly due to the insecticidal resistance occurred for this pest in UK (Table 3E.4). Although in 2010, a HGCA study found that pyrethroids were efficient against pollen beetle (about 90% control, Ellis & Berry 2012), experts in our study only expressed a median 21-50% control, possibly due to growing resistance since its appearance in 2006 (Table 3E.4).

The perceived low confidence in cabbage stem flea beetle control is worrying. Apart from neonicotinoid seed treatments, the other available chemical pyrethroids were perceived to exert lower than 50% control, which could partly due to the resistance occurred in this pest (Table 3E.4) (Zimmer et al. 2014; IRAC 2015).

Across all experts, the perceived efficacy rarely exceeded 90% from all available chemical groups used in UK oilseed rape in 2013/14. This may reflect the lack of confidence in assigning efficacy for insecticides used in oilseed rape, but also the fact that many insecticides, even when newly introduced, cannot provide 90% pest control (Buntin 1986). The perceived low and/ or uncertain efficacy in the available chemical groups and the uncertainty in pest control after the neonicotinoid restriction indicate an urgent need for robust, accountable and updated information about efficiency of insecticides for pest control for this crop in the local fields.

3.4.3 Side effects of seed treatments versus sprays

Experts generally perceived seed treatments to be less harmful than sprays. This is to be expected as: (i) compared with sprays, seed treatments have less direct contact with operators and non-target species (Elbert et al. 2008); (ii) less surface runoff (Palmquist et al. 2012); and (iii) reduced concentration in the environment (Nuyttens et al. 2013). However, many counter-arguments have arisen in the past few years against this application method, especially for the neonicotinoid group. Traces of neonicotinoid residues have been detected in humans (Ueyama et al. 2015), pollinators and beehives (Mullin et al. 2010; Hladik et al. 2016), soil (Jones et al. 2014) and water (Morrissey et al. 2015). Negative impacts have also been found on human health (Mason 2013), pollinators (Godfray et al. 2014; Godfray et al. 2015), natural enemies (EASAC 2015), earthworms (Pisa et al. 2014) and aquatic invertebrates (Morrissey et al. 2015). Possible reasons behind these side effects are the systemic characteristics of neonicotinoids (residues in treated plant tissues) (Bonmatin et al. 2015), low soil absorption (high leaching potentials) (EFSA 2008), and great toxicity to invertebrates (Morrissey et al. 2015).

On the other hand, sprays can also cause side effects for human health and the wider environment. For example, although relatively few human poisonings from pyrethroids have been reported despite their extensive use worldwide (Bradberry et al. 2005), sub-lethal reactions have been found, including paresthesia and nausea (Bradberry et al. 2005). Negative impacts have also been detected for pollinators (van dame et al. 1995; Sanchez-Bayo & Goka 2014; Charreton et al. 2015; Hladik et al. 2016), natural enemies (Holland & Luff 2000; Desneux et al. 2004; Devotto et al. 2007), soil (Hartnik et al. 2008; Tripathi et al. 2010; Das Gupta et al. 2011; Song et al. 2015) and water systems (Amweg et al. 2005; Ng et al. 2008).

Since the survey finished in June 2015, more knowledge has been accumulated on the side effects of insecticides toward non-target species and the wider environment. Take the impacts of neonicotinoid seed treatments on pollinators as an example: since the research gaps were identified by Lundin et al. (2015) (a literature review up to June 2015), many studies have investigated other active ingredients besides imidacloprid (Mogren & Lundgren 2016), pollinator species besides honey bees (*Apis*) (Woodcock et al. 2016), and/or impacts on the colony besides individual development (Wu-Smart & Spivak 2016). Although more work needs to be done to improve the evidence base on this issue (Walters 2016), respondents’ opinions could be changed by the new evidence.

However, with the currently available evidence, it is still difficult to compare the overall side effects of the two insecticidal application methods, especially between neonicotinoids and pyrethroids, since little research has done so (but see Wang et al. 2012 on earthworms).

3.4.4 Hazard Quotient ratios from sprays

By using the in-field Hazard Quotient method, a temporal comparison of hazard levels on non-target arthropods among available foliar active ingredients for UK oilseed rape was presented (Fig 3.2). However, limitations exist in interpreting the results because this method is based on the laboratory acute toxicity tests, one being that these tests are difficult to account for the influence from the environment (Appendix 3D) (Kimball & Levin 1985; Ellis et al. 2007).

The high toxicity of dimethoate to human health and the wider environment has been widely recognized (pan-UK 2002). Although its use in UK oilseed rape was stopped a decade ago, it is still approved for use in wheat. The high threat potential of lambda-cyhalothrin towards non-target arthropods has also been reflected in previous studies (Langhof et al. 2003; Desneux et al. 2007; Ceuppens et al. 2015). Although thiacloprid has been shown to have negative effects on arthropod natural enemies (Jansen & Gomez 2014), it has been found to have limited side effects on bees by some studies (Elbert et al. 2008; Jeschke et al. 2010). According to Jansen et al. (2011), pymetrozine has less of an effect than pirimicarb on aphid natural enemies. Indoxacarb has been shown to be less toxic than lambda-cyhalothrin to arthropod predators and parasitoids (Nowak et al. 2001; Galvan et al. 2005), but its potential hazard to honey bees could be high (Stoner & Eitzer 2013). Relatively low side effects from pirimicarb against natural enemies have also been recorded (Bacci et al. 2012).

3.4.5 Perceptions on neonicotinoid restriction

The tendency for respondents from the universities, private research institutes and government to choose the ‘Neutral’ opinion on the neonicotinoid restriction debate is worth discussing. These respondents may have had an actual mid-point opinion on this issue, that they neither opposed nor favoured the restriction. It may have been because there was a lack of interest in this topic, or they considered similar overall costs and benefits for either side (DeMars & Erwin 2004).

Uncertainty could also have been important to this group: they may have had more recent information about the effects of neonicotinoids on crop yields, pollinators and the wider environment, but because of the complexity of this issue and gaps in the current evidence base (Godfray et al. 2015), they could not estimate the net costs and benefits of neonicotinoids. This is also reflected in that the reasons most frequently chosen for both the *oppose* and *favour* groups were all around pollinators and the wider environment (Figs 3.5 and 3.6). On the other hand, they may have been less well informed about the field situations or other related risks for farmers than consultants (Harwood et al. 1999), who have provided more advice services to farmers (Fig 3.4, Table 3E.3).

It is also possible that some respondents chose the neutral option to avoid the cognitive costs of selecting the most appropriate opinion, even though they may lean towards one side (Krosnick 1991), while others chose this midpoint as a 'hidden don't know' (Sturgis et al. 2014). Nevertheless, the proportion of the last reason is estimated to be small in this study, since a 'Not sure' was included as an option to avoid the ambiguity (Ryan & Garland 1999), and online surveys potentially have less of this issue since people are more free to express their true opinions (Dillman 2000).

3.4.6 Expected time, money and yield comparisons between 2013/14 and 2014/15

To our knowledge, little publicly available information has been made available on the time and money spent before and after the neonicotinoid restrictions, and limited research has been done regarding the impact of neonicotinoids on crop yield (Godfray et al. 2015; but see Ahmed et al. 2001, Stanley et al. 2015, Budge et al. 2015). According to the average response on this issue, compared with 2013/14 season, agronomists spent more time on inspecting oilseed rape crops for pest damage, farmers spent more money for insecticide purchases, and crop yield would be reduced in 2014/15.

Changes in the time spent on pest control activities should be taken into account when considering the pros and cons of neonicotinoid seed treatments, because it represents a hidden benefit if agronomists/ farmers spend less time on pest control, but more time on other activities. As for insecticide purchases, Budge et al. (2015) indicates a negative relationships between neonicotinoid seed treatments and foliar sprays for UK oilseed rape, which could potentially lead to more insecticide costs to farmers after the restriction (Nicholls 2013).

Although most respondents expected lower oilseed rape yield in 2014/2015 than 2013/2014, this does not reflect the actual average yields (3.9 and 3.6 t/ ha respectively, DEFRA 2015a). It is difficult to assess the impact of neonicotinoid restriction on the yield change based on one year data, since the increased yield may well be due to nicer weather and lower pest pressure during the year (DEFRA 2015a).

3.4.7 Alternative methods of pest control in oilseed rape

The results from this study suggest a clear preference towards using new insecticides if these become available. This partly reflected a lack of confidence in the old chemical groups, but also an acknowledgement of the importance of insecticides for crop protection (Cooper & Dobson 2007). Developing new insecticides (especially with new modes of action) would help current insecticide resistance problems in oilseed rape. However, insecticide discovery has been a challenge, with the shrinking number of agri-chemical companies involved in the research, and the expensive and time-consuming development process (Sparks 2013).

Respondents also advised growers to use new oilseed rape varieties if available. Indeed, crop breeding in the UK has contributed to yield protection by improving crop resistance to pests and diseases (Carter et al. 2015). A new oilseed rape variety 'Amalie' has been recommended for use against TuYV in the 2016/17 growing season (AHDB 2016b), and a recently completed pre-breeding project has further explored the potential to develop commercial oilseed rape varieties to tolerate this virus infection (CIRC 2016).

With those who advised farmers to grow small areas of oilseed rape in the future, this concern has also been expressed through a farmer survey during 2014/15 by the Farm Business Survey (FBS) team (Scott & Bilsborrow 2015), where the most important reasons for a future reduction in area were crop rotations, reduced crop price, and cabbage stem flea beetle damage. When comparing the 2014/15 with 2013/14 (DEFRA 2015a), the total area has decreased by about 3% (22,000 ha).

In line with the experts' suggestions, the importance of IPM has also been emphasized by EU and UK policymakers (Hillocks 2012), and numerous UK organizations (e.g., LEAF - Linking Environment and Farming, Natural England). In order to develop further IPM for oilseed rape production, one of the most crucial aspects is to understand insecticide efficacy on pest control, and its changes over time due to resistance: this will be important for developing action thresholds to use chemicals strategically (Nault & Anthony 2010). Another crucial aspect of IPM, as expressed by experts in this study, is natural pest control. Many studies have been carried out to evaluate the impact of natural enemies on pest suppression in oilseed rape, and to seek methods of conserving them (Williams 2010). However, knowledge gaps still exist in this area (Williams 2010).

A big challenge will be to combine these two aspects when developing IPM strategies, so that the side effects of insecticides on natural enemies could be reduced to a minimum. Indeed, by conducting research among eight EU countries, (Geiger et al. 2010) have found consistent negative effects of insecticides on biological control potential.

Farmers would adopt new strategies only if they work better than current practices (Hillocks 2012). Profit is one fundamental aspect in the judgement. However, to our knowledge, little literature is available which estimates the influence of natural enemies on crop yield or net profits, especially for large scale field crops by conventional or IPM farmers (Sandhu et al. 2015; Letourneau et al. 2015), and none has focused on oilseed rape, partly because of the difficulty of conducting field experiments. More research is needed to estimate the economic value of this important service provided by natural enemies.

3.5 Conclusion

Insecticides used in UK oilseed rape production have been designed to be more efficient in controlling pests, and less harmful to non-target species and the wider environment. However, their efficacy levels are not fully understood, and may not be sufficient in the long-term, due to the limited publicly available studies and fast development of insecticide resistance in pest species. Similarly, it is difficult to assess their side effects, partly because little research has comprehensively compared the impacts of different insecticides in a standardised manner. The type and extent of benefits for farmers are also fundamental when assessing insecticides. For these reasons, the decision as to whether further to restrict neonicotinoid seed treatments in oilseed rape needs careful evaluation. It is a challenge to take into account the multi-faceted aspects when assessing an insecticide; one way forward could be to translate each aspect into economic values, and then apply cost benefit analysis. In order to do so, more research is needed regarding the influence of a chemical on crop protection, farm profit, the environment and related ecosystem services. This study provided an insight into these aspects, but limitations exist due to a relatively small sample of expert opinions.

Integrated pest management presents an important potential future strategy for oilseed rape production, and the importance of insecticides and natural pest control should be better recognised and incorporated. Economic valuation of pest control services by natural enemies for oilseed rape needs to be quantified, coupled with improved communication and knowledge exchange between government, researchers, consultants and growers.

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Chapter 4: European farmers’ incentives to promote natural pest control service in arable fields‡

Abstract

Integrated pest management (IPM) is widely encouraged among the European Union (EU) member states. The successful adoption of IPM techniques requires strong farmer motivation and participation. However, few studies have explored EU farmers’ incentives to promote natural enemies of crop pests in the fields, and none have addressed how this could be influenced by farmers’ recognition of natural pest control service. Based on interviews among arable farmers involved in an EU funded agri-environmental project across seven member states, natural pest control was perceived to be a less important contributor to crop production than soil fertility and pollination. Preferences toward managing semi-natural habitats for natural enemies were also relatively low, while insecticides were commonly used among participants. Ordinal logistic regression indicates that farmers’ decision to promote natural pest control was positively associated with the perceived importance of this ecosystem service for crop production. However, they expressed a relatively low confidence in the pest control efficacies of natural enemies compared with insecticides, especially under high pest damage levels. Farmers with greater income have more financial flexibility to adopt either pest control method. The environment surrounding a farm may also influence its owner’s willingness to promote natural pest control.

4.1 Introduction

Since Stern et al. (1959) introduced the concept of integrated pest management (IPM) as ‘applied pest control which combines and integrates biological and chemical control’, this method has gradually gained recognition worldwide as a key element in more sustainable agricultural systems (Birch et al. 2011; Barzman et al. 2015). Although its definition varies

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‡ This chapter has been submitted to a peer-reviewed journal as Zhang H., Potts S.G., Breeze T., Bailey A., 2017. European farmers’ incentives to promote natural pest control service in arable crops, *under review* (Land Use Policy, 2017/7/9). Zhang developed the concepts, reviewed, manipulated and interpreted the raw data sheets provided by each country participant, conducted the subsequent analyses, and wrote the manuscript. Bailey led on the development of the protocol for the farmer interviews from which the data for the analyses was derived. All co-authors provided assistance, and feedback on development of the manuscript. The estimated percentage contribution made by Zhang is 80%.

among studies and organizations (Bajwa & Kogan 2002), the key message is that IPM is a systemic approach which encourages the integration of multiple methods to control pests in a ‘safe, cost-effective, and environmentally friendly manner’ (Parsa et al. 2014).

IPM is also highly encouraged under the ‘EU Pesticide Package’, a suite of European Union legislation (EU 2009a-d). Member states are required to develop National Action Plans to support their professional pesticide users in following the eight general principles of IPM (EU 2009b-c). The first principle (prevention and suppression) stresses the importance of protecting and enhancing natural pest control in the fields (EU 2009b).

Indeed, natural pest control is an important ecosystem service in the agricultural sector, which could help suppress pest damage and, by reducing the unnecessary insecticide inputs, reduce incidence of pest resistance (Power 2010). Its value towards crop protection has been characterised through field experiments (Thies et al. 2011; Safarzoda et al. 2014), ecological modelling (Jonsson et al. 2014) and economic evaluation (Naranjo et al. 2015). In this study, ‘pests’ referred to are animal pests, and natural enemies as the related species that target these pests.

Natural pest control is negatively influenced by the on-going agricultural intensification (Crowder & Jabbour 2014), either through a subsequent increase in pesticides (especially insecticides) (Geiger et al. 2010), or the loss of (semi-) natural habitats from cropland expansion (Zhao et al. 2015). To enhance the contribution of this ecosystem service to crop protection, the EU Framework Directive 2009/128/EC has provided guidelines on using insecticides strategically: e.g., monitoring pest populations in the fields and using action thresholds to determine applications (Hallett et al. 2014). Also, as an important tool to conserve biodiversity, the agri-environment schemes (AES) have provided EU farmers options to establish/manage semi-natural habitats on their farmland (Batáry et al. 2015). This has shown positive effects on promoting natural pest control (Holland et al. 2016): e.g., hedgerows (Stutz & Entling 2011), beetle banks (Collins et al. 2002), and cover crops (Aguilar-Fenollosa et al. 2011).

Nonetheless, the successful adoption of these techniques requires strong farmer participation, which is also an important element in the IPM regime (Junge et al. 2009; Lefebvre et al. 2015). However, knowledge gaps remain in understanding EU farmers’ incentives to apply related techniques to promote natural pest control in the fields (Lefebvre et al. 2015). Although numerous studies have shown natural pest control is valuable for sustainable agriculture (Letourneau et al. 2009), few have examined whether it is valuable from a farmer’s perspective (Segura et al. 2004). To our knowledge, no studies have analysed the influence of farmers’ perceptions of natural pest control on their decision-making in promoting this ecosystem service.

Based on an interview survey with arable farmers in seven EU countries, this study assesses the potential factors influencing farmers’ decisions on whether to promote natural pest control in their fields. In particular, it focuses on how farmers’ perceptions of natural pest control service influence their conservation actions. In parallel, the potential factors influencing farmers’ decisions on using insecticides are analysed.

4.2 Materials and Methods

4.2.1 Interview area and process

To gather relevant information on farmer perception and management, 85 farmers participating in the EU funded LIBERATION (Linking farmland biodiversity to ecosystem services for effective eco-functional intensification, www.fp7liberation.eu) project across Germany (GE: 11 participants), Hungary (HU: 18), Italy (IT: 13), Netherlands (NL: 20), Poland (PL: 10), Sweden (SW: 5), and the United Kingdom (UK: 8) were face-to-face interviewed. They were recruited from the farmer networks associated with the research institutes involved in the LIBERATION project in each country. The interviewees represented the farm businesses who provided field sites to support experimental work within this project, which aims to quantify the contribution of multiple ecosystem services (e.g., natural pest control) towards crop production, and to analyse the effectiveness of environmental management practices (e.g., hedgerows) for promoting these ecosystem services. The participants were a combination of farm owners (82%), managers (27%) and tenants (18%). They were primarily arable farmers, and grew mostly wheat (100%), maize (45%), sugar beet (41%), and oilseed rape (34%). The interviews were conducted in the autumn and winter of 2014, after field sites were selected and initial experimental works undertaken.

