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A review of pest management in cereals and oilseed rape in the UK

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1. Abstract

The importance of pests in UK cropping was comprehensively reviewed for AHDB Cereals & Oilseeds by Holland and Oakley (2007; RR64) in relation to natural enemies and changing farming practices. This was followed by RR73, which reviewed invertebrate pest thresholds and how they could be improved (Ellis et al., 2009) and three others, RR70, RR77 and RR79, which addressed the loss of specific insecticide active ingredients due to regulatory changes and the impact of this on pest management practice (Clark et al., 2009; Nicholls, 2013). This review builds on these previous targeted reviews to examine the changing pest management needs for individual pests of oilseed rape and cereals in response to changing pest status and crop husbandry.

The review looks at 25 species in detail to establish their continuing threats to arable farming in the UK and Europe, and to recommend where further research should be done.

Control of slugs in cereals and oilseeds is a key priority amongst growers and is still largely dependent on one chemical, metaldehyde, which was first discovered 75 years ago. In recent years however, with the increasing acreage devoted to oilseed rape, and restrictions imposed by water authorities on metaldehyde residues in run-off water, slug control has become a priority focus.

More frequent pests of cereals are: aphids causing both direct feeding damage and spreading barley yellow dwarf virus, orange wheat blossom midge and wheat bulb fly. Control of these vastly diverging pests requires different approaches but the old established methods of the past are no longer achievable due to changes in availability of insecticides following withdrawal after critical EU reviews, or to the development of resistance to insecticides.

Similar problems confound the control of important pests of oilseed rape – pollen beetles, cabbage stem flea beetles, brassica pod midge, rape winter stem weevil and peach–potato aphids spreading turnip yellows virus – especially following the ban on neonicotinoid seed treatments in 2013.

Control of pests of cereals and oilseed rape in the future is likely to require a much more integrated approach in view of the lack of new active ingredients coming

through the development mill. This review draws on research conducted in the last 10–15 years to allow legislators and funders alike to identify strategies that might give better control in the future than current practices.

2. Introduction

Recent years have seen increasing threats to the success of invertebrate pest management in broad-acre crops in the UK. At the root of these pressures is a combination of factors that include: a lack of confidence in (and support for) risk assessment techniques and control thresholds; insecticide resistance; regulatory restrictions or bans on insecticide actives; changing cropping and agronomic practices; and extreme weather that may be linked to climate change. The importance of pests in UK cropping was last comprehensively reviewed for AHDB Cereals & Oilseeds by Holland and Oakley (2007; RR64) in relation to natural enemies and changing farming practices. This was followed by RR73, which reviewed invertebrate pest thresholds and how they could be improved (Ellis et al., 2009) and three reviews, RR70, RR77 and RR79, that explicitly addressed the loss of insecticide actives due to regulatory changes and the impact on pest management practice (Clark et al., 2009; Nicholls, 2013). These documents provide the starting point from which we have embarked on an up-to-date review of pest management needs in 25 pest species. We comprehensively review the current status of these pests, as well as current management practices, threats and opportunities. We draw on a wide range of recently published research and extension literature from the last 10–15 years to assess whether the lessons learned can be incorporated into current best practice, and we make recommendations for future research priorities.

Pesticide Usage Survey data suggests that more insecticides are applied than is necessary, often as cheap insurance, even though most growers are aware of thresholds and consider them an important component of pest management. In oilseed rape there is an excessive level of insecticide use compared with the proportion of crops in which pests exceed the control thresholds, and in most years all of the British oilseed rape area is sprayed at least once for unspecified reasons (CropMonitor™ 2014; Garthwaite et al, 2007, 2009, 2011, 2013, 2015). Of the 25 pest species reviewed that attack cereals and oilseed rape, thresholds have been developed for 16 and the origin of eight of these is unknown. Of the eight thresholds of known origin, two are more than thirty years old. Lack of confidence in existing thresholds, together with time consuming and complex pest assessment methods and inexpensive pyrethroid insecticides, are all reasons why farmers/agronomists may not use thresholds to assess pest risk (Ellis et al., 2009. RR73). Clearly there is a need to understand why some thresholds have not been adopted as they are the foundation for integrated pest management that reduces unnecessary insecticide use and optimises the influence of cultural control methods and natural enemies. RR73 serves as our starting point for investigating whether new research done in the last 10 years can shed some light on the lack of adoption by the farming community of thresholds that are well established, and for those pests where no thresholds exist, for examining the prospects for their development.