4.2.2 Interview contents

The questionnaire (Appendix 4A) elicited information on farmers’ perspectives on three ecosystem services (natural pest control, pollination, and soil fertility) and disservices (pest, weed, and disease damage). For the scope of this paper, we focus on the following areas: (i) background information about the farms, (ii) preferences towards on-farm environmental management practices, (iii) perceptions of natural pest control service and pest damage.

The information about the farms included agricultural area (ha), average number of crops used in a rotation, average annual farm income (€, following a seven point scale from 1 = loss through to 7 => €100,000, and included a 'Prefer not to say' option) for the last two financial years, years of farming, whether a farm is in a designated area of environmental interest (0 = 'No', 1 = 'Yes'; the following questions with the same structure also used this code), and whether a farm is involved in an agri-environment scheme (AES).

The farmers were then asked to indicate their attitudes towards 17 environmental management practices (Table 4B.1 in Appendix 4B), covering those being implemented across the study sites and additional environmental options not implemented. This followed a three point scale: 1 = 'Dislike' to 3 = 'Like' (and also included an 'Unfamiliar' option).

Finally, the perceived importance of natural enemies and pest damage for crop production were captured by a four point scale, from 1 = 'Relatively unimportant' to 4 = 'Very important'. The number of perceived important natural enemy and pest species on-farm were also recorded. In terms of pest management, the number of methods used to promote natural pest control (Table 4B.2 in Appendix 4B) and whether the farmers use chemicals to manage pests were recorded.

4.2.3 Statistical analyses

All analyses were done using R 3.2.5 (R Core Team 2016), with significance levels set as 0.05. Mean values and standard deviations were used to summarize the data in the tables. If a data distribution is skewed, median values were also used to present the results to take into account outliers.

Information about farms and the perceptions of natural pest control service and pest damage were compared among seven countries using a Kruskal-Wallis one-way analysis of variance by ranks (R Core Team 2016) and related post-hoc tests (Pohlert 2014), to account for ordinal data characteristics and difference in data distribution. The main purpose to display the pairwise comparisons among countries for these variables is to describe the data.

For the environmental management practices provided in the survey, those that potentially provide semi-natural habitats with forage, shelter and reproductive opportunities for natural enemies were selected and grouped by the habitat management types reviewed from Holland et al. (2016) (Table 4B.1 and Fig 4B.1 in Appendix 4B). For multiple management practices in the same group, the average preference score was calculated to represent a respondent's opinion for this habitat type. The perceived preference for each habitat management was compared among seven countries using the same method as for the information about farms and the farmers' perceptions outlined above.

To compare the perceived preferences among habitat management types, the Skillings–Mack (Srisuradetchai 2015) and related post-hoc tests (Pohlert 2014) were conducted. Following the same method, the perceived importance of natural pest control was compared with the other ecosystem services and disservices in this study.

Then, ordinal logistic regressions were used to analyse the potential factors that influenced the farmers' decision to promote natural pest control (Christensen 2015a). The response variable was the number of methods mentioned by each participant to promote natural pest control, and the potential explanatory variables were the information about farms (Table 4.1) and perceptions of natural pest control service and pest damage (Table 4.3). Preferences for the habitat management practices (Table 4.2) were excluded in the model, because semi-natural habitats could potentially promote multiple ecosystem services, and it is unclear whether a respondent's opinion on a habitat type is mainly related with promoting natural pest control.

Based on the Kendall's Tau b association and related post-hoc tests (McLeod 2011; R Core Team 2016), the initial model included all variables from Table 4.1 and 4.3 that have statistically significant associations with the response variable (i.e., importance of natural pest control, farm income, and whether a farm was located in a designated area of environmental interest; Appendix 4B.3). Because country differences were acknowledged for several variables (Table 4.1, Table 4.3), the variable 'Country' was firstly included as a random effect in the initial model, but was then taken out due to its non-significance by a likelihood ratio test (Christensen 2015b).

Then, Wald statistics (the ratio of the coefficient to its standard error) were used to test whether the coefficient of each variable in the initial model was significantly different from zero, based on the normal distribution. If so, that variable was removed. Then, the rest of variables from Table 4.1 and 4.3 were added to the model one at a time. At each step, each variable that was not in the model was tested for inclusion in the model, and the most significant one was added to the model. This process continued until none of the remaining variables were significant when added to the model. Model convergence and fitness were assessed (Christensen 2015c), and McFadden's Pseudo R-Square was then estimated (McFadden 1973). Potential factors that influenced a farmer's decision to use insecticides for crop protection were modelled using the same methods.

4.3 Results

4.3.1 Information about farms

Based on the 85 EU farmers involved in the LIBERATION project, there were significant differences between countries in terms of farm size, with the UK participants having the greatest agricultural area (average 446 ha) and IT participants the smallest (average 17 ha) (Table 4.1). This was also reflected in the farm income, with UK reaching the highest annual income level (average >= € 100,000), and PL and IT the lowest (€1-20,000). Differences also existed in terms of the agri-environment scheme (AES) participation, with UK having the most participants involved (88%), while no participants in PL were involved. Across all countries there were similarities in the number of crops within a rotation (average three) and the number of years in farming (average 25 years).

Table 4.1. Pairwise comparisons among countries of the general information about the farms: mean (# of respondents; standard deviations).

	GE	HU	IT	NL	PL	SW	UK
Agriculture area (hectare)	94.9 (11; 70.5) ac	114.3 (18; 73.4) a	17.1 (13; 28.6) b	122.6 (20; 176.7) ac	43.7 (10; 52.8) bc	330.0 (5; 460.4) ad	446.3 (8; 178.8) d
# of Crops for a rotation	3.3 (11; 0.4) ab	2.9 (18; 0.8) b	3.3 (13; 0.9) ab	3.9 (20; 0.7) a	3.5 (9; 0.8) ab	3.4 (5; 0.6) ab	3.0 (8; 0.5) ab
Farm income	4.8 (8; 1.6) ac	4.3 (15; 2.2) ad	1.9 (13; 0.6) b	5.3 (12; 1.6) ac	2.4 (7; 0.5) bd	4.4 (5; 1.5) acd	6.6 (8; 1.1) c
Years of farming	25.3 (10; 15.5)	25.3 (18; 10.1)	29.3 (13; 9.2)	26.5 (20; 7.1)	21.8 (10; 7.8)	26.2 (5; 14.8)	26.5 (8; 18.1)
In a designated area of environmental interests?	0.09 (11; 0.3) ac	0.8 (18; 0.4) b	0.08 (13; 0.3) cd	0.0 (20; 0) ad	0.3 (9; 0.5) bcd	0.2 (5; 0.5) ac	0.5 (8; 0.5) bc
In an agri-environment scheme?	0.1 (7; 0.4) ab	0.6 (18; 0.5) ab	0.5 (10; 0.5) ab	0.5 (17; 0.5) ab	0 (7; 0) a	0.3 (4; 0.5) ab	0.9 (8; 0.4) b

Note: '#' denotes 'number'; farm income: the average annual farm income for the last two financial years, preceding the date of the survey (€, following a seven point scale: 1 = loss, 2 = 1-20,000, 3 = 20,001-40,000,…, 6 = 80,000-100,000, 7 = >100,000); questions follow the codes of: 0 = 'No', 1 = 'Yes'; different letters within a row indicate significant differences at $p < 0.05$.

4.3.2 Preferences toward habitat management types

Overall, the EU farmer participants had similar preferences towards various habitat management types suggested by the AES (average opinion 'Indifferent') (Fig 4.1). Preferences for the herbaceous ungrazed habitat, low-input cereal headlands, and undersowing/ cover crops were similar across countries ('Indifferent'). Italian and UK respondents expressed relatively high preferences for linear woody, grassy linear, and other AES habitats. Except for other AES habitats, Hungarian respondents expressed relatively low preference towards all options (Table 4.2).

Table 4.2. Pairwise comparisons among countries of the preferences toward habitat management types: mean (number of respondents; number of 'Unfamiliar' option; standard deviations).

	GE	HU	IT	NL	PL	SW	UK
Linear woody	2.6 (9; 0; 0.9) ab	1.5 (18; 0; 0.7) c	2.8 (13; 2; 0.4) a	NA	1.6 (8; 1; 1.0) bc	2.4 (5; 0; 0.9) ac	2.9 (8; 0; 0.4) a
Grassy linear	2.0 (8; 0; 0.6) ab	1.8 (18; 0; 0.7) a	2.6 (13; 1; 0.4) b	2.5 (10; 1; 0.8) b	1.7 (9; 2; 0.8) ab	2.8 (3; 0; 0.4) ab	2.4 (8; 0; 0.5) ab
Herbaceous ungrazed	2.3 (9; 0; 1.0)	1.8 (18; 0; 0.7)	1.4 (13; 1; 0.7)	1.9 (20; 3; 0.9)	1.4 (10; 3; 0.8)	NA	2.3 (8; 0; 1.0)
Low-input cereal headlands	2.3 (8; 0; 0.9)	1.7 (18; 1; 0.7)	2.6 (13; 4; 0.7)	NA	2.0 (9; 2; 1.0)	NA	2.0 (7; 0; 1.0)
Undersowing and cover crops	2.1 (8; 1; 0.4)	1.6 (18; 1; 0.6)	2.1 (13; 3; 0.8)	NA	1.6 (9; 0; 0.7)	2.2 (5; 0; 0.6)	2.0 (8; 2; 0.7)
Other AES habitats	1.9 (9; 1; 0.6) ab	1.9 (18; 1; 0.5) b	2.1 (13; 1; 0.9) b	1.2 (10; 1; 0.5) a	1.3 (9; 0; 0.6) a	1.4 (5; 1; 0.7) ab	2.3 (8; 0; 0.7) b

Note: these variables follow a three point scale: 1 = 'Dislike', 2 = 'Indifferent', 3 = 'Like'; different letters within a row indicate significant differences at $p < 0.05$. 'NA' is where no participants have provided answers. Linear woody habitat consists of hedgerows; grassy linear consists of buffer strips, grass field margins, and beetle banks; herbaceous ungrazed consists of wildflower strips; undersowing denotes undersown spring cereals; other AES habitats consist of land set aside and over winter stubbles. For detailed summaries see Table 4B.1 and Fig 4B.1.

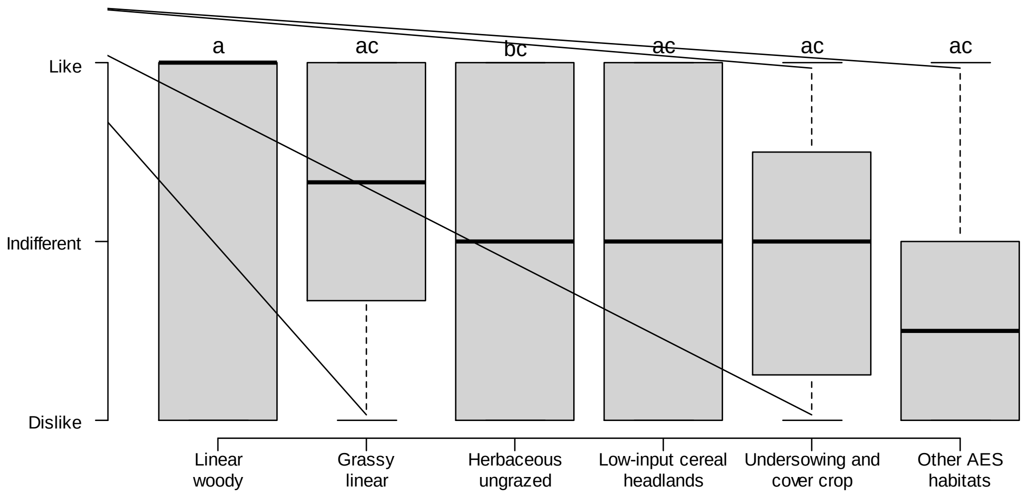

Fig 4.1. Boxplot of EU farmers' preferences toward habitat management types.

Different letters denote significant difference between two groups, with $p<0.05$.The number of respondents is 84. The p value for the Skillings–Mack test is 0.04.

4.3.3 Perceptions of natural pest control service and pest damage

The perceived importance of natural enemies for crop production was highest among SW and IT farmer respondents (average 'Very important'), and lowest for HU respondents ('Not as important') (Table 4.3). The average response from other countries was 'Important'. In terms of the most important natural enemies on farm, NL participants mentioned more species (average two) than GE and UK (one). Insecticides were commonly used across all countries (average 80%). The incentives to use chemicals due to a lack of natural enemies were highest among the NL, PL, SW and UK participants (average 88%) and were lowest among HU (24%). The number of ways used by respondents to promote natural pest control was lowest with HU and PL (median zero).

Table 4.3 Pairwise comparisons among countries of the perceptions of natural pest control service and pest damage: mean (# of respondents; standard deviations)

	GE	HU	IT	NL	PL	SW	UK
Importance of natural pest control	3.2 (9; 0.8) ab	2.1 (18; 1.0) a	3.3 (12; 1.1) b	2.7 (20; 0.7) ab	2.8 (9; 0.8) ab	3.6 (5; 0.6) b	2.8 (8; 1.4) ab
# of important natural enemies mentioned	1.0 (4; 0) ac	2.1 (15; 1.0) ab	1.0 (2; 0) abc	2.1 (17; 0.7) b	1.0 (3; 0) abc	2.0 (4; 2.0) abc	0.9 (8; 0.6) c
Importance of pest damage	3.4 (9; 0.7)	3.3 (18; 0.5)	3.2 (12; 1.0)	3.0 (20; 0.7)	3.7 (9; 0.5)	3.8 (5; 0.5)	3.4 (8; 0.8)
# of important pests mentioned	1.3 (9; 0.9) a	3.2 (18; 1.0) b	1.4 (9; 1.0) a	3.6 (18; 1.2) b	2.3 (8; 0.9) ab	3.0 (5; 3.5) ab	2.1 (8; 1.1) ab
Do you use chemicals to manage pests?	0.9 (8; 0.4)	0.8 (18; 0.4)	0.5 (11; 0.5)	1.0 (20; 0.2)	0.8 (10; 0.4)	1.0 (5; 0)	0.8 (8; 0.5)
Do you use chemicals due to lack of natural enemies?	0.4 (7; 0.5) ab	0.2 (17; 0.4) a	0.5 (6; 0.5) ab	0.8 (19; 0.4) b	1.0 (9; 0) b	1.0 (5; 0) b	0.9 (8; 0.4) b
# of ways mentioned to promote natural pest control	1.4 (9; 0.5) a	0.4 (18; 0.6) b	0.8 (13; 0.4) ab	1.4 (20; 0.9) a	0.1 (9; 0.3) b	1.4 (5; 0.5) a	1.6 (8; 1.3) a

Note: '#' denotes 'number'; importance of natural pest control/ pest damage follows the codes of: 1= 'Relatively unimportant', 2='Not as important', 3='Important', 4='Very important'; questions follow the codes of: 0 = 'No', 1 = 'Yes'; different letters within a row indicate significant differences at p < 0.05.

When comparing the perceived importance of different ecosystem services and disservices towards the success/failure of crop production among the member states (Fig 4.2), participants perceived natural pest control as the least important (average 'Important'), followed by three types of ecosystem disservices. Soil fertility received the most importance ('Very important'). The perceived importance of natural pest control also had the largest variation (from 'Not as important' to 'Very important'), whereas the others, except for soil ('Very important'), varied from 'Important' to 'Very important'.

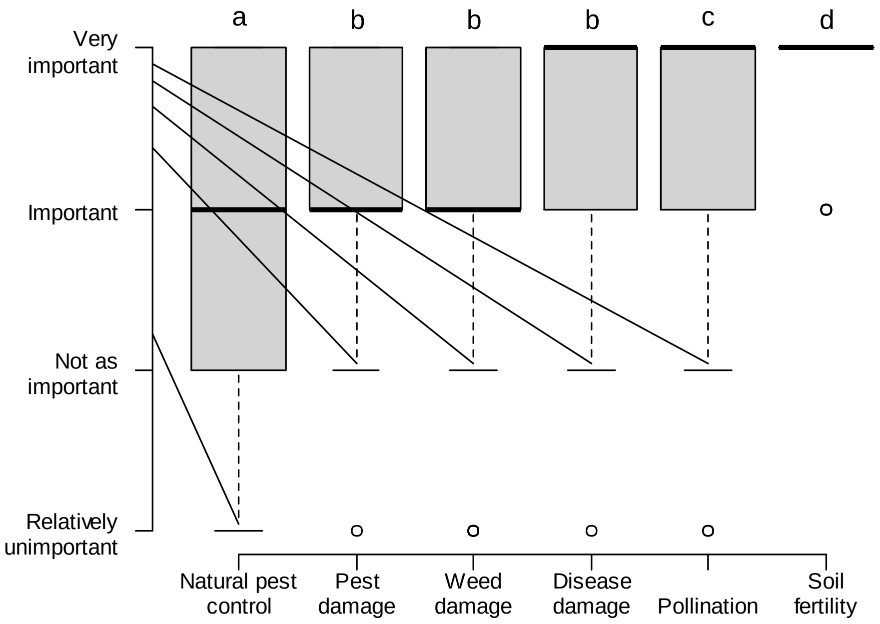

Fig 4.2. Boxplots of EU farmers' perceived importance of ecosystem services and disservices on the success/failure of crop production.

Different letters above the boxplots denote significant differences among groups, with p<0.05. The number of respondents is 83. The p value for the Skillings–Mack test is < 0.00001.

4.3.4 What influences EU farmers' decision to promote natural pest control?

The coefficients (β) of the ordinal logistic regression models are log-transformed (base=e) odds ratios (Table 4.4 and 4.5). Odds ratios (e^{β}) are achieved by comparing the odds/likelihood that an outcome will occur given an exposure, with the odds/likelihood of outcome occurring without that exposure (Szumilas 2010). For example, the predictor 'Importance of natural pest control' (Table 4.4) indicates that, the likelihood for an EU farmer to promote natural pest control when he/her view on the importance of natural pest control is 'Not as important' is 13 times higher than when the view is 'relatively not important'.