For pests that have developed insecticide resistance, this has radically changed the economics of relying on insurance treatments and the risk of resistance now looms over the management of many other pest species too. As pesticides are phased out because of reduced efficacy or regulatory changes, the grower is faced with a smaller choice of more expensive alternatives, and some of these are older and less environmentally friendly chemistries, e.g. organophosphate pesticides (OPs). Given the low prospect of new insecticide actives becoming available in the short term, farmer-friendly alternative strategies need to be in place to reduce the likelihood of further resistance development and preserve the effectiveness of existing actives. Maximizing the roles of thresholds and decision-support systems, plant resistance, cultural control and natural enemies becomes essential to the long-term sustainability of pest management. Global food security concerns linked to climate change only emphasise the importance of a long-term sustainable approach to integrated pest management.

Here, we review the status of each of 25 pests of cereals and oilseed rape in the UK, and current practices in their management. We examine opportunities to improve the sustainability of their management with insecticides through developments in risk modelling and forecasting, monitoring and thresholds. We explore the potential of a variety of non-insecticide options for the management of each pest, including plant resistance, cultural methods, and biological control through conservation agriculture or augmentation of natural enemies. Changes that may impact on pest status and the effectiveness of their control are explored, e.g. the development of insecticide resistance, withdrawals of insecticides, the increased adoption of reduced tillage, the continuing increase in area of oilseed rape, and climate change. For each pest, recommendations are made for research to tackle the pest management needs identified.

3. General pests

3.1. Slugs

Despite the fact that slugs damage both cereals and oilseed rape, these pests were not included in the review by Holland and Oakley (2007). Nevertheless, they are an important pest on both cereals and oilseeds, especially in wet autumns.

3.1.1. Species causing problems

The grey field slug, *Deroceras reticulatum,* and the garden slug, *Arion ater,* are the main pests of arable field crops in the UK (Jone and Jones, 1984; AHDB 2013), but many other species of *Arion, Milax and Tandonia* cause problems in these and other crops (Barker, 2002), especially vegetables, orchards and herbal plants (Kozlowski, 2005). Most recently, the Spanish slug, *Arion lusitanicus* (syn. *A. vulgaris*), has been causing problems across southern and central Europe (Kozlowski et al., 2010) and there has been recent concern about it in the UK (Gray, 2013), although it has probably been here for some time (Kerney, 1999).

3.1.2. Life cycles

Life cycles of slugs vary considerably in length, but that of the main arable pest species are relatively similar, with mating and egg-laying occurring when conditions are generaly favourable for activity, namely moist and temperate (Glen and Moens, 2002; Moens and Glen, 2002; McKinley et al., 1992). In northern Europe, where the life cycle of *D. reticulatum* takes 12–15 months, it breeds throughout the year. However, there is usually a mixed age structure with overlapping generations, with peaks of egg laying in March–April and September–October (Jones and Jones, 1984). About 300 eggs are laid in batches of 10–30 in crevices in the soil or in decaying organic matter and are able to withstand freezing (Runham and Hunter, 1970). Eggs hatch into miniature versions of the adults.

3.1.3. Damage

The increased pest status of slugs over the last 30 years in the temperate regions of Europe has been exacerbated by changes in husbandry practices, specifically a major shift from spring to winter cropping of cereals, the expansion of dense-canopy crops such as oilseed rape in the autumn, and the adoption of minimum tillage techniques, which are designed to conserve moisture, but also preserve the organic matter on which moisture-loving slugs thrive (Henderson and Triebskorm, 2002).

Slugs damage cereals in two ways – by hollowing out the grain before and during germination, and by shredding the young leaves after emergence. The former sometimes has serious effects of field plant populations sufficient to require re-drilling. Wheat seems to be more vulnerable than barley or oats, which is reflected in the control measures applied to that crop (Table 3).

Damage to oilseed rape, especially when autumn sown, is to the emerging seedlings; seeds do not seem to be attacked, perhaps because they are relatively small. Slugs can decimate plant populations and cause severe defoliation on quite large plants.

There is very little published evidence to show precisely the effects of slugs on yield, either in cereals or in oilseed rape (DEFRA, 2010), despite the perceived importance of slugs in arable cropping and despite expert opinion-based estimates of potential losses in the absence of molluscicides of 1.1%, worth £25.5m in wheat and 2.4% worth 18m in oilseed rape. Many trials have shown the efficacy of treatments, but few have been taken to harvest, and of those that have, few have shown statistically significant effects, with large variability in field trials being cited as the reason. Yield benefits of 2–8% were obtained in many ADAS trials undertaken between 1987 and1992, but many of them were not significant (DEFRA, 2010).