Thus, based on the 85 participants, EU farmers' decision to encourage natural pest control was positively associated with farm income and the perceived importance of natural pest control on crop production, but negatively associated with the number of perceived important pests listed, and whether a farm was located in a designated area of environmental interest (Table 4.4). The decision to use insecticide was positively associated with both income and a farmer’s perception of the importance of pest damage on crop production (Table 4.5). Country effect was not significant for either model.

Table 4.4. Ordinal logistic regression results of EU farmers’ decision to promote natural pest control. McFadden's Pseudo R-Square is 0.5.

Explanatory variables	β (standard error)	*z* value	*p*	Odds ratios (e^{β})
Importance of natural pest control*				
Not as important	2.6 (1.1)	2.3	0.02	13.0
Important	2.9 (1.1)	2.7	0.007	17.7
Very important	3.5 (1.1)	3.2	0.002	32.7
# of important pests mentioned	-0.4 (0.2)	-2.0	0.05	0.7
Farm income	0.6 (0.2)	3.5	0.0005	1.9
In a designated area of environmental interest?	-1.5 (0.6)	-2.4	0.02	0.2

Note: * Baseline category is 'Relatively unimportant'; ‘#’ denotes ‘number’; importance of natural pest control follows the codes of: 1= ‘Relatively unimportant’, 2=’Not as important’, 3=’Important’, 4=’Very important’; farm income: the average annual farm income for the last two financial years, preceding the date of the survey (€, following a seven point scale: 1 = loss, 2 = 1-20,000, 3 = 20,001-40,000,…, 6 = 80,000-100,000, 7 = >100,000); questions follow the codes of: 0 = ‘No’, 1 = ‘Yes’.

Table 4.5. Ordinal logistic regression results of EU farmers’ decisions to use chemical control. McFadden's Pseudo R-Square is 0.4.

Coefficients	β (standard error)	z value	*p*	Odds ratios (e^{β})
Importance of pest damage*				
Important	1.5 (1.2)	1.2	0.2	4.4
Very important	2.4 (1.3)	1.9	0.06	11.5
Farm income	0.6 (0.3)	2.6	0.009	1.9

Note: * Baseline category is ‘Not as important’; ‘Relatively unimportant’ is not included because only one respondent selected this category; importance of pest damage follows the codes of: 1= ‘Relatively unimportant’, 2=’Not as important’, 3=’Important’, 4=’Very important’; farm income: the average annual farm income for the last two financial years, preceding the date of the survey (€, following a seven point scale: 1 = loss, 2 = 1-20,000, 3 = 20,001-40,000,…, 6 = 80,000-100,000, 7 = >100,000).

The predicted probabilities of the response variables were plotted against each predictor, while keeping other predictors constant at their average values (perceived importance of natural pest control = ‘Important’, number of important pests mentioned= 3, farm income = € 40-60,000, whether a farm is in a designated area of environmental interests = ‘No’).

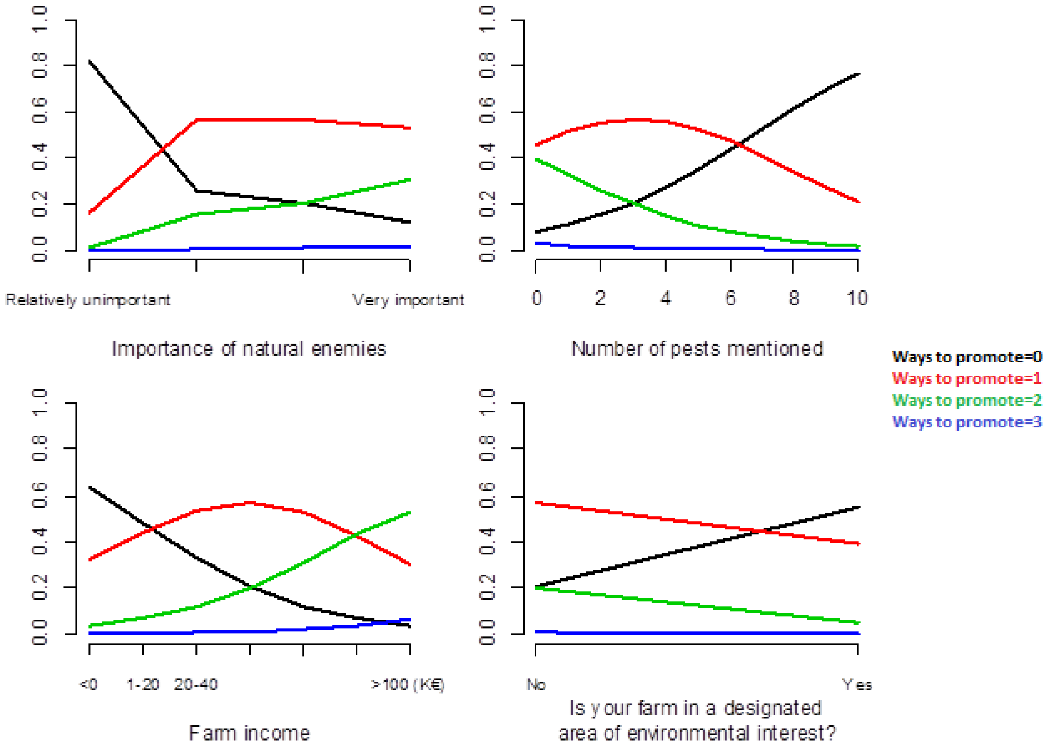

Fig 4.3. The predicted probabilities of EU farmers’ decision to promote natural pest control in relation to each predictor, while keeping other predictors constant at their average values.

For the predicted 95% confidence intervals see Table 4B.4 in Appendix 4B.

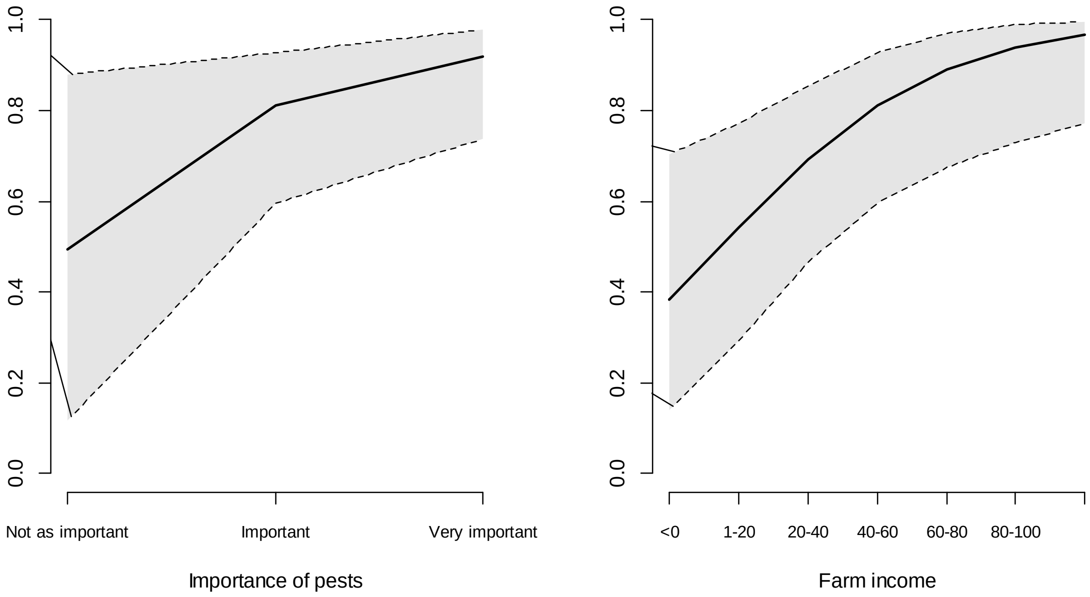

Fig 4.4. The predicted probabilities of EU farmers' decision to use insecticides in relation to each predictor, while keeping other predictors constant at their average values.

Grey areas denote 95% confidence intervals.

Based on the farmer interviews, an increase in farm income (Fig 4.3) decreases the probability that an EU farmer does not use any methods to promote natural pest control (zero method - denoted by the black line, from 64 to 4%), whereas the probability of taking actions increase (denoted by the green line, from 4 to 53%). Similar effects could be found for the perceived importance of natural enemies. By contrast, with an increase in the number of perceived important pests mentioned, the probability that a farmer takes actions to conserve would decrease, whereas the probability for no conservation effort increase (8 to 70%). It is also clear that (Fig 4.4), with an increase in farm income and the perceived importance of pest damage to crop production, the probability of using insecticides increases.

4.4 Discussion

Based on interviews with 85 farmers participating in the EU funded LIBERATION project across seven member states, we found that EU farmers' decisions on pest control practices were associated with psychological, financial, and environmental factors. For the first time, we quantified the influence of farmers' perceptions of natural pest control service and pest damage disservice on their behaviour in pest management. This is also one of the first studies that analysed how attitudes toward an ecosystem service would influence decision-making at an individual level (Poppenborg & Koellner 2013; Lamarque et al. 2014).

The positive association between the perceived value of an ecosystem service (in this study, natural pest control) and decision-making in related conservation action (promoting natural pest control in the cropland) has also been illustrated in Poppenborg & Koellner (2013). From the questionnaire design (Appendix 4A), a participant's evaluation of the importance of natural pest control service was based on its perceived contribution to crop production, and Fig 4.2 highlights a limited recognition for this ecosystem service compared with others (e.g., soil fertility). This issue has also been revealed in other studies (e.g. Heong and Escalada, 1999; Wyckhuys and O'Neil, 2007). One possible reason is that, despite some related reviews demonstrating the contribution of crop protection by natural enemies (Symondson et al. 2002; Letourneau et al. 2009; Thies et al. 2011), there are relatively large variations among individual studies. These variations are the product of a number of factors: e.g., climate (Abbott et al. 2014), landscape structure (Chaplin-Kramer et al. 2011; Martin et al. 2013), and farm management (Zhao et al. 2015). It is thus difficult to devise an experiment that would provide sufficient, observable evidence that natural pest control would contribute to a crop production system in a certain location that matches any individual farmer's situation. This potentially decreases EU farmers' confidence towards this ecosystem service.

However, the perceived value of natural pest control could potentially be increased if other contributions by this ecosystem service were taken into account: e.g., reduction in insecticide resistance, improvement in workers' health, and protection of the wider environment (Lefebvre et al. 2015; Naranjo et al. 2015). Consequently, EU farmers' willingness to promote natural pest control would be increased.

This study revealed a negative association between the number of perceived important pest species mentioned by a farmer participant with his/her decision to promote natural pest control in the fields. The association test also showed a negative link between the perceived importance of pest damage to crop production and decisions on the conservation actions (Table 4B.3; Kendall's tau b test = -0.16). This may further justify farmers' relatively low confidence in sufficient crop protection by natural enemies, especially when pest damage is at a high level. Indeed, limits of natural pest control under high pest damage levels have been demonstrated by field experimental studies (Collins et al. 2002). By comparison, a positive association between the perceived importance of pest damage and decision to use chemical control was revealed (Fig 4.4). Since their introduction, insecticides have proved their effectiveness in controlling pests and improving crop production worldwide (Cooper & Dobson 2007). They are also commonly used during the post-harvest storage phase (Waterfield & Zilberman 2012). However, it should be noted that using chemicals does not guarantee success: failures have occurred partly due to the development of insecticide resistance in pests (Sparks & Nauen 2015). Insecticide efficacy could also be negatively influenced by weather conditions and the timing and method of application. Nonetheless, it is economically reasonable for farmers to apply insecticides, especially when they perceive pest damage to be high (Popp et al. 2013). They would also apply insecticides for insurance purposes to reduce potential risk of crop loss by pests (Cooper & Dobson 2007).

The negative association between the number of perceived important pest species with the decision-making on conservation, however, may also indicate that farmers have relatively low confidence that the related environmental management options could enhance natural pest control in croplands. This could be reflected by the relatively low preference levels ('Indifferent') with large variations among the semi-natural habitat management types (Fig 4.1). Indeed, although mounting evidence suggests that semi-natural habitats could support natural enemies by providing food resources and shelters (Bianchi et al. 2013; Holland et al. 2016), limited studies have been conducted to show that they could enhance natural enemy densities in the adjacent crop fields and/or increase natural pest control efficacies (Dicks et al. 2016; Holland et al. 2016).

Studies have found that farmers' perception of risk could influence their behaviour in pest control (Milne et al. 2016), and that farmers with more income are on average less risk adverse (Bar-Shira et al. 1997). This could partly explain the positive association between farm income and farmers' decision to adopt related environmental managements to promote natural pest control service (Chandran 2014; Allahyari et al. 2016). Indeed, higher income gives farmers a greater ability to bear the risk of potential financial loss from a less effective management option. It also allows farmers to have more flexibility to invest in related technologies in the first place (e.g., by purchasing related equipment and hiring expertise) (Cullen & Warner 2008; Waterfield & Zilberman 2012; Lefebvre et al. 2015). More financial flexibility may also play a positive role in farmers' decision to use insecticides (Fig 4.4; Anang & Amikuzuno 2015). On the other hand, effective insecticides could help maintain or increase crop yields, thus deliver more income to the users (Cooper & Dobson 2007; Popp et al. 2013).

Environmental factors may also influence a farmer's decision-making processes (Singh & Dhillon 2004; Wyckhuys & O'Neil 2010). It is not clear why an EU farmer's decision to encourage natural pest control was negatively associated with whether his/her farm was located in a designated area of environmental interest (e.g., nature reserve). One possible reason is that a farm located in such protected locations is potentially adjacent to already well-structured (semi-) natural habitats, thus reducing the willingness/needs of its owners to take conservation actions. Another reason could be that farm owners in these locations have specific restrictions on managing the land (JNCC 2016).

In addition to the factors assessed in this study, many other factors may also influence farmers' behaviour in pest control. One of the most important is the individual knowledge level. Studies show that by gaining more awareness of the existence and role of natural enemies in the fields, farmers become more capable to adopt alternative pest control techniques (Segura et al. 2004; Wyckhuys & O'Neil 2007). Other potential influences include: farmers' environmental awareness, accessibility to information, and market interventions (Lefebvre et al. 2015). Because the farmer participants in this study were involved in an agri-environmental project, they might be more aware of the natural pest control service and/or environmental protection than the general EU arable farmer population. Thus the average EU arable farmers' recognition of this ecosystem service and related conservation options might be even lower.

Compared among the seven EU countries, HU participants expressed relatively low preference for most of the habitat management types, while IT participants had relatively high preference for these aspects. Because few studies have analysed farmers' attitudes to biodiversity conservation/sustainable farming in these two countries (Siebert et al. 2006; Defrancesco et al. 2007; Kelemen et al. 2013), the reasons for the difference are not clear. One reason might be that as a relatively new EU member state, HU farmers have less experience and/or less support historically from the government to adopt various management options. This may be reflected by the lower AES expenditure (€/ha) in HU than in IT (Batáry et al. 2015). Also, because of the variations in the agricultural systems and social-economic factors among EU member states, the drivers influencing a farmer's decision in pest management could differ by countries. These differences could potentially be identified with a larger sample size. Indeed, to better implement IPM and related conservation policies in the EU, more research should be conducted to compare farmers' attitudes to these aspects among the member states (Babai et al. 2015; Lefebvre et al. 2015).

4.5 Conclusion

Based on the interviews among EU arable farmers who participated in an agri-environmental project, this study analysed farmers' incentives to promote natural pest control in the fields. Although strongly encouraged under the EU IPM legislation, farmer participants expressed a relatively low recognition for this ecosystem service, and low preference towards the related AES habitat management types. On the other hand, using insecticides was a consensus among the member states. EU farmers' decision to promote natural pest control was positively associated with their attitudes toward the perceived importance of this ecosystem service on crop production. However, they expressed a relatively low confidence in the effectiveness of pest suppression by this mechanism, especially under high pest damage levels. Farmers with greater income would have more financial flexibility to adopt related conservation actions. The environment surrounding a farm may also influence its owners' willingness to promote natural pest control. More field studies should be conducted to analyse the efficacy of natural pest control and the effectiveness of related conservation management options for the major crop production systems that are relevant for the EU arable farmers. Future work should also explore the drivers of potential differences in farmers' uptake of these conservation actions within and between the member states.

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Chapter 5: Discussion

5.1 Overview

Integrated pest management (IPM) is a sustainable pest management system which is thought to provide long term economic, health, and environmental benefits to farmers and society. Encouraging natural pest control service, strategic use of insecticides, and strong farmer participation are three key and complementary tools to promote IPM; however, major knowledge gaps remain in these areas for arable crop production. This thesis provides new insights into three of these gaps: Chapter 2 presents the first study to estimate the economic values of natural pest control service in wheat within a UK context; Chapter 3 presents work comparing experts' perceptions of the pest control efficacies and side effects among the available insecticides used in UK oilseed rape (Godfray et al. 2015; Zhang et al. 2017); and Chapter 4 presents the first study to analyse the influence of farmers' perceptions of natural pest control on their decision-making in promoting this ecosystem service. In this discussion chapter, findings from the case studies are summarised, and recommendations derived for researchers and policymakers. Limitations of the methodologies used in the research chapters are discussed, and potential opportunities for future work are highlighted.

5.2 Synthesis of findings in the wider context

5.2.1 Valuing natural pest control service in arable crops

This thesis estimated the value of natural pest control service in arable crops from three perspectives.

First, by using an economic surplus model and a natural enemy exclusion experiment, Chapter 2 demonstrated that the predators and parasitoids of the grain aphid in wheat fields could provide economic benefits of up to £2.3 Million per year to growers and consumers in the South East England wheat market. However, because of the conservative assumptions used in the model, this value could potentially be higher. 71% of these economic benefits would go to farmers, therefore providing an incentive for them to promote natural pest control service in their wheat fields (Östman et al. 2003). However, the scale and especially the distribution of benefits is influenced by the variations of price elasticities of supply and demand for wheat in South East England (Alston et al. 1998). Although sensitivity analyses on elasticities suggest that the proportion of benefits received by farmers is likely to remain fairly large (Table 2.3), this estimate is uncertain due to the paucity of existing data on these two indicators.