Another reason for the difficulty in demonstrating yield benefits of slug control treatments could be the capacity of crops to compensate for loss of plants or seeds. For example, wheat overproduces the number of tillers required to obtain optimum yields (Ellis et al., 2009) such that, at normal seed rates (375 seeds/m^2 (AHDB Cereals & Oilseeds, 2014), there is no change in yield. Losses of plants down to fewer than 200 per m^2, even down to 62 plants per m^2 with September sowings, could probably be tolerated without serious losses of yield (Spink et al., 2004; Defra, 2010). Oilseed rape also has a legendary capacity to compensate for plant loss, largely by producing lots of side branches on surviving plants. Populations between 20 and 100 plants per m^2 can often produce the same yields in the absence of other pest problems (e.g. pigeons) (Ellis et al., 2012), so this crop can tolerate big losses of young plants before yields are compromised. Higher seed rates in both crops in high-risk situations could be a method of overcoming the problem, so long as there is an even distribution of remaining plants. Certainly low plant population or poor establishment does not reduce yield unless significant areas of the field have few or no plants, and conditions are unsuitable for compensatory growth (Sylvester-Bradley et al., 2008).

3.1.4. Thresholds for control

The current threshold for *D. reticulatum* in the UK is four or more slugs caught per refuge trap (containing layers mash chicken feed) (Glen et al., 2006; Ellis et al., 2009; RR73). Unfortunately, it would seem that little notice is taken of this threshold, as, in an AHDB Cereals & Oilseeds survey reported by Ellis et al. (2009), the response scores for slugs was between 2–3, i.e. between 'disagree' and 'agree' that 'a threshold is a valuable tool when deciding to apply a treatment against this pest'. We suspect that the hour of management time needed to monitor slug numbers over the susceptible period (i.e. set up and check the nine recommended refuge traps per field or 13 traps in fields over 20 ha) prior to deciding whether to apply slug pellets is perceived as too long, certainly by agronomist advisors, and possibly also by growers themselves. Thus insurance applications are more likely to be applied, based on the crop species being sown (with oilseed rape having a greater risk), previous history of slug damage in the field, soil type and local weather conditions. Ironically, the weather conditions that encourage slugs to multiply (very wet), are also the conditions that reduce the persistence of the pelleted baits that are applied to control them, breaking them down and contributing to the accumulation of active ingredients in run-off to watercourses.

3.1.5. Current control methods

Efficacy of pellets

Current control measures rely heavily on the use of slug pellets containing molluscicides (see Henderson and Triebskorn, 2002, for an extensive review of the evolution of molluscicides), of which metaldehyde (discovered in 1934) is still the most popular in various guises, followed until recently by methiocarb (discovered in 1962 but banned in 2015). Small hectarages are treated with calcium chloride or ferric phosphate treatments, and other unspecified molluscicides (Garthwaite et al., 2011, 2013, 2015). In 2010, 2012 and 2014, respectively, 16, 13 and 22% of wheat crops (over 400,000 ha), and 40, 50 and 76% of oilseed rape crops (>350,000 ha) received a molluscicide, but only around 3-6% of winter barley and less than 2% of spring barley was treated in those three years, confirming the perception that the latter crops are relatively tolerant of slug attack (Garthwaite et al., 2011, 2013, 2015; Table 3). Neither oats nor linseed received any molluscicides in the 2010 survey, but they did in the 2014 one. These figures were different from previous usage (DEFRA, 2010; Garthwaite et al., 2008), although variation from year to year is probably more due to local weather conditions prevailing at the normal time of application.

Of the treatments used, metaldehyde accounted for over 90% of applications to all of these crops (Tables 3a and b), largely because it is the cheapest active ingredient, not necessarily because it is the most effective. Methiocarb use varied from 2-7% in winter cereals and oilseed rape, but has now ceased following the withdrawal of approval by the EU in 2014 (Bayer 2014). Effectively, 2014 was the last year that methiocarb could be used for slug control. Use of ferric phosphate products increased substantially in 2014, probably as a result of the withdrawal of methiocarb (Table 3a and b)

In any case, the efficacy of all pellets is relatively poor compared to other crop protection products, and this is often due to ineffective targeting and placement of the pellets (DEFRA, 2010). Despite the high usage of pellets, slug damage is as common now as it was before the large increase in their usage, suggesting that there is still some way to go to achieve good control.