Second, two thirds (67%) of agronomists and entomologists surveyed perceived that arthropod natural enemies were important for UK oilseed rape production (Chapter 3; Zhang et al. 2017). Without insecticide treatments, 57% of respondents suggested that arthropod natural enemies in the fields could exert 1-20% control of the major pests of oilseed rape (cabbage stem flea beetle, pollen beetle, peach – potato aphid), and 32% suggested that 21-50% control could be achieved. The potential to use this ecosystem service for oilseed rape protection has been summarised by Williams (2010). However, because of the difficulty of conducting field experiments, little data is available on the actual contribution of natural enemies towards the economic gains of oilseed rape growers (either by maintenance of yields or reduction of insecticide inputs) (Naranjo et al. 2015; Zhang et al. 2017).

Similarly, 64% of European Union (EU) arable farmers interviewed also acknowledged the importance of this natural pest regulation service for crop production (Chapter 4). However, natural control of animal pests was considered to be the least important contributor to the success/failure of crop production among the other surveyed ecosystem services (soil fertility and pollination) and disservices (animal pests, diseases, and weeds) (Fig 4.2). Indeed, previous studies have also identified the limited recognition of natural pest control service by farmers (Heong & Escalada 1999; Wyckhuys & O'Neil 2007). One possible reason for this is farmers' low confidence of the pest control efficacies of natural enemies relatively to insecticides, especially when pest damage is at a high level (Chapter 4).

Indeed, by integrating three grain aphid infestation levels in the ecological-economic model, Chapter 2 estimated that the annual economic benefits provided by natural pest control (predators and parasitoids) under high pest infestation level would be £1.5 Million lower than medium level (£0.8 Million and £2.3 Million respectively). Field experimental studies have also shown the lowered pest control efficacies by natural enemies under high pest infestation levels (Collins et al. 2002).

5.2.2 Understanding the benefits and risks of insecticides

As another important tool in the IPM regime, the reliance on insecticides is expressed by both experts and arable farmers. In a hypothetical situation, where neonicotinoid seed treatments would be permanently banned for oilseed rape protection in the UK, the most popular alternative pest management strategies favoured by three quarters of experts (76%) is to use new insecticides if available (Fig 3.10). Most European arable farmer respondents (80%) apply insecticides with little difference among countries (Table 4.3), and their willingness to use chemical pest control would be expected to increase with higher perceived pest damage problems (Fig 4.4).

The relatively high confidence in chemical pest control, in comparison to natural pest control expressed by the survey respondents, relates to the relatively high pest control efficacies of insecticides (Cooper & Dobson 2007; Popp et al. 2013). However, insecticide pest control efficacies can be influenced by various factors, such as: weather conditions, timing and methods of application, and plant growth stage (Nault & Anthony 2010; Slater et al. 2011). Further, a more prominent effect on efficacy comes from the evolving insecticide resistance in target pests (Sparks & Nauen 2015). Indeed, for each key pest in UK oilseed rape, older insecticidal chemical groups were perceived to be less efficient than the newer ones (Table 3.3), which has also been revealed in Bass et al. (2014).

For example, due to the resistance developed in peach–potato aphid in UK (Table 3E.4), experts perceived that pyrethroids were able to suppress 1-20% of this pest in oilseed rape in the 2013/14 season, the lowest rate among the six available insecticides (Table 3.3). As for controlling grain aphid damage in UK wheat, although pyrethroids are currently relatively efficient, their efficacies could potentially decrease due to further development of resistance in this pest (Foster et al. 2014; AHDB 2015; Dewar et al. 2016). Chapter 2 illustrated that the potential evolving resistance in grain aphid may raise input costs as greater numbers of treatments become necessary, increasing the potential economic value of natural pest control service (Table 2.3). This further supports growing worldwide efforts to encourage natural pest control, and reduce the volume of unnecessary insecticide applications through well-designed IPM programs.

In addition to the risk of decreasing efficacies in pest control, insecticides may also cause side effects on non-target species and the wider environment (Zhang et al. 2017).

Indeed, the neonicotinoid restriction in EU (since end of 2013) is primarily based on the Commission adoption of the precautionary principle given the well-established evidence showing that there are a range of negative lethal and sub-lethal impacts on both managed and wild pollinators (European Commission 2013). However, although many studies contributed to this evidence base (e.g., Godfray et al. 2015; van der Sluijs et al. 2015; EASAC 2015; IPBES 2016), it still has many gaps and biases, including study areas (mostly in Europe or North America), active ingredients (mostly imidacloprid), and bee species (mostly the western honey bee) (Lundin et al. 2015; Walters 2016). The uncertainty over the broader side effects of neonicotinoid use has also been highlighted in this study (Fig 3.5 and 3.6). Furthermore, little is known about whether neonicotinoids would cause more overall side effects on non-target species and the wider environment than other chemicals, a key criterion when selecting insecticides in the IPM programs (Damalas & Eleftherohorinos 2011; Zhang et al. 2017).

5.2.3 Arable farmers' incentives to promote natural pest control

In Chapter 4, EU arable farmer participants were less motivated to rely on natural pest control service than to use insecticides. Although the agri-environment schemes (AES) have provided EU farmers with support to help establish and/or manage semi-natural habitats on their farmland (Batáry et al. 2015), the farmer participants in this study showed a low preference towards these options (Table 4.2, Fig 4.1). This could be partly because limited evidence is available to demonstrate that these conservation management efforts can enhance the pest control efficacies by natural enemies in the crop fields (Dicks et al. 2016; Holland et al. 2016).

By using ordinal logistic regression, this study showed for the first time that EU arable farmers' decisions to encourage natural pest control are positively associated with the perceived importance of this ecosystem service to crop production (Fig 4.3). Thus, their willingness to promote natural enemies of pests could be further enhanced if more evidence on the effectiveness of natural pest control service is generated and disseminated in a manner meaningful to farmers (Segura et al. 2004; Wyckhuys & O'Neil 2007). Arable farmers with more income tend to have more financial flexibility to adopt natural pest regulation related conservation actions (Waterfield & Zilberman 2012; Allahyari et al. 2016). This study also indicated that an EU farmer's decision to encourage natural pest control service was negatively associated with whether his/her farm was located in a designated area of environmental interest (e.g., nature reserve) (Fig 4.3). One possible reason for this is that farms located in protected locations are potentially adjacent to already high quality (semi-) natural habitats, thus reducing farmers' willingness/need to undertake conservation actions.

5.3 Recommendations

5.3.1 Better integration of natural enemies with insecticide use in pest control decision-making

The three case studies in this thesis reveal that both natural and chemical pest control have benefits and risks, depending on context, in arable crop fields. As two key elements in the IPM regime, it is thus of vital importance to integrate them in an additive and complementary manner to reduce the risks associated with pest damage. Indeed, this has been one of the main goals of IPM since its inception (Stern et al. 1959).

However, up to now, few explicitly validated examples of such integration have been made (Naranjo et al. 2015). One important reason for this lack of integration is the negative side effects of insecticides on natural enemy populations and the pest control service they provide (Zhang et al. 2017). However, as suggested by Naranjo et al. (2015), because more selective insecticides have become available, their negative impacts on beneficial species (including natural enemies) could potentially be reduced. For example, the in-field Hazard Quotient method showed that pirimicarb (a Carbamate active ingredient that targets aphids) has relatively low side effects on non-target arthropods (Fig 3.2; Bacci et al. 2012). Thus, pest suppression by natural enemies may become less hindered by insecticide applications in the same crop fields (Gentz et al. 2010).

Apart from selecting a more targeted insecticide, application methods should also be carefully designed to reduce the exposure of natural enemies. One potentially viable strategy is to use the action threshold methods (applying insecticides only when the threshold level of pest infestation is reached so as to prevent subsequent crop damage) to control pests, which could potentially reduce the intensities of insecticide applications (Nault & Anthony 2010; Hallett et al. 2014; Barzman et al. 2015). Chapter 2 also indicated that using this method to control grain aphid could enhance the economic benefits provided by natural enemies to wheat farmers, providing a financial incentive for farmers to use this spraying strategy (Fig 2.4). However, action thresholds in IPM programs need to be further refined to be more effective (e.g., accounting for insecticide efficacies; Nault & Anthony 2010) and more practical to farmers (e.g., developing quick and simple sampling methods; Castle & Naranjo 2009).

5.3.2 Improve knowledge exchange among scientists and stakeholders

Through analysing three aspects of IPM in arable crops, this study revealed the importance and value of having strong interaction and knowledge exchange among diverse scientists and stakeholder groups (Naranjo et al. 2015).

Indeed, IPM is a complex regime that requires cooperation among scientists of various disciplines (e.g., crop scientists, ecologists and economists) and stakeholders (e.g. government, growers, extensionists and agrochemical industry) to properly develop and implement (Lamichhane et al. 2016). This is demonstrated when valuing the economic benefits provided by natural pest control in wheat production, where ecological data (from natural enemy exclusion experiments) and economic methods (economic surplus) are integrated (Chapter 2). Another interdisciplinary research example in IPM is to analyse the net benefits/costs of using a certain insecticide for crop protection, taking into account its influences on pest control, crop yields, human health and the wider environment (Pimentel 2005). To ensure efficient cooperation between ecologists and economists, ecologists are encouraged to measure economic indicators when conducting field experiments (e.g., costs of machineries and labour; Letourneau et al. 2015), and economists need to understand ecological processes in order to properly integrate these aspects into the evaluation modelling (e.g., phenology of the pest and natural enemy species; Harrington et al. 2007).

Decision-making regarding IPM often relates to the interests of particular stakeholders. This is prominent in insecticide regulations (e.g., neonicotinoid restriction; Maxim & van der Sluijs 2007; Zhang et al. 2017) where different stakeholder groups have their own concerns regarding the regulations (e.g., farmers are concerned about future crop production risks, environmental agencies are concerned about environmental risks), and those providing scientific evidence on the benefits/risks of an insecticide are rarely those making the political decisions. Thus, in order to achieve more sustainable use of insecticides, it is of vital importance to provide platforms (e.g., surveys, seminars, and focus groups) to exchange relevant knowledge and concerns among stakeholders (Calliera et al. 2013; Zhang et al. 2017).

Among the stakeholder groups, farmer participation is crucial to ensure the wide adoption of IPM (Lefebvre et al. 2015), which has been stressed throughout this study. Foremost, impacts on farmer profits need to be taken into account when designing/testing/promoting alternative pest management strategies (Chapter 2 & 3). However, other factors (e.g., farmers' perspectives toward natural pest control service, complexity of the related techniques) which may influence farmers' behaviour in pest control also need to be considered (Chapter 2 & 4).

5.4 Assumptions and methodological limitations

5.4.1 Assumptions of ecological-economic modelling

In Chapter 2, the economic surplus method was used to estimate the monetary value of natural pest control service. To our knowledge, this method is among the best available means to estimate the flows of economic values provided by an ecosystem service in agriculture (Letourneau et al. 2015; Breeze et al. 2016). However, some implicit assumptions need to be made to apply this method: i) the agricultural product is homogeneous in a competitive market, and ii) the cost changes for which we have data are applicable across the whole region of production for the market (Alston et al. 1998). Similar to Letourneau et al. (2015), the wheat crop has been modelled as homogeneous competitive product before, and South East England is a relatively small geographic area compared with the wheat market available to the UK, so these assumptions are unlikely to be too problematic.

Then, specific to this case study, various assumptions were necessary to make due to the limitations of available data and/or knowledge, which could potentially influence the model output (as outlined below). However, as discussed in Chapter 2, these assumptions have probably led to a conservative, under-estimate of the economic value of natural pest control service. Furthermore, a set of sensitivity analyses were also conducted to investigate the influences of several key indicators (Table 2.3). Specifically:

1) It was assumed that pyrethroid sprays could successfully control grain aphid damage to the extent that wheat yields would not be influenced (Song & Swinton 2009; Letourneau et al. 2015). This is a reasonable assumption since pyrethroid sprays are currently relatively

efficient to control grain aphid (Dewar et al. 2016). However, failures could occur due to specific field conditions (e.g., high wind speeds may deposit chemicals off the target crops before they take effects; Gill & Garg 2014).

2) It was assumed that this experiment represents a normal level of natural pest control in the wheat fields in South East England. This could be a fair assumption because the crop management practices in the experimental field sites represent the typical practices done in this region (e.g., fertiliser doses, sowing dates), thus the potential anthropogenic disturbance towards natural enemies could be similar. However, the abundance and performance of natural enemies could also be influenced by numerous other complex biotic and abiotic factors (e.g., soil characteristics, climates; Chapter 1).

3) A linear relationship was assumed between the peak grain aphid densities with natural enemies in the fields and those without (Eq. 7). This is a conservative assumption, because higher pest densities could potentially increase the probability of natural enemies encountering their prey, thus increasing the efficacy of natural pest control (Safarzoda et al. 2014). Thus the economic benefits provided by these natural enemies could potentially by higher.

4) It was assumed that the natural pest control rates are the same between no-spray and action threshold-based spray (AT) fields (Eq. 7), whereas the control rates in the no-spray fields are potentially higher (due to less disturbance towards the performance of natural enemies from insecticides; Birkhofer et al. 2011); Thus this is a conservative assumption, and the economic benefits provided by these natural enemies could potentially by higher.

5) To estimate the proportion of no-spray wheat fields in South East England ($\sigma_{\text{no-spray}}$ in Eq. 1), the average percentage of organic wheat fields in England for the past five years (2010 to 2014) was used (Table 2.2; DEFRA 2016). However, this indicator may vary among the English regions. Similarly, the price elasticities of supply and demand for wheat in the South East England were the same as the estimates for the EU15 (the 15 Member States, including UK, in the European Union prior to the accession of ten candidate countries on 1 May 2004). However, they may vary for a smaller regional market.

6) To estimate the proportion of AT fields (σ_{AT} in Eq. 1), we assumed that the average percentage of wheat fields without insecticide sprays from 2010 to 2014 represented the

sum of no-spray and AT fields (Table 2.2; Garthwaite et al. 2010, 2012, 2014). However, in reality, the proportion of AT fields to control grain aphid might be higher, because many insecticide sprays in wheat fields are applied to prevent/control aphid vectors of the barley yellow dwarf virus in the autumn, rather than to control grain aphid damage in the summer (Dewar et al. 2016).

5.4.2 Limits of survey research

Survey research is another main tool used in this thesis: first an online survey targeting experts in UK oilseed rape production (Chapter 3; Zhang et al. 2017), and second face-to-face interviews among EU arable farmers who participated in the EU-funded LIBERATION project (Chapter 4). Survey research methods are indispensable in social science approaches (Saris & Gallhofer 2007), and are commonly used to exchange knowledge on an issue among stakeholders (Verbeke et al. 2015; Zhang et al. 2017), and to conduct behavioural research (Mullendore et al. 2015; Chapter 4). However, like all other research methods, survey research has its limitations, with the two main ones being the potential sampling error (when the survey sample does not represent the population from which it has been drawn) and the measurement error (when the survey statistics differ from the true values) (Kelley et al. 2003; Stanton et al. 2012).

To minimize sampling error, it is very important to distribute the survey to a representative sub-population, so that the collected data sample is representative of the larger population (Kelley et al. 2003). However, this is often difficult to achieve, partly because of the difficulty in collecting the relevant contact information across a sufficient sample. One way to reduce sampling error (within the limits of funding and time) is to contact as many relevant people as possible, which has been the method used in Chapter 3. In Chapter 4, however, the farmer respondents were all already participating in agri-environmental projects, meaning that they might be more aware of the natural pest control service and/or environmental protection than the general EU arable farmer population. Thus the average EU arable farmers' recognition of this ecosystem service and related conservation options might be even lower than was revealed in Chapter 4. It should also be noted, however, that even if the survey was sent to a wider group of all relevant farmers, those that are more interested in the topic will still have higher tendencies to participate in the study (Khazaal et al. 2014).

To minimize measurement error, both Chapters have used appropriate statistical analyses to account for the characteristics of survey data, which are often ordinal from the Likert-type scales used in the questionnaires (Appendix 3B & 4A). Unavoidably, however, many survey data are based on estimates by respondents (especially in Chapter 3), which may not reflect the actual effects within the field. To address this limitation, besides carefully designing each question and searching for relevant experts, we also captured the certainty levels of some responses, to reflect the confidence of experts in their answers (Table 3.2). This may also help identify general knowledge gaps in the issues.

5.5 Future work

Overall, as highlighted in several places in the thesis, much more research is needed to provide the evidence necessary to facilitate the wider adoption of IPM in arable crops.

The ecological economic model developed to analyse the economic value of natural pest control service in Chapter 2 could potentially be adapted to other crop-pest systems in other regions. Because IPM is a holistic and systematic system that involves multiple strategies (Ehler 2006; Barzman et al. 2015), further work should also address the potential contribution from other related elements of IPM, and if possible, the interactive effects of integrating different methods (e.g., timing of insecticide applications, installation of beetle banks; Lefebvre et al. 2015). This would require the researchers to measure the monetary inputs and outputs in field experiments when testing the efficiencies of these other related IPM techniques (Letourneau et al. 2015). Other potential factors could also be included in the evaluation process, e.g.: how trophic interactions between natural enemy assemblages may affect their pest control efficacies (Martin et al. 2013); if several insecticidal products are available to control a certain pest, which one(s) could mostly enhance the values of natural pest control when using IPM related application methods (e.g., action thresholds; Nault & Anthony 2010); and how future climate change may influence the levels of pest infestation, the abundance of related natural enemies, and their pest control efficacies (Diehl et al. 2013).

When deciding which insecticides to use in IPM, both efficacies and side effects need to be compared among the available insecticides for a target pest. In order to do so, more research is needed regarding the influence of a chemical on i) crop protection, ii) farm profit, iii) the environment, and iv) related ecosystem services, and how these may vary under potential changes of insecticide resistance, climate, and insecticide regulations (Godfray et al. 2015; Budge et al. 2015; IPBES 2016). It is a challenge to take into account these multi-faceted aspects when assessing an insecticide; one way forward could be to translate each aspect into economic values, and then apply full cost benefit analyses (Pimentel 2005; Zhang et al. 2017). Surveys among relevant stakeholders provide an important platform to exchange knowledge and concerns on insecticide regulation issues, and the questionnaire designed in Chapter 3 could potentially be adapted to assess other insecticides.

The survey designed in Chapter 4 and its related statistical analyses could also be adapted to analyse farmers' incentives and concerns to promote natural enemies in the arable crop fields in other regions. Future survey research could target a key arable crop grown in a region (e.g., wheat in UK) in order to have a better understanding about farmers' perspectives to adopt IPM principles to manage that specific crop. This would help researchers and policymakers to design/promote better targeted IPM tools. A larger scale survey across different regions would also help to explore the drivers of potential geographical differences in farmers' uptake of these techniques (Babai et al. 2015; Lefebvre et al. 2015). Besides the ones analysed in this study, other potential factors that may influence farmers' adoption of IPM principles could be included in the questionnaire, including farmers' knowledge on the existence and role of natural enemies in the fields (Wyckhuys & O'Neil 2007), their risk perspectives about potential health hazards and environmental pollutions from insecticide exposure (Cuyno et al. 2001; Khan & Damalas 2015), and the pest management strategies adopted by neighbours (Meir & Williamson 2005).

5.6 Concluding remarks

By conducting three case studies on the key elements of integrated pest management, this thesis provides important new evidence which could help promote more sustainable approaches to arable crop production. It quantifies the economic value of natural pest control service, while acknowledging its limits in crop protection, especially under high pest infestation levels. The study also highlights the reliance and importance of insecticidal pest control in current agriculture, and the difficulty in selecting suitable insecticides for IPM; primarily due to a lack of information on the net benefits/costs of a chemical when taking into account its pest control efficacies as well as its side effects. Importantly, this research suggests that great potential exists to integrate both these two pest control mechanisms in arable crop protection. Interdisciplinary research (especially between ecology and economics) and knowledge exchange among stakeholders are essential to understand the challenges and identify opportunities for further development and adoption of IPM in arable crops.

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Appendix 3A: Insecticide development for oilseed rape protection in UK: methods and figures

Information on insecticides was collected from the Fera pesticide usage surveys (Fera 2015) . Since 1990, the surveys on oilseed rape have been conducted biennially, and did not include Northern Ireland until 2010. However, oilseed rape has not been widely grown in Northern Ireland. In order to be comparable, information for Northern Ireland was omitted. Foliar sprays and seed treatments were analysed separately by insecticide chemical groups, and total weights (kg), total area treated (ha) and application rates (g/ha) were compared.

Before 1990, only four surveys of arable crops, including oilseed rape, were conducted, mainly targeting England and Wales. Due to the lack of information on the formulated mixtures within individual products, the total weight of individual active ingredients cannot be separated. Thus only the total treated areas (ha) with individual chemical groups could be compared.

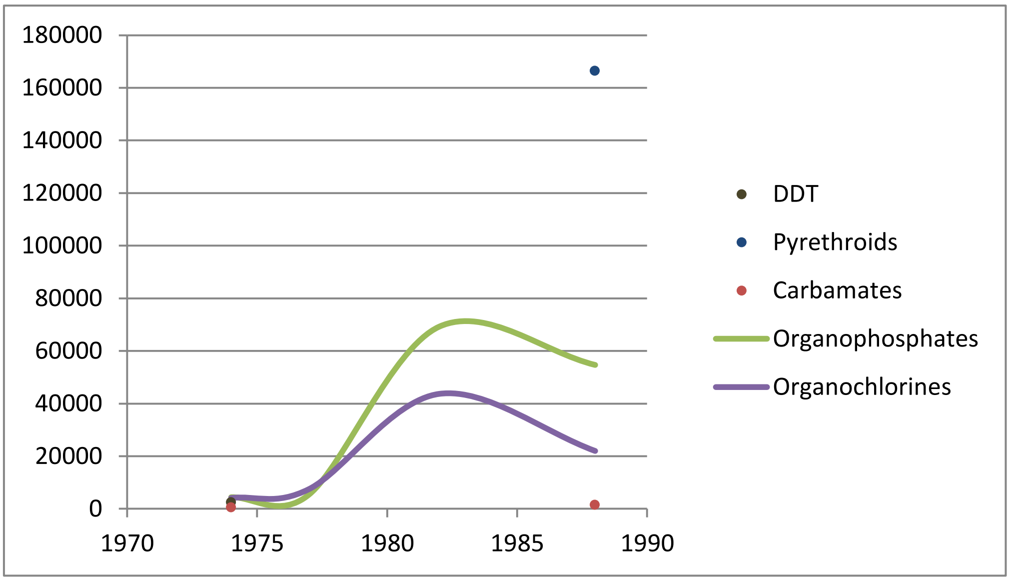

Fig 3A.1. Total treated area (ha) for various chemical groups in England and Wales pre-1990 (excluding seed treatments).

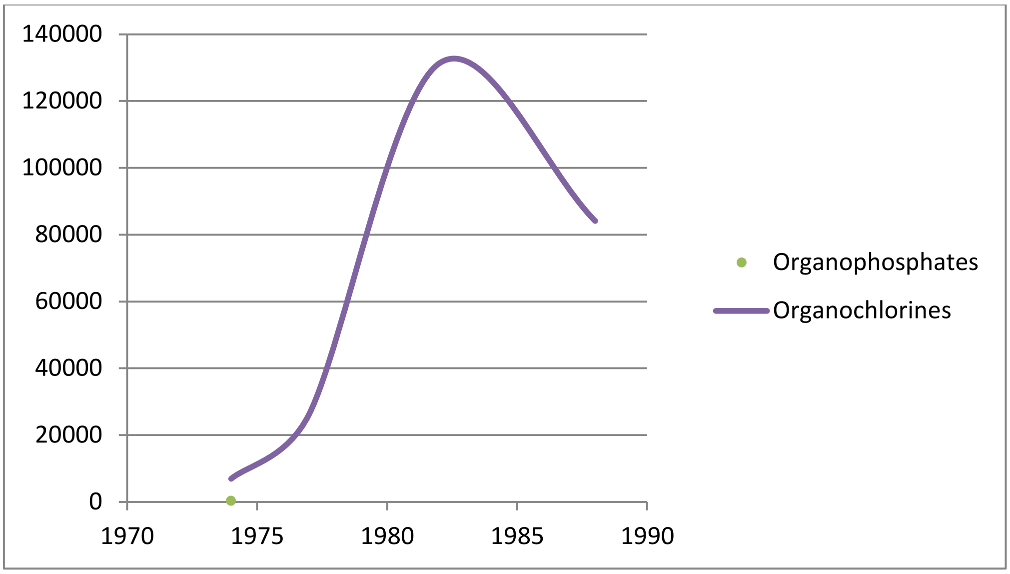

Fig 3A.2. Total treated areas (ha) for various chemical groups in England and Wales pre-1990 (Seed treatments only).

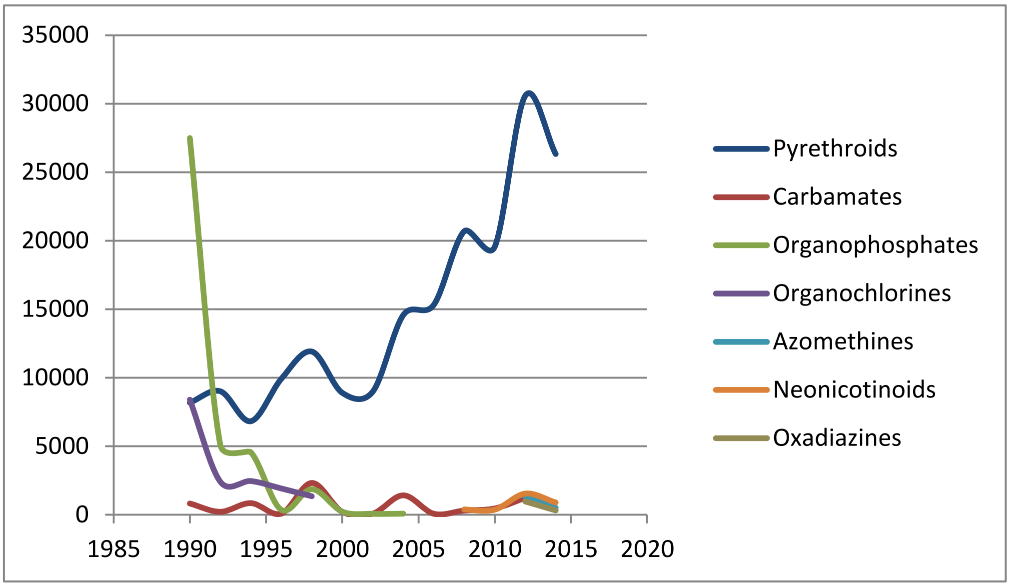

Fig 3A.3. Total weights (kg) for various chemical groups in Great Britain post- 1990 (excluding seed treatments).

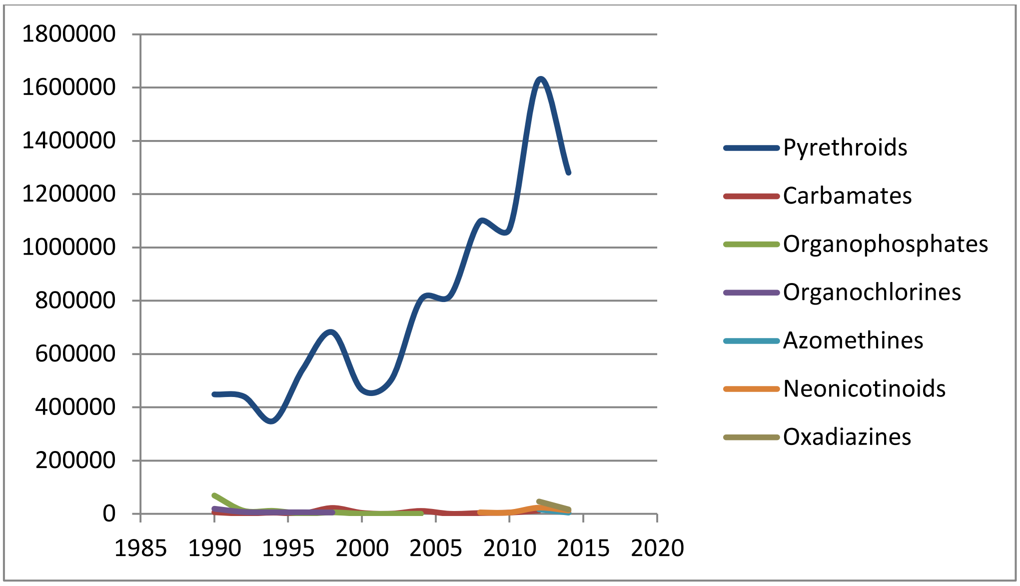

Fig 3A.4. Total treated areas (ha) for various chemical groups in Great Britain post- 1990 (excluding seed treatments).

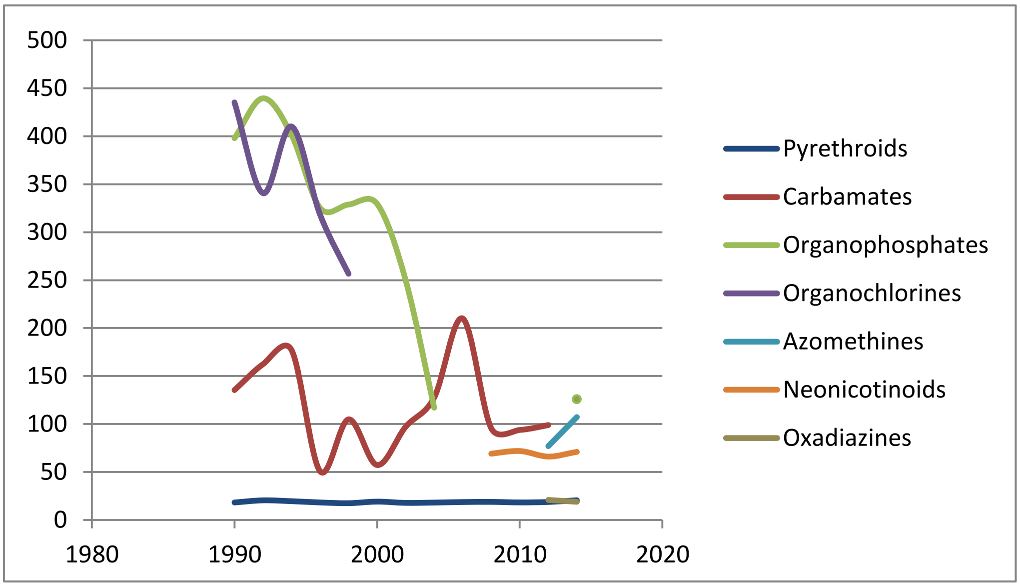

Fig 3A.5. Application rates (g/ha) for various chemical groups in Great Britain post- 1990 (excluding seed treatments).

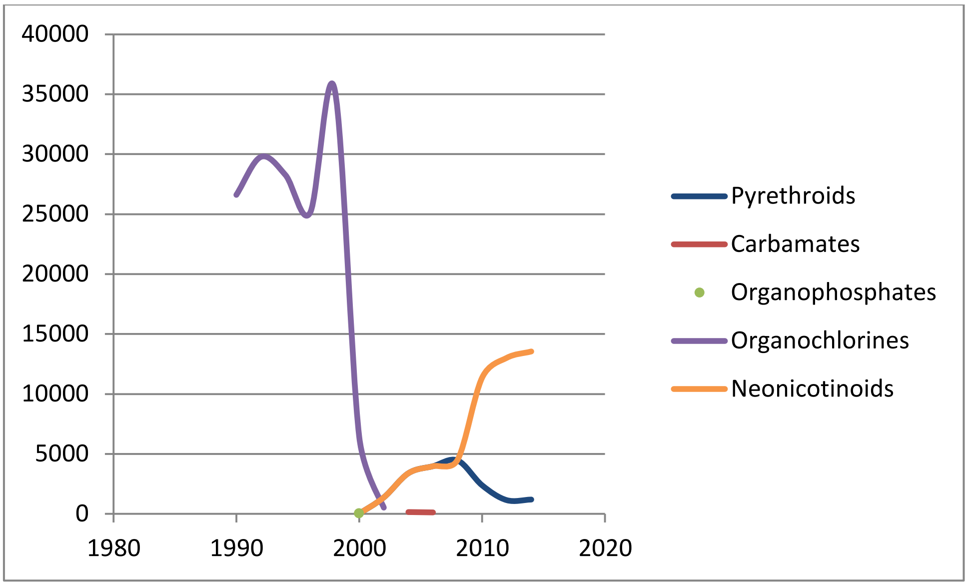

Fig 3A.6. Total weights (kg) for various chemical groups in Great Britain post- 1990 (seed treatments only).

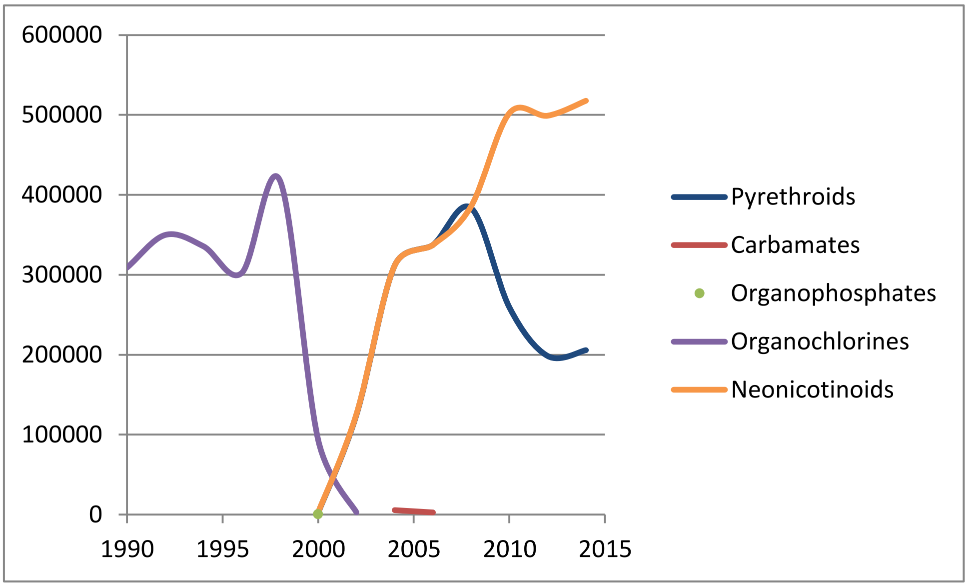

Fig 3A.7. Total treated areas (ha) for various chemical groups in Great Britain post- 1990 (seed treatments only).

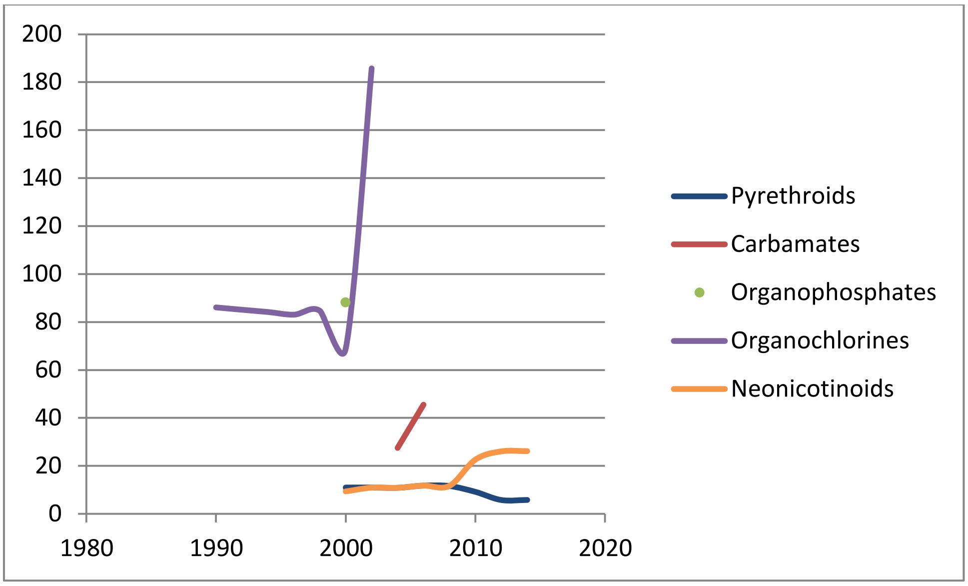

Fig 3A.8. Application rates (g/ha) for various chemical groups in Great Britain post- 1990 (seed treatments only).