Poor efficacy is often due to poor targeting. For example, protection of wheat seed from hollowing could perhaps be better achieved by placing pellets alongside seed. However, even this does not prevent damage if the pellets are well spread out in relation to the seeds and their efficacy may also be affected by the degree of compaction in the soil, especially if the crop has been rolled after sowing. Underground, most damage occurs in cloddy seedbeds that have not been consolidated, and in such conditions ad-mixed applications may give better control (AHDB Cereals & Oilseeds, 2005a). In general however, soil surface applications made prior to, but especially just after, sowing are more effective (Green et al., 1992; AHDB Cereals & Oilseeds, 2005 b and c).

Poor efficacy can also be caused by the negative feedback response of slugs to ingestion of poisonous baits, which leads to cessation of feeding before a lethal dose has been consumed (Bailey et al., 1989).

Given the poor efficacy of the most widely used active ingredients, it is surprising that better, safer products have not rapidly come to market in the last 70 years. However, in recent years pellets based on ferric phosphate have been developed which do give demonstrable control of slugs. Speiser and Kistler (2002) found that ferric phosphate controlled slugs in lettuce, although less effectively than metaldehyde. More recent studies by Rae et al. (2009) showed that iron phosphate pellets at 5 g/m^2 provided an excellent reduction in leaf damage by *D. reticulatum* and *A. ater* in chinese cabbage, being as effective as metaldehyde and significantly better than using parasitic nematodes. Horgan et al., (2011) showed similar results for chinese cabbage and cabbage, and significant reductions to oilseed rape seedling damage using 3% ferric phosphate pellets applied at 7 kg/ha to control three genera of slugs, including *Arion* spp, *Helix* spp, and *Deroceras* spp.

Future of pellet treatments

Despite the inadequacies of metaldehyde pellets, they remain the most popular method of control, but continuation of their use is now under threat from regulatory authorities, who are detecting levels of metaldehyde above the legal limits (0.1 µg/L = 0.1 ppb) in many water sources around the UK (Brown and Beulke, 2010). In a recent Water UK Briefing Paper (Marshall, 2012), the response of the agro-chemical companies to this problem was described, notably the establishment of the Metaldehyde Stewardship Group which has introduced the voluntary 'Get Pelletwise' campaign to persuade farmers to reduce the number and quantity of metaldehyde applications (Colin Myram pers. comm). If this voluntary approach does not result in reductions in levels of water contamination, there is a strong likelihood that metaldehyde will be banned, which would force farmers to switch to the more expensive alternatives such as ferric salts (Lambion, 2005; Horgan et al., 2011). Both metaldehyde and methiocarb are poisonous to vertebrates (Homeida and Cooke, 1982; Fletcher et al., 1991; Fletcher et al., 1994; EFSA, 2012)), and methiocarb is toxic to beneficial invertebrates such as earthworms and carabid beetles (Purves and Bannon, 1992). There would not be the same concerns about ferric phosphate, as this product breaks down to iron and phosphate, neither of which is harmful to the environment (Horgan et al., 2011). Their limited use since introduction in 2005 is probably due to the price, and perhaps also to lack of prior experience of their performance. Their efficacy can be as good as that of the current alternatives (Gengotti et al., 2008; Rae et al., 2009; Horgan et al., 2011) but the perception of growers is that they are not as effective because slugs treated with ferric phosphate tend to die underground (Alan Horgan, pers. comm.). In some respects this is more environmentally friendly than the death of many metaldehyde or methiocarb-consuming slugs on the soil surface where they can be found and eaten by birds, which might then suffer adverse consequences from consuming molluscicide residues. However, farmers like to see evidence of control.