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Appendix 3B: Pesticide questionnaire

Section 1: Some questions about you

* Could you create a code of 4-6 letters/ numbers, in case if you'd like to withdraw from the study later?

1. What type(s) of organizations have you worked for in the last 5 years? Tick all that apply.

☐ Government
☐ Universities
☐ Private research institutes
☐ Agri-chemical companies
☐ NGOs
☐ Commercial consulting firms
☐ Independent consultants/ consulting organizations
☐ Food industries
☐ Growers
☐ Other, please state: ____________________

2. Do you provide or have you provided advice services to farmers in the last 5 years?

○ Yes
○ No

3. Are you familiar with some aspects about arthropod pests (e.g: aphids), and related control methods (insecticides and natural enemies) in wheat?

○ Yes
○ No

(Note: For online version, if answered for No, the survey would be terminated, and answers would be recorded. The same applied for Question 4.)

4. Are you familiar with some aspects about arthropod pests (e.g: aphids), and related control methods (insecticides and natural enemies) in oilseed rape?

○ Yes
○ No

Section 2: Wheat crop, pests, and related control methods (2009/10-2013/14)

5. Which county/ region/ country(s) in UK do you refer to when providing wheat information for this section?

6. What have been the typical wheat yields in the last 5 years?

	Yield (t/ha)
Winter wheat	
Spring wheat	

7. Please rank from 1-3 (1 being most important) the 3 most significant pests for wheat (2009/10-2013/14). If you are not sure about the specific species (e.g.: Rose—grain aphids), just choose the general term (e.g.: Aphids).

______ Aphids

______ Rose—grain aphids

______ Grain aphids

______ Bird cherry—oat aphids

______ Flies

______ Gout fly larvae

______ Wheat bulb fly larvae

______ Yellow cereal fly larvae

______ Grey field slugs

______ Wireworms

______ Leatherjackets

______ Orange wheat blossom midges

______ Other 1

______ Other 2

______ Other 3

8. Without insecticide treatments, how much wheat yield loss (%) would have been typically caused by direct feeding in the last 5 years (could be a range or a number)? Referring to the pests from Question 7. Please also provide how certain you are about each answer (1-5, 5 being most certain).

	Wheat yield losses (%)	Certainty scale (1-5)
1st important pest		
2nd important pest		
3rd important pest		

(Note: for the online version, answers provided in Question 7 would be automatically copied to the first column of Question 8 and 9.)

9 . How efficient do you think the following insecticide chemical groups used in wheat protection were in 2013/14? Referring to the pests from Question 7.

Please use the 0-6 efficacy labels as below:

0	1	2	3	4	5	6
Not sure	0% pest control	1-20% control	21-50% control	51-80% control	81-90% control	91-100% control

	Carbamates (eg: Aphox)	Organophosphates (eg: Govern)	Pyrethroids (eg: Alert)	Neonicotinoid seed treatments (eg: Deter)	Neonicotinoid sprays (eg: Biscaya)	Flonicamids (eg: Teppeki)	Others (please specify below with efficacy after)
1st important pest							
2nd important pest							
3rd important pest							

10. Without insecticide treatments, how much yield loss would have been typically caused by the Barley yellow dwarf virus in the last 5 years (could be a range or a number)? Please also provide how certain you are about this answer (1-5, 5 being most certain).

	Wheat yield losses (%)	Certainty scale (1-5)
Barley yellow dwarf virus		

11. To what extent do you agree or disagree that, arthropod natural enemies (ladybirds, ground beetles, spiders, etc.) are important for wheat production?

○ Strongly Agree
○ Agree
○ Neutral
○ Disagree
○ Strongly Disagree
○ Not sure

12. Without insecticides, how much do you think arthropod natural enemies as a whole could control key pests in wheat?

○ 0% pest control
○ 1-20% control
○ 21-50% control
○ 51-80% control
○ 81-90% control
○ 91-100% control

* How certain are you about this question (1-5, 5 being most certain)?

Section 3: Oilseed rape crop, pests, and related control methods (2009/10-2013/14)

13. Which county/ region/ country(s) in UK do you refer to when providing oilseed rape information for this section?

14. What have been the typical oilseed rape yields in the last 5 years?

	Yield (t/ha)
Winter oilseed rape	
Spring oilseed rape	

15. Please rank from 1-3 (1 being most important) the 3 most significant pests for oilseed rape in the last 5 years. If you are not sure about the specific species (e.g.: Peach—potato aphids), just choose the general term (e.g.: Aphids).

______ Aphids

______ Peach—potato aphids

______ Cabbage aphids

______ Brassica pod midges

______ Beetles

______ Pollen beetles

______ Cabbage stem flea beetles

______ Weevils

______ Cabbage seed weevils

______ Cabbage stem weevils

______ Other 1

______ Other 2

______ Other 3

16. Without insecticide treatments, how much oilseed rape yield loss (%) could have been typically caused by direct feeding in the last 5 years (could be a range or a number)? Referring to the pests from Question 15. Please also provide how certain you are about each answer (1-5, 5 being most certain).

	Wheat yield losses (%)	Certainty scale (1-5)
1st important pest		
2nd important pest		
3rd important pest		

(Note: for the online version, answers provided in Question 15 would be automatically copied to the first column of Question 16 and 17.)

17. How efficient do you think the following insecticide chemical groups used in oilseed rape protection were in 2013/14 season? Referring to the pests from Question 15. Please use the 0-6 efficacy labels as below:

0	1	2	3	4	5	6
Not sure	0% pest control	1-20% control	21-50% control	51-80% control	81-90% control	91-100% control

	Carbamates (eg: Aphox)	Pyrethroids (eg: Alert)	Neonicotinoid seed treatments (eg: Chinook)	Neonicotinoid sprays (eg: Biscaya)	Oxadiazines (eg: Explicit)	Azomethines (eg: Plenum)	Others (please specify below with efficacy after)
1st important pest							
2nd important pest							
3rd important pest							

18. Without insecticide treatments, how much yield loss would you estimate to have been typically caused by the Turnip yellows virus in the last 5 years (could be a range or a number)?

Please also provide how certain you are about this answer (1-5, 5 being most certain).

	Oilseed rape yield losses (%)	Certainty scale (1-5)
Turnip yellows virus		

19. To what extent do you agree or disagree that arthropod natural enemies (ladybirds, ground beetles, spiders, etc.) are important for oilseed rape production?

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree
○ Not sure

20. Without insecticides, how much do you think arthropod natural enemies as a whole could control key pests in oilseed rape?

○ 0% pest control
○ 1-20% control
○ 21-50% control
○ 51-80% control
○ 81-90% control
○ 91-100% control

* How certain are you about this question (1-5, 5 being most certain)?

Section 4: Neonicotinoid seed treatment restriction in oilseed rape

21. Which county/ region/ country(s) in UK do you refer to with this neonicotinoid section?

22. To what extent do you favour or oppose the restriction on the neonicotinoid seed treatments in oilseed rape?

○ Strongly favour
○ Favour
○ Neutral
○ Oppose
○ Strongly oppose
○ Not sure

* Why do you pick ‘Favour’ or ‘Strongly favour’? Tick all that apply.

☐ Neonicotinoids are not that efficient for crop protection
☐ Concerns for pollinators and environment
☐ Other products are efficient enough
☐ Arthropod pest problems are not severe
☐ Farmers can adjust management accordingly
☐ Others ____________________

* Why do you pick ‘Oppose’ or ‘Strongly oppose’? Tick all that apply.

☐ Oilseed rape production will be greatly reduced
☐ Neonicotinoid seed treatments are better for the environment than sprays
☐ Neonicotinoid impacts on pollinators are not proven
☐ The restrictions came in too soon and did not give farmers enough time to adjust
☐ Other products are not as efficient as neonicotinoids
☐ Others ____________________

(Note: for the online version, respondents would be automatically directed to the added question based on his choice in Question 22.)

23. If neonicotinoid seed treatments were permanently banned in the future, what alternative pest management strategies would you suggest? Please tick all that apply.

☐ Stop growing oilseed rape and switch to other crops
☐ Grow a smaller area of oilseed rape
☐ Grow oilseed rape less often
☐ Use new oilseed rape varieties
☐ Use new insecticides if available
☐ Use currently available insecticides, please specify product names:
____
☐ Do nothing
☐ No opinions
☐ Others, please state: ____________________

24. After the neonicotinoid restriction, what are the expected yields for winter oilseed rape production for 2014/15 (compare with typical yields in the last 5 years)?

○ < 3 t/ ha less
○ 2-3 t/ ha less
○ 1-2 t/ ha less
○ 0-1 t/ ha less
○ about the same
○ 0-1 t/ ha more
○ 1-2 t/ ha more
○ 2-3 t/ ha more
○ >3 t/ ha more
○ not sure

25. After the neonicotinoid restriction, what are the expected yields for spring oilseed rape production for 2014/15 (compare with typical yields in the last 5 years)?

○ < 3 t/ ha less
○ 2-3 t/ ha less
○ 1-2 t/ ha less
○ 0-1 t/ ha less
○ about the same
○ 0-1 t/ ha more
○ 1-2 t/ ha more
○ 2-3 t/ ha more
○ >3 t/ ha more
○ not sure

26. Following the restriction, did oilseed rape farmers spend more money on insecticide products in 2014/15 (compare with 2013/14)?

○ Yes, much more
○ Yes, but just a bit more
○ About the same
○ No, a bit less
○ No, much less
○ Not sure

27. Following the restriction, did you and/ or other agronomists spend more time to inspect the oilseed rape fields for arthropod pests' abundance in 2014/15 (compare with 2013/14)?

○ Yes
○ No
○ Not sure

28. Do general seed treatments and sprays have negative influences on the following aspects? Please use the 0-5 influence levels (0 being no influence, 5 being greatest influence).

	Users' health	Natural enemies	Pollinators	Water	Soil
Seed treatments					
Sprays					

Appendix 3C. Regional distributions

Methods: In order to take into account regional differences in pest damage and controls for oilseed rape, respondents were asked to mention the regions they referred to at the beginning of survey. Defra classification of UK regions was used. If a respondent represented several cities or counties, these were re-categorised into regions. If a respondent represented several regions (e.g., South East and South West), we assumed that his/ her opinion on each individual region was the same and recorded the same answers for both regions. If a respondent had not mentioned any regions (left blank), we assumed they were for UK in general. Because of the large range covered, if a respondent answered 'England' or 'UK', they were used as two separate regions.

Results: Most people represented east (20% out of 90) or south east (~19%) areas when providing information for oilseed rape and neonicotinoid sections, where most oilseed rape is grown in the UK. About 18% represented the midlands, and 5% north. Six respondents were from Scotland, two from Northern Ireland and one from Wales. Ten respondents have not had specific regions, so we assume they represented UK in general (in total 22).

Table 3C.1 Regional distributions of respondents for oilseed rape and neonicotinoid sections

Regions	One	Two	Three	Four	Total
East	16	1	1		18
South East	10	5	1	1	17
South West	2	4	2	1	9
East Midlands	4	1	1	1	7
West Midlands	6	1	1	1	9
Yorkshire & the Humber	6				6
North East	2	1			3
North West		2			2
Scotland	6				6
Northern Ireland	2				2
Wales	0	1			1
England	4				4
UK	22				22

Note: '1' is the counts for respondents who only mentioned one region; '2' is for those who mentioned two regions, and so on.

Appendix 3D. Hazard Quotient approach

The Hazard Quotient approach for the non-target arthropod species (HQ_N) has been developed by the 'European Standard Characteristics of Non-target Arthropod Regulatory Testing' workshop (ESCORT 2000), and has been used as a required assessment of pesticide registration in the EU. The in-field HQ_N method is:

$$\text{In}-\text{field}\ HQ_N = \frac{Application\ rate \times MAF}{LR_{50}(N)}$$

where the 'application rate' is the single application rate in g a.i. (active ingredient) /ha, MAF is the Multiple Application Factor (maximum residue level after multiple applications of the products), $LR_{50}(N)$ is the lethal rate 50 for natural enemies in g a.i. /ha (application rate causing 50% mortality of the organisms under worst-case laboratory conditions). This method is used to assess the initial toxicity experiment of the two most sensitive non-target arthropod species, *Aphidius rhopalosiphi* and *Typhlodromus pyri*. If one or both the HQ results exceed 2, it indicates a potential hazard to the non-target species. In this study due to lack of information on the toxicity test for *Typhlodromus pyri*, only *Aphidius rhopalosiphi* is used.

The application rates of the available active ingredients were estimated from the Fera pesticide use database (Fera 2015). It is assumed that the derived application rate is the single application rate. As for the MAF, because the average spray rounds of insecticides used in the UK in the past 14 years is 1.1 (calculated from Fera 2015), it is assumed that MAF is 1 for all the active ingredients.

$LR_{50}(N)$ were mainly collected from the European Food Safety Authority (EFSA 2015):

Active ingredients	Chemical groups	$LR_{50}(N)$ (g/ha)
Pirimicarb	Carbamate	620
Lambda-cyhalothrin	Pyrethroid	0.59
Dimethoate	Organophosphate	0.014
Thiacloprid	Neonicotinoid	6.8
Indoxacarb	Oxadiazine	49
Pymetrozine	Azomethine	75

References

EFSA, 2015. Rapporteur Member State assessment reports submitted for the EU peer review of active substances used in plant protection products. Parma, Italy: European Food Safety Authority.

ESCORT, 2000. *Guidance document on regulatory testing and risk assessment procedures for plant protection products with non-target arthropods*. Wageningen,the Netherlands: European Standard Characteristics of Non-Target Arthropod Regulatory Testing.

Fera, 2015. *Pesticide Usage Surveys*. York: Fera Science Ltd. Available at: http://pusstats.fera.defra.gov.uk/index.cfm [Accessed 26 Aug, 2015].

Appendix 3E. Other figures and tables

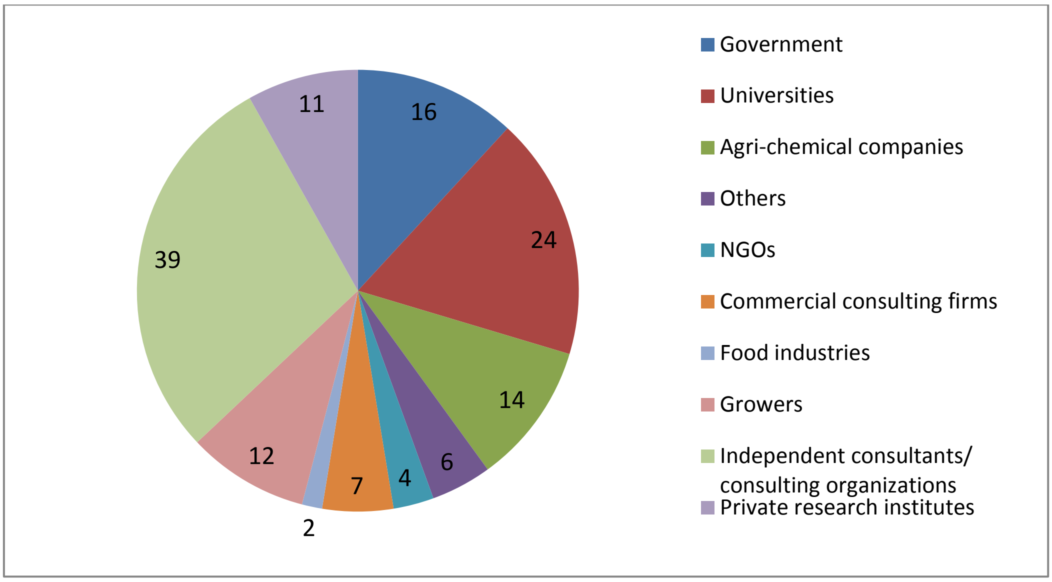

Fig 3E.1. Organization distribution for respondents to the neonicotinoid section. Figures on the pie charts are the number of respondents. In total 90 respondents provided this information (N=90).

Table 3E.1. Weighted average response for the three main arthropod pests in UK oilseed rape by regions. Numbers in brackets are the number of respondents.