Table 3a. Area (spray ha) of cereal crops treated with molluscicides in the UK in 2010 and 2012

AI	Winter wheat						Winter barley						Spring Barley					
	Area treated (spray ha)			%			Area treated (spray ha)			%			Area treated (spray ha)			%		
	2010	2012	2014	‘10	‘12	‘14	2010	2012	2014	‘10	‘12	‘14	2010	2012	2014	‘10	‘12	‘14
Metaldehyde	362625	233698	366618	91	92	88	16749	9219	16228	90	89	67	234	1201	4725	100	65	78
Methiocarb	35922	19154	28859	9	8	7	322	879	2539	2	8	11	0	637	762	0	35	13
Ferric phosphate			21379			5			5181			22			584			10
Others	1696	3320	70	0.4	0.1		1536	298	82	8	3	0.3	0	0	0	0	0	0
Total	400243	255172	416926	100	100	100	18607	10395	24030	100	100	100	234	1838	6071	100	100	100
Area grown			1935737						429023						650803			
% of crop area grown	16	13	22				3.4	2.7	5.6				0.1	0.3	1.2			

*including calcium chloride, ferric phosphate and unspecified molluscicides in 2010 and 2012 (Garthwaite et al., 2011, 2013)

Table 3b. Area (spray ha) of oilseed rape crops treated with molluscicides in the UK in 2010 and 2012

AI	Oilseed rape					
	Area treated (spray ha)			%		
	2010	2012	2014	‘10	‘12	‘14
Metaldehyde	321660	340984	460375	91	90	89
Methiocarb	23165	24706	25515	7	7	5
Ferric phosphate			28377			6
Others	7118	11929	1090	2	3	0.2
Total	351943	377619	515357	100	100	100
Area grown			674580			
% of crop area grown	40	50	76			

*including calcium chloride, ferric phosphate and unspecified molluscicides in 2010 and 2012 (Garthwaite et al., 2011, 2013)

Seed treatments

If rational use of molluscicides is difficult to achieve due to the onerous method of determining need, then the use of molluscicide seed treatments is even less rational, because most seed needs to be ordered long before the need can be ascertained. Very little seed is now treated on farm immediately before sowing. However, seed treatments are perceived to be less environmentally damaging, so long as the seeds are sown correctly and not left on the soil surface where they can be consumed by non-target organisms, such as birds and mammals.

There is some evidence from the literature that methiocarb or metaldehyde seed treatments have given good control of slug damage, if not of the slugs themselves, at least in laboratory conditions. As far back as 1984, Scott et al., demonstrated that methiocarb applied as a seed coating could give good protection. More recently, Simms et al., (2002; 2006) showed that both metaldehyde and methiocarb gave good protection in mini plots, although protection given by metaldehyde was short lived compared to that given by methiocarb, which lasted for 4 weeks. However, neither seed treatment gave as good protection as baited pellets. In any case, the withdrawal of methiocarb as an active is also applicable to seed treatments, so these are no longer an option.

From a different class of pesticides, the neonicotinoid imidacloprid, when applied as a seed treatment at between 0.35 and 1.05 g a.i./kg seed, acted as a repellent in to slugs in field trials conducted by Bayer in wheat (Rose and Oades, 2001; Adam and Hopkinson, 2006). This activity was confirmed in lab and in field studies in wheat and oilseed rape, although the rates necessary to provide significant deterrent activity were quite a lot higher than those used in the Bayer trials (2.8–8.1 g a.i./kg seed; Simms et al., 2006) and well above the approved rate. Lower rates (0.7–1.4 g a.i./kg seed) reduced slug damage in field trials to less than obtained with pellets, but this effect was short-lived and inconsistent. Repellency to slugs was considered, at best, to be a useful biproduct of the control of other pests.

Since this work was done, imidacloprid (sold as Secur by Bayer) has been largely supplanted in wheat by clothianidin (Deter; from Bayer) although it is still available as Tripod Plus (from Mahkteshim). In oilseed rape, up until 2013, when all three chemicals were banned (EU, 2013; EFSA, 2013; Nicholls, 2013), imidacloprid (as Chinook from Bayer) was largely replaced by clothianidin plus betacyfluthrin (Modesto from Bayer) or thiamethoxam (Cruiser OSR from Syngenta). Clothianidin had repellent activity against slugs in wheat at 0.5 g a.i./kg seed, resulting in a mean increase of 29% in plant number in seven trials (Adam and Hopkinson, 2006). This activity has been included on the label for this crop, the first such approval for a seed treatment in the UK.

Besides these examples, many other seed treatments for slug control have been examined (reviewed by Kozlowski et al, 2010), but none have been developed commercially, probably due to their phytotoxicity and lack of stability.

Integrated control

Integrated control systems have been developed and promoted by AHDB (see AHDB information sheet 04). These include the use of trapping methods to assess risk prior to sowing the crops, cultivation and rolling, if necessary, to consolidate seed beds and reduce slug numbers within fields, altering sowing depth (wheat only) in cloddy seed beds, and the use of slug pellets if thresholds are exceeded. Pellet use is guided by further monitoring of slug activity in the early stages of crop growth and by consideration of the weather. All this requires significant amounts of time to carry out assessments, which may discourage many farmers or their agronomists from following the suggestions. However, useful decision trees are also provided, together with comparisons of effectiveness of pellets applied with different timings dependent on weather conditions (AHDB 2016).