	Aphids	Peach—potato aphid	Cabbage aphid	Cabbage stem weevil	Brassica pod midge	Beetles	Pollen beetle	Cabbage stem flea beetle	Weevils	Cabbage seed weevil
East (18)	1.17	1.33	0.33	0.00	0.50	0.50	3.83	6.67	1.33	0.33
South East (17)	1.83	1.67	0.17	0.00	0.67	0.00	3.83	6.67	0.67	0.17
South West (9)	0.50	1.50	0.17	0.17	0.33	0.00	1.83	3.67	0.67	0.00
East Midlands (7)	0.00	1.50	0.17	0.00	0.00	0.00	1.00	1.83	0.50	0.33
West Midlands (9)	0.67	1.33	0.17	0.00	0.67	0.00	1.67	2.67	0.33	0.00
York (6)	0.00	0.17	0.00	0.00	1.00	0.00	1.00	1.83	0.00	0.67
North East (3)	0.00	0.00	0.00	0.00	0.33	0.00	0.83	1.33	0.17	0.33
North West (2)	0.17	0.00	0.00	0.00	0.17	0.00	0.00	0.83	0.00	0.33
Scotland (6)	0.33	0.67	0.00	0.83	0.00	0.50	0.83	1.33	0.33	0.17
Northern Ireland (2)	0.50	0.00	0.33	0.00	0.00	0.00	0.50	0.33	0.00	0.17
Wales (1)	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00
England (4)	0.00	0.00	0.50	0.00	0.17	0.00	0.83	1.83	0.33	0.17
UK (19)	1.00	2.50	0.67	0.17	0.67	1.67	3.50	4.67	0.83	1.00

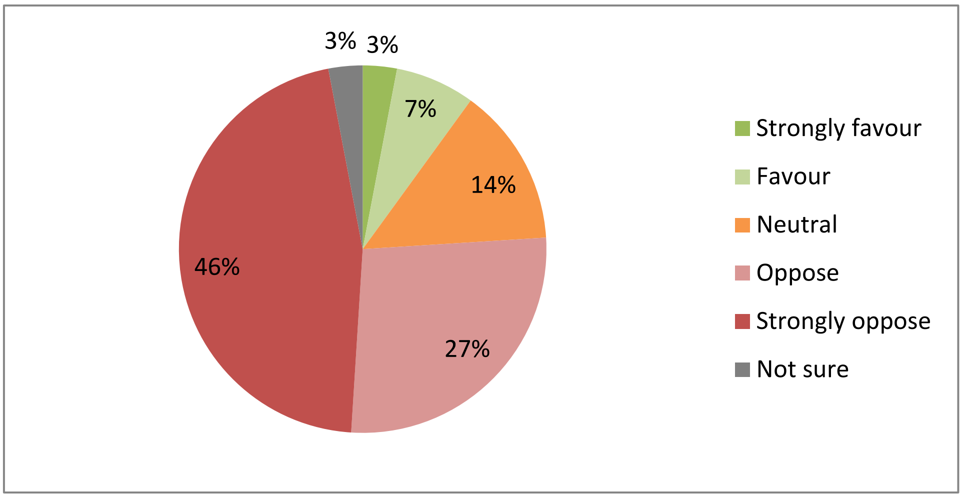

Fig 3E.2. Percentage of respondents' opinions on the restriction on the neonicotinoid seed treatments in oilseed rape (Total number of respondents = 90).

Table 3E.2. Pairwise comparisons among organizations of the opinions on the neonicotinoid seed treatments restriction in UK oilseed rape. Test method is Fisher's exact test (with Monte Carlo simulated p value, 100,000 replicates), level of significance is 0.05.

(1) *oppose* (including 'Oppose' and 'Strongly oppose') versus *favour* (including 'Favour' and 'Strongly favour')

	Universities	Private research institutes	Agri-chemical companies	Commercial consulting firms	Growers	Independent consultants
Government	1	1	0.6	1	0.6	0.04
Universities		1	0.4	0.6	0.2	0.007
Private research institutes			0.6	0.5	0.5	0.08
Agri-chemical companies				1	1	0.2
Commercial consulting firms					1	0.3
Growers						0.4

(2) having an opinion (*oppose*/ *favour*) versus ‘Neutral’/ ‘Not sure’

	Universities	Private research institutes	Agri-chemical companies	Commercial consulting firms	Growers	Independent consultants
Government	0.7	1	0.1	0.3	0.1	0.05
Universities		1	0.02	0.2	0.03	0.005
Private research institutes			0.07	0.3	0.09	0.06
Agri-chemical companies				1	1	1
Commercial consulting firms					1	1
Growers						1

Table 3E.3. Pairwise comparisons among organizations of whether they have provided farming advice services from 2009/10 to 2013/14. Test method is Fisher’s exact test (with Monte Carlo simulated p value, 100,000 replicates), level of significance is 0.05.

	Universities	Private research institutes	Agri-chemical companies	Commercial consulting firms	Growers	Independent consultants
Government	0.05	0.3	0.7	1	0.2	0.05
Universities		0.7	0.02	0.08	0.0009	0.000001
Private research institutes			0.1	0.3	0.009	0.0008
Agri-chemical companies				1	0.3	0.2
Commercial consulting firms					0.5	0.2
Growers						1

Table 3E.4. **First reported year for insecticide resistance in main arthropod pests in UK oilseed rape**

Species	Resistance target sites	Affected chemical groups	Approximate Resistance first reported date
Pollen beetle	kdr	Pyrethroids	2006 (HGCA 2011)
Cabbage stem flea beetle	kdr	Pyrethroids	2014 (IRAC 2015)
Peach–potato aphid	kdr	Pyrethroids	1997 (IRAG 2005)
	E4	Mainly OPs, also Carbamates and Pyrethroids	Early 1970s (IRAG 2005)
	MACE	Carbamates	1996 (IRAG 2005)

References:

HGCA, 2011. *Controlling pollen beetle and combating insecticide resistance in oilseed rape*. Kenilworth,UK: Agriculture and Horticulture Development Board.

IRAC, 2015. *IRAC Newsletter Issue 37: Cabbage stem flea beetle (CSFB), Psylliodes chrysocephala-Resistance on the move*. Insecticide Resistance Action Committee.

IRAG, 2005. Guidelines for preventing and managing insecticide resistance in the peach-potato aphid , *Myzus persicae*. London: Insecticide Resistance Action Group.

Appendix 4A. LIBERATION farmer interview

Section 1: Some questions about your farm

1. What was your total agricultural area in 2013, excluding water, woodland and hard standing? ☐ ha/acres

2. How much of this agricultural area was …? Owned ☐ Rented ☐ Contracted ☐

3. Which of the following best describes your farm? Please tick

Cereals	☐	General cropping	☐	Horticulture	☐	Pigs or poultry	☐
Dairy	☐	Lowland grazing livestock	☐	LFA grazing livestock	☐	Mixed, unclassified	☐

4. Please provide details of a typical rotation (or rotations, up to three) for your farm. There is no requirement to complete all the rows and columns, e.g. if a typical rotation is only four or five years.

Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Crop 7

5. Please provide details on the area and yields of the crops that you grow.

Crops	Approximate area totals (ha/ac)	Approximate yields (t/ha or t/ac)	Minimum yield in last 10 years	Maximum yield in last 10 years	Market
e.g. wheat	60 ha	8t/ha	6t/ha	8.5t/ha	Milling (contract)
1.					
2.					
3.					
4.					
5.					
6.					

6. How would you describe the soils on your farm? Please tick one box from Row 6a and one box from Row 6b.

Row 6a Light ☐ Medium ☐ Heavy ☐

Row 6b Chalk ☐ Peat ☐ Sand ☐ Silt ☐ Clay ☐ Loam ☐

7. What tillage practices do you currently adopt? Please tick all that apply

Type	Please tick	Frequency, e.g. annually, one year in five
Deep cultivation		
Shallow cultivation		
Zero (no) tillage		
Other, please state		

Section 2: Some questions about environmental features on your farm and their importance

1. Is your farm in a protected or designated area? Please tick Yes ☐ No ☐

If yes, please state which ones. For example, National Park or Nature Reserve

☐

2. If you are in a protected or designated area, do you feel that:

(i) the environment within and around your farm has improved as a result? Please tick the most appropriate option

Strongly Agree ☐ Agree ☐ Neither Agree nor Disagree ☐ Disagree ☐ Strongly Disagree ☐

(ii) the productivity of your farm has improved as a result? Please tick the most appropriate option

Strongly Agree ☐ Agree ☐ Neither Agree nor Disagree ☐ Disagree ☐ Strongly Disagree ☐

3. What environmental features do you have on your farm?

Features	Please tick	Please specify area/length/number as appropriate
Woodland		
Hedges		
Ditches		
Ponds		
River/stream		
Other, please state		

4. Are you in a scheme to protect/manage these features? Please tick Yes ☐ No ☐
If yes, please state which ones, the area of land entered in each, and year of entry

Scheme	Area entered (ha/acres)/Number	Year of entry

5. If you are in a scheme, do you feel that:

(i) the environment within and around your farm has improved as a result? Please tick the most appropriate option

Strongly Agree ☐ Agree ☐ Neither Agree nor Disagree ☐ Disagree ☐ Strongly Disagree ☐

(ii) the productivity of your farm has improved as a result? Please tick the most appropriate option

Strongly Agree ☐ Agree ☐ Neither Agree nor Disagree ☐ Disagree ☐ Strongly Disagree ☐

6. Are you a member of an environmental conservation body? Please tick. Yes ☐ No ☐

If yes, please state which ones:

Section 3: Some questions about the experimental work taking place on your and other EU farms

For the following options, please consider what consequences you foresee as a result of their implementation, what are the potential advantages, what are the potential disadvantages?

Rotation (UK, Poland, Germany, Italy)

Imagine you are advised to adopt a crop rotation which in addition to winter cereals must incorporate some spring cropping (e.g. oilseed, protein or root crops) and legume (e.g. winter vetch) or brassica (e.g. mustard) covers prior to those crops.

What advantages can you think of regarding this option?

What disadvantages can you think of regarding this option?

Crop establishment with reduced tillage (Germany, Italy)

Imagine you are advised to establish your crops using zero tillage.

What advantages can you think of regarding this option?

What disadvantages can you think of regarding this option?

Mixed cropping (Poland, Germany)

Imagine you are advised to adopt mixed cropping within your rotation, for example, a combination of winter cereals (e.g. wheat, triticale and rye) grown in one field or a legume (e.g. lupine) and winter cereal or oilseed crop combined.

What advantages can you think of regarding this option?

What disadvantages can you think of regarding this option?

Set-aside (whole field) (Hungary)

Imagine you are advised to set aside a field for three years. You are allowed to sow it with a perennial forage legume such as alfalfa/lucerne which can be mown mid-summer but you cannot undertake any other crop management on the field.

What advantages can you think of regarding this option?

What disadvantages can you think of regarding this option?

(Set-aside (field margin) (Netherlands)

Imagine you are advised to establish a 3-5m wide margin at a field edge by sowing a mixture of perennial forb (flower and herb) and grass species. The vegetation may not be treated with pesticides with the exception of patch-wise application to problem weeds (*Rumex obtusifolius, Urtica dioica, Cirsium arvense*). The strips must be mown at least once a year and the cuttings need to be removed. It is allowed to drive on the perennial strips with farming machinery.

What advantages can you think of regarding this option?

What disadvantages can you think of regarding this option?

Hedgerow (Italy, UK)

Imagine you have a long established hedgerow adjacent to your arable fields. It may contain gaps, be dense or sparse in places, consist of a single species or be a complex hedgerow composed of several tree and shrub species.

What advantages can you think of regarding hedges and different hedge compositions?

What disadvantages can you think of regarding hedges and different hedge compositions?

And now a different type of decision, an investment decision

For this option you must consider investing in a new piece of machinery, for example a more powerful tractor than the one you currently have available.

What is the maximum you would be prepared to invest? € ____
What would be your desired rate of return from such an investment? ____ %
How soon would you require a return from your investment? ____ years

What advantages can you think of regarding this investment?

What disadvantages can you think of regarding this investment?

Section 4: Some questions about your objectives and the factors that influence your decision making

1. What objectives do you have for your business? Can you rank these in order of importance, with 1. being most important? (Prompt: improve profit, turnover, expand business, wind down business, switch enterprises (add/remove an enterprise)

Objective	Rank

2. What are the key influences on your businesses? Can you rank these in order of importance, with 1. being most important? (Prompt : Policy, economics, soil, climate)

Influence	Rank

3. Who influences your business the most? Can you rank these in order of importance, with 1. being most important? (Prompt: Government, government agency, environmental NGOs, bank, business partner, owner, family, neighbours,)

Influence	Rank

4. What objectives do you have for yourself, beyond farming? Can you rank these in order of importance, with 1. being most important? (Prompt: lifestyle, status, free time, retirement)

Objectives	Rank

Section 5: Some questions about possible farm business objectives and your preferences

Farm Business Income (€)
Specifically consider the INCOME generated by your farm. Decide the highest possible and lowest possible amount of income (that would not cause you to give up farming) using the following definition: Crop enterprise output + single farm payment + agri-environment payments + other agricultural grants and subsidies + land-based diversification income – variable costs – fixed costs

Lowest possible income		Highest possible income	

Absolute variation in Farm Business Income (€)
Consider your willingness to deal with about plus or minus variation in your yearly income from farming. If you are prepared to cope with a widely varying income on the chance that some years will be very good, while other years will be very bad, then the absolute deviation in Farm Business Income that you envisage will be larger than if you would rather have an income that is more constant but potentially lower.

Please indicate your likelihood of investing in management options/crops, which generate income that is…

	(extremely unlikely)	1	2	3	4	5	(extremely likely)
high above average in some years, and high below average in other years							
fairly above average in some years, and fairly below average in other years							
slightly above average in some years, and slightly below average in other years							

Please indicate your feeling about how risky it is to invest in management options/crops, which generate income that is…

	(not at all risky)	1	2	3	4	5	(extremely risky)
high above average in some years, and high below average in other years							
fairly above average in some years, and fairly below average in other years							
slightly above average in some years, and slightly below average in other years							

Number of different crop types to manage
Consider the COMPLEXITY OF MANAGEMENT involved with growing different numbers of crops simultaneously (i.e. within one harvest year). Decide the most preferred and least preferred NUMBER of crops to grow on your farm (a list of crops is provided as guidance):

Most preferred number of crops		Least preferred number of crops	

Milling wheat
Feed wheat
Malting barley
Feed barley
Oilseed rape
Linseed
Peas
Beans
Sugar beet
Potatoes
Field scale vegetables, please specify
Other, please specify

Number of different environmental management practices adopted
Consider the COMPLEXITY OF MANAGEMENT involved with managing environmental features on your farm. Decide the most preferred and least preferred number of environmental management practices to adopt on your farm using the categories listed:

Most preferred number of options		Least preferred number of options	

Please also indicate the options you like, those you are indifferent to, those you are unfamiliar with and those you dislike.

	Like	Indifferent	Dislike	Unfamiliar
Land set aside				
Crop rotation				
Mixed cropping				
Cover crop				
Overwintered stubbles				
Undersown spring cereals				
Erosion management (interventions)				
Conservation headlands				
Field corner management				
Buffer strips				
Grass field margins				
Wildflower strips				
Beetle banks				
Hedgerow management				
Ditch management				
Protection of in-field trees				
Management of woodland edges				

Section 6: Some questions regarding your understanding of the services that the natural environment can provide

1. Relative to each other how important are the following for determining whether you have a satisfactory or poor crop?

	Very important	Important	Not as important	Relatively unimportant
Soil fertility				
Water availability				
Amount of weed presence				
Amount of pest damage				
Amount of disease damage				
Regulation of pests by their natural enemies				
Pollination				

Soil

2. Do you have problems with soil structure? Yes ☐ No ☐
3. Do you have problems with soil erosion? Yes ☐ No ☐
4. Do you have problems with soil water storage? Too much water ☐ Too little water ☐ Both ☐ No ☐
5. Do you have problems with soil nutrient availability? Yes ☐ No ☐
6. Do you believe healthy soil biology can improve soil productivity? Yes ☐ No ☐

7. Do you do anything to encourage soil biology? Please state what
E.g. minimum/zero tillage; organic matter incorporation; reduced pesticide use

8. If you don't would you be averse to adopting? Yes ☐ No ☐

Please explain your answer

Weeds

9. What weeds are most problematic for your crop productivity? Please state

10. Do you use agrochemicals to manage these weeds? Yes ☐ No ☐

11. Do you use any other forms of control?
E.g. through use of crop rotation; differing crop establishment techniques; mechanical weeding; other, please state

☐

12. If you don't would you be averse to adopting? Yes ☐ No ☐

Please explain your answer

☐

Pests

13. What pests are most responsible for damage to your crops? Please state

☐

14. Do you use agrochemicals to manage these crop pests? Yes ☐ No ☐
15. Do you spray because you perceive a lack of natural enemies? Yes ☐ No ☐

16. What are the most important biological control agents, e.g. natural enemies? Please state

☐

17. Do you do anything to encourage these natural enemies?
E.g. Restrict pesticide application; provide habitat for beneficial species; provide nesting and/or overwintering sites; release natural enemies; other, please state

☐

18. If you don't would you be averse to adopting? Yes ☐ No ☐

Please explain your answer

☐

Diseases

19. What diseases are most responsible for damage to your crops? Please state

☐

20. Do you use agrochemicals to manage these diseases? Yes ☐ No ☐

21. Do you use any other forms of control?
E.g. through use of crop rotation; variety choice; harvest to sowing interval; clean seed bed; other, please state

22. If you don't would you be averse to adopting? Yes ☐ No ☐

Please explain your answer

Pollination

23. Is lack of pollination an issue? Yes ☐ No ☐

24. How much do you believe your yield is affected by pollination? A lot ☐ A little ☐ Not at all ☐

25. Which of your crops are pollinated party or wholly? Please state

26. What are your most important pollinator species? Please state

27. Do you do anything to improve pollination/encourage pollinators?
E.g. Rent beehives; restrict pesticide application; provide habitat for pollinators, i.e. wildflower strip; provide nesting and/or overwintering sites; other, please state

28. If you don't would you be averse to adopting? Yes ☐ No ☐

Please explain your answer

29. Do you agree that: "it is worth reducing intensity of production and yield today to obtain economic benefits in the future". Please tick the most appropriate option that reflects your response

Strongly Agree ☐ Agree ☐ Neither Agree nor Disagree ☐ Disagree ☐ Strongly Disagree ☐

Section 7: Some questions about you and your farm business

1. What is your role on the farm? Please tick.

Owner ☐ Tenant ☐ Manager ☐ Other, please state ☐

2. How many years have you worked in farming? ☐ years

3 Do you work exclusively on the farm? Please tick Yes ☐ No ☐

4. How many full time equivalent staff work on the farm, including you and paid and unpaid family members? ☐

5. How many seasonal workers do you employ? ☐ Over what period? ☐

6. Have you identified a successor? Please tick. Yes ☐ Possibly ☐ No ☐

7. In what proportion do the following sources of revenue contribute to your business?

Revenue source	Contribution (%)
Agricultural output	
Agri-environment income	
Single Payment Scheme	
Other income, please state (e.g. diversification)	

8. Please indicate (by tick) your average farm income in your last two financial years using the categories below:

Less than €0 (loss)	☐	€1 – 20,000	☐	€20,001 – 40,000	☐
€40,001 – 60,000	☐	€60,001 – 80,000	☐	€80,001 – 100,000	☐
€100,000 +	☐	Prefer not to say	☐		

Appendix 4B. Other figures and tables

Table 4B.1. Farmer participants' preferences toward environmental management practices among seven European Union member states. Mean (number of respondents; number of 'Unfamiliar' option; standard deviations).

Habitats	Practices	GE	HU	IT	NL	PL	SW	UK
Linear woody	Hedgerow	2.6 (9; 0; 0.9)	1.5 (18; 0; 0.7)	2.8 (13; 2; 0.4)	NA	1.6 (8; 1; 1.0)	2.4 (5; 0; 0.9)	2.9 (8; 0; 0.4)
	Buffer strips	2.3 (9; 0; 1.0)	1.8 (18; 0; 0.7)	2.8 (13; 1; 0.4)	3.0 (1; 0; 0)	1.2 (9; 3; 0.4)	2.8 (5; 0; 0.4)	2.8 (8; 0; 0.7)
Grassy linear	Grass field margins	1.8 (8; 0; 1.0)	1.8 (18; 0; 0.7)	2.8 (13; 1; 0.6)	2.5 (18; 2; 0.8)	1.9 (9; 0; 1.1)	NA	2.4 (8; 0; 1.0)
	Beetle banks	1.8 (8; 0; 0.9)	1.9 (18; 0; 0.8)	2.1 (13; 2; 0.8)	NA	1.7 (10; 3; 1.0)	NA	2.0 (8; 1; 1.0)
Herbaceous ungrazed	Wildflower strips	2.3 (9; 0; 1.0)	1.8 (18; 0; 0.7)	1.4 (13; 1; 0.7)	1.9 (20; 3; 0.9)	1.4 (10; 3; 0.8)	NA	2.3 (8; 0; 1.0)
Low-input cereal headlands	Conservation headlands	2.3 (8; 0; 0.9)	1.7 (18; 1; 0.7)	2.6 (13; 4; 0.7)	NA	2.0 (9; 2; 1.0)	NA	2.0 (7; 0; 1.0)
Undersowing and cover crops	Cover crop	2.6 (8; 0; 0.5)	1.7 (18; 0; 0.7)	2.1 (13; 4; 0.9)	NA	1.5 (8; 0; 0.8)	2.6 (5; 0; 0.5)	2.3 (8; 0; 0.7)
	Undersown spring cereals	1.3 (8; 2; 0.8)	1.6 (18; 1; 0.7)	2.3 (13; 1; 1.0)	NA	1.8 (9; 0; 1.0)	1.8 (5; 0; 0.8)	1.2 (8; 3; 0.4)
Other AES habitats	Land set aside	2.0 (9; 0; 1.0)	2.3 (18; 0; 0.9)	1.8 (13; 1; 1.0)	1.2 (20; 1; 0.5)	1.1 (9; 0; 0.3)	1.6 (5; 0; 0.9)	2.0 (7; 0; 1.0)
	Over winter stubbles	1.6 (8; 1; 1.0)	1.5(18; 1; 0.5)	2.2 (12; 0; 0.8)	NA	1.2 (9; 0; 0.7)	1.3 (5; 1; 0.5)	2.6 (8; 0; 0.7)
Other practices	Crop rotation	2.8 (9; 0; 0.7)	3.0 (18; 0; 0)	2.9 (13; 0; 0.3)	2.8 (19; 0; 0.5)	2.8 (10; 0; 0.6)	2.6 (5; 0; 0.9)	2.9 (8; 0; 0.4)
	Mixed cropping	1.6 (8; 0; 0.7)	1.8 (18; 0; 0.8)	2.8 (12; 1; 0.6)	1.9 (20; 11; 0.8)	2.4 (10; 0; 0.8)	NA	3.0 (8; 1; 0)
	Erosion	2.8 (8; 0; 0.7)	2.0 (18; 16; 0)	2.9 (13; 5; 0.4)	NA	2.9 (9; 0; 0.3)	NA	2.5 (7; 1; 0.5)
	Field corner management	1.8 (8; 0; 0.7)	2.1 (18; 0; 0.8)	2.9 (13; 0; 0.3)	1.8 (20; 14; 1.0)	1.5 (9; 1; 0.8)	NA	2.9 (8; 0; 0.4)
	Ditch management	2.5 (8; 0; 0.9)	2.5 (18; 0; 0.7)	2.8 (13; 1; 0.4)	1.9 (20; 3; 0.9)	2.4 (10; 0; 0.8)	NA	2.7 (7; 0; 0.5)
	Protection of in-field trees	2.1 (8; 1; 1.1)	2.7 (18; 0; 0.5)	2.2 (13; 2; 0.8)	NA	2.1 (9; 0; 0.9)	2.4 (5; 0; 0.9)	2.3 (8; 0; 0.7)
	Management of woodland edges	2.5 (9; 1; 0.9)	2.6 (18; 1; 0.5)	2.6 (13; 2; 0.5)	NA	2.0 (9; 1; 0.9)	NA	2.5 (8; 0; 0.8)

Note: The environmental management practices were grouped into various habitat management types, followed by a review of Holland et al. (2016). 'Other practices' were the ones not included in this review, thus not included in the manuscript.

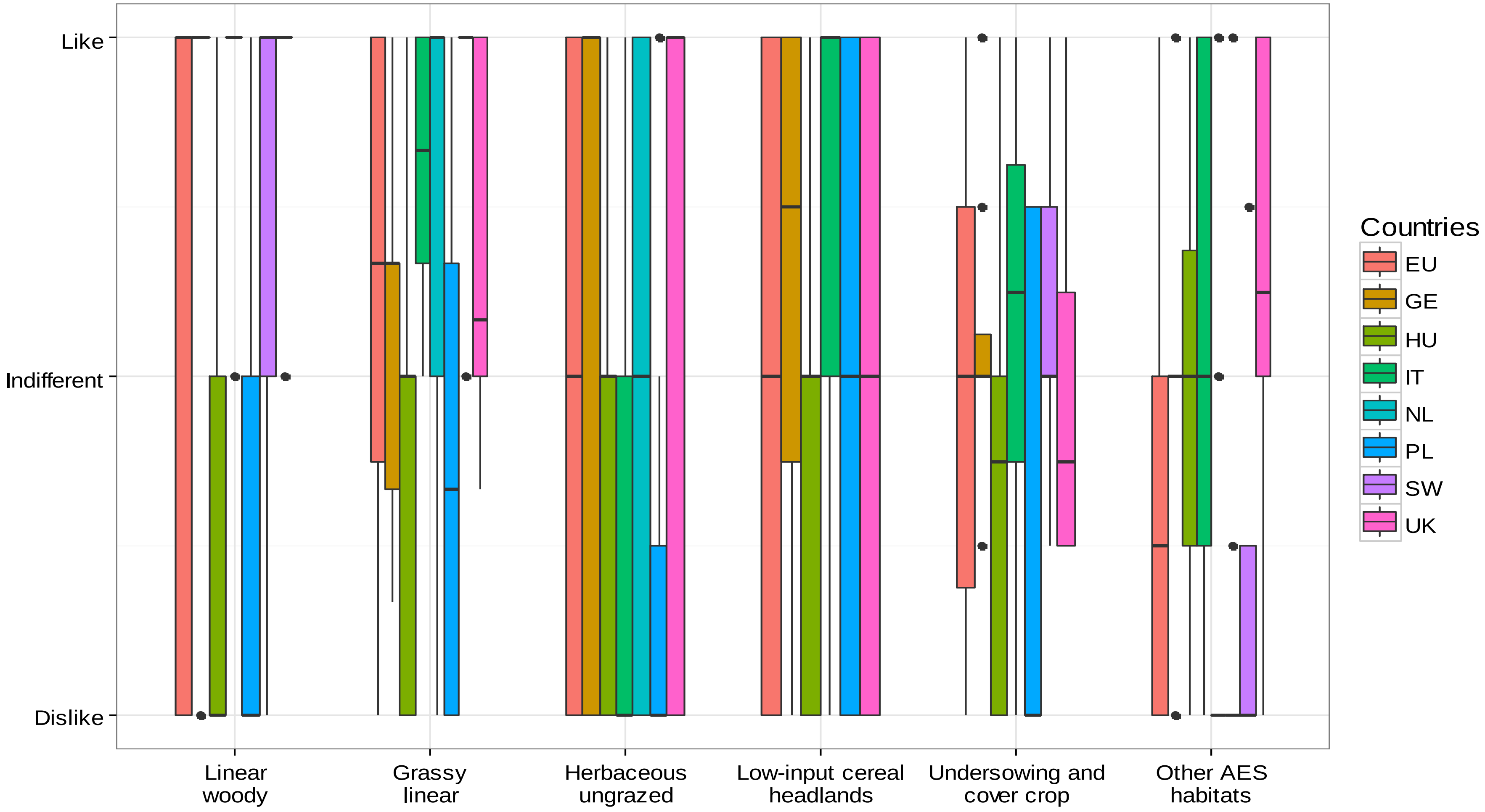

Fig 4B.1. Boxplot of EU farmers' preferences toward habitat management types. The number of respondents is 84.

Table 4B.2. Methods to promote natural pest control and the related number of times mentioned by farmer participants from seven European Union member states

GE	Reduce pesticide	Timing of pesticide	Intensive protection methods	Provide habitat	Flower strips	Cover crops in winter	Soil biota				
	3	2	1	4	1	1	1				
HU	Provide bird habitat										
	6										
IT	Reduce pesticide	Provide habitat	None								
	9	2	1								
NL	Reduce pesticide	Avoid pesticide resistance	Provide bird habitat	Rotation	Bring natural enemies	Margin/flower strip management	None				
	14	1	1	1	4	7	2				
PL	Reduce pesticide										
	4										
SW	Reduce pesticide	Provide habitat									
	4	2									
UK	Reduce pesticide	Sensitive spraying	Seed dressing	Provide habitat	Beetle banks	Hedgerow management	Grass margin	ELS	HLS	Bring bees	None
	2	1	1	2	1	1	1	2	1	1	2

Table 4B.3. Association coefficient table (Kendall’s tau b) among relevant variables

	Importance of natural pest control	# of natural enemies mentioned	Importance of pest damage	# of pests mentioned	Use chemicals to manage pests?	Do you use chemicals due to lack of natural enemies?	# to promote natural pest control	Agriculture area (hectare)	Farm income	# of Crops for a rotation	In a designated area of environmental interests?	In an agri-environment scheme?	Years of farming
Importance of natural pest control	1.00												
# of important natural enemies mentioned	-0.05	1.00											
Importance of pest damage	0.16	-0.02	1.00										
# of important pests mentioned	-0.26***	0.17	-0.05	1.00									
Do you use chemicals to manage pests?	0.08	0.02	0.19*	0.14	1.00								
Do you use chemicals due to lack of natural enemies?	0.08	-0.07	0.06	0.05	0.17	1.00							
# of ways mentioned to promote natural pest control	0.29***	0.11	-0.16	-0.05	0.17	0.17	1.00						
Agriculture area (hectare)	-0.16	-0.15	0.07	0.11	0.20**	-0.04	0.12	1.00					
Farm income	-0.15	-0.11	-0.09	0.24**	0.34***	-0.01	0.29***	0.61***	1.00				
# of Crops for a rotation	0.22**	0.10	0.06	-0.03	0.11	-0.04	0.16*	-0.09	-0.09	1.00			
In a designated area of environmental interests?	-0.19*	0.05	0.09	0.04	-0.08	-0.29**	-0.29***	0.24***	0.11	-0.17*	1.00		
In an agri-environment scheme?	0.12	0.05	0.09	0.08	0.13	-0.10	0.16	0.21**	0.19	-0.18	0.22*	1.00	
Years of farming	0.05	-0.04	-0.01	-0.01	-0.02	-0.14	-0.06	-0.08	-0.06	0.05	-0.02	-0.08	1.00

Note: '#' denotes 'number'; importance of natural pest control/ pest damage follows the codes of: 1= 'Relatively unimportant', 2='Not as important', 3='Important', 4='Very important'; questions follow the codes of: 0 = 'No', 1 = 'Yes'; farm income: the average annual farm income for the last two financial years, preceding the date of the survey (€, following a seven point scale: 1 = loss, 2 = 1-20,000, 3 = 20,001-40,000,…, 6 = 80,000-100,000, 7 = >100,000); significance levels: * p<0.1, ** p<0.05, ***p<0.01.

Table 4B.4. The predicted probabilities of EU farmers' decision to promote natural pest control in relation to each predictor, while keeping other predictors constant at their average values (perceived importance of natural pest control = 'Important', number of important pests mentioned= 3, farm income = € 40-60,000, whether a farm is in a designated area of environmental interests = 'No').

(1) The predicted probabilities of EU farmers' decision to promote natural pest control in relation to the perceived importance of natural pest control

Importance of natural pest control	Predicted probabilities (95% confidence intervals)				
	# Promotion=0	# Promotion=1	# Promotion=2	# Promotion=3	# Promotion=4
Relatively unimportant	0.82 (0.41, 0.97)	0.16 (0.03, 0.55)	0.01 (0, 0.11)	0 (0, 0.01)	0 (0, 0.01)
Not as important	0.26 (0.08, 0.58)	0.56 (0.39, 0.72)	0.16 (0.05, 0.42)	0.01 (0, 0.08)	0.01 (0, 0.08)
Important	0.21 (0.08, 0.43)	0.57 (0.41, 0.72)	0.2 (0.08, 0.42)	0.01 (0, 0.09)	0.01 (0, 0.09)
Very important	0.12 (0.04, 0.31)	0.53 (0.35, 0.7)	0.31 (0.14, 0.54)	0.02 (0, 0.15)	0.02 (0, 0.14)

Note: # Promotion denotes number of ways that a respondent mentioned to promote natural pest control. This is the same for the following tables.

(2) The predicted probabilities of EU farmers' decision to promote natural pest control in relation to the number of important pests mentioned

# of pest mentioned	Predicted probabilities (95% confidence intervals)				
	# Promotion=0	# Promotion=1	# Promotion=2	# Promotion=3	# Promotion=4
1	0.08 (0.02, 0.29)	0.46 (0.23, 0.71)	0.4 (0.17, 0.69)	0.03 (0, 0.24)	0.03 (0, 0.22)
2	0.11 (0.03, 0.32)	0.52 (0.32, 0.71)	0.33 (0.14, 0.59)	0.02 (0, 0.17)	0.02 (0, 0.16)
3	0.15 (0.06, 0.36)	0.55 (0.38, 0.71)	0.26 (0.11, 0.5)	0.02 (0, 0.13)	0.01 (0, 0.11)
4	0.21 (0.08, 0.43)	0.57 (0.41, 0.72)	0.2 (0.08, 0.42)	0.01 (0, 0.09)	0.01 (0, 0.09)
5	0.27 (0.11, 0.54)	0.56 (0.39, 0.72)	0.15 (0.05, 0.37)	0.01 (0, 0.07)	0.01 (0, 0.07)
6	0.35 (0.13, 0.67)	0.53 (0.33, 0.72)	0.11 (0.03, 0.33)	0.01 (0, 0.06)	0 (0, 0.06)
7	0.44 (0.14, 0.78)	0.47 (0.23, 0.73)	0.08 (0.02, 0.31)	0 (0, 0.05)	0 (0, 0.05)
8	0.53 (0.15, 0.87)	0.41 (0.14, 0.75)	0.06 (0.01, 0.3)	0 (0, 0.04)	0 (0, 0.04)
9	0.62 (0.16, 0.93)	0.34 (0.07, 0.76)	0.04 (0, 0.29)	0 (0, 0.04)	0 (0, 0.04)
10	0.7 (0.17, 0.96)	0.27 (0.04, 0.78)	0.03 (0, 0.29)	0 (0, 0.04)	0 (0, 0.03)

(3) The predicted probabilities of EU farmers' decision to promote natural pest control in relation to the farm income

Farm income (K€)	Predicted probabilities (95% confidence intervals)				
	# Promotion=0	# Promotion=1	# Promotion=2	# Promotion=3	# Promotion=4
<0	0.64 (0.29, 0.88)	0.32 (0.11, 0.64)	0.04 (0.01, 0.18)	0 (0, 0.02)	0 (0, 0.02)
1-20	0.48 (0.21, 0.76)	0.44 (0.23, 0.68)	0.07 (0.02, 0.24)	0 (0, 0.04)	0 (0, 0.03)
20-40	0.33 (0.14, 0.6)	0.54 (0.36, 0.71)	0.12 (0.04, 0.31)	0.01 (0, 0.06)	0 (0, 0.05)
40-60	0.21 (0.08, 0.43)	0.57 (0.41, 0.72)	0.2 (0.08, 0.42)	0.01 (0, 0.09)	0.01 (0, 0.09)
60-80	0.12 (0.04, 0.31)	0.53 (0.35, 0.7)	0.31 (0.14, 0.55)	0.02 (0, 0.15)	0.02 (0, 0.14)
80-100	0.07 (0.02, 0.22)	0.43 (0.23, 0.65)	0.43 (0.22, 0.67)	0.04 (0, 0.25)	0.03 (0, 0.23)
>100	0.04 (0.01, 0.16)	0.31 (0.12, 0.59)	0.53 (0.3, 0.75)	0.07 (0.01, 0.38)	0.06 (0.01, 0.37)

(4) The predicted probabilities of EU farmers' decision to promote natural pest control in relation to 'whether a farm is located in a designated area of environmental interests'

Designated area	Predicted probabilities (95% confidence intervals)				
	# Promotion=0	# Promotion=1	# Promotion=2	# Promotion=3	# Promotion=4
No	0.21 (0.08, 0.43)	0.57 (0.41, 0.72)	0.2 (0.08, 0.42)	0.01 (0, 0.09)	0.01 (0, 0.09)
Yes	0.55 (0.25, 0.82)	0.39 (0.18, 0.66)	0.05 (0.01, 0.2)	0 (0, 0.03)	0 (0, 0.03)