Cultural control

A wide variety of cultural control methods (copper barriers, eggshells, hair, diatomaceous earth, bark, pine needles, sand, lime, salt etc.) have been tried and are in use in gardens and in small high value crops (Schüder et al., 2003; Glen, 2002; Rae et al., 2007), but they are not applicable to broad-acre arable crops. As mentioned earlier, soil cultivation kills slugs directly, but also increases opportunities for predation by vertebrates, exposes their eggs to desiccation, and removes organic matter from the soil surface, which can encourage their feeding (Glen and Symondson, 2002; Rae et al., 2007). However, cultivation also decreases soil moisture, which it is important to conserve in some soil types and at certain times of year, to ensure good and uniform germination. One of the reasons for the major increase in minimum tillage practices in oilseed rape is precisely to conserve moisture in August when, in most years (although not 2012), the soil is very dry. Early establishment of an oilseed rape crop allows the plants to develop deep root systems before the winter sets in, which in turn helps the crop to withstand other overwintering pressures such as damage from frost and pigeon grazing. Small, later-sown plants tend to succumb more easily to these pressures. Moisture conservation in cereals is also important for September sown crops, but less so in later months.

Biological control

The nematode, *Phasmarhabditis hermaphrodita,* is a lethal parasite of many slug species (Wilson et al., 1993; Glen et al., 2000; reviewed by Rae et al, 2007) and has been available as a commercial molluscicide (Nemaslug, from Becker Underwood) since 1994 (Rae et al., 2007). However, it is expensive and, therefore, more commonly used in high-value vegetable crops rather than in arable agriculture, not least because it has to be kept refrigerated (Glen, 2002). Applications at lower rates would reduce costs, and still inhibit feeding by slugs (Glen et al., 2000). Maintaining persistence of *P. hermaphrodita* using slow release gels and improving the virulence of strains are targets for research (Rae et al., 2007).

Carabid beetles, especially the larger species such as *Pterostichus melanarius,* which is one of the most abundant on arable land (Kromp, 1999; Brookes et al., 2004), have been shown to eat slugs (Symondson et al., 2002a and b)) and give good control of slug populations (Bohan et al., 2000). Their abundance in crops can be encouraged by provision of beetle banks (Lys and Nentwig, 1992; Sotherton, 1995), but also by use of non-inversion tillage (Holland, 2004; Kromp, 1999), which, ironically, are also the techniques that increase the abundance of slugs. However, the ability of carabids to control slugs can depend on the species of slug present and the species of carabid (Oberholzer et al., 2003). Damage to oilseed rape by *D. reticulatum* was reduced by *P. melanarius* but not by *Poecilus cupreus* in laboratory trials in Switzerland, but damage by the closely related *D. laeve,* was not prevented by either carabid as this slug species feeds underground, and was thus not accessible to the beetles. Availability of alternative prey, such as aphids or dipteran larvae, which might be more palatable to beetles than slugs, can divert predators away from attacking slugs (Symondson et al., 2006).

Alternative control methods

Spray treatments for slugs do not seem to have been a priority for researchers in the past, as none have been developed commercially. Such sprays could be applied in response to need rather than as insurance, at least in crops where above-ground damage is important, such as oilseed rape and vegetables. They would probably not be effective in protecting wheat seeds after sowing. However, in a recent study Kozlowski et al. (2010) confirmed the effectiveness of methiocarb and metaldehyde as repellent spray treatments against *A. lusitanicus* when sprayed on oilseed rape leaves, but also flagged up abamectin as a potential slug repellent; this latter active ingredient showed significant persistence for 19 days after application. Copper hydroxide (Thompson et al., 2005), caffeine (Hollingsworth et al., 2002), garlic, urea, formaldehyde and cinnamamide (Schüder et al, 2003) have also shown promise as molluscicides.

3.1.6. Recommendations for research

Given the increasing pressures on growers from water authorities, it is likely that the use of metaldehyde could be banned, or at least severely restricted to areas where water is less likely to be contaminated by run-off (DEFRA, 2009). Thus, it is imperative that viable alternatives are developed that will not be associated with similar concerns. In this respect, chemicals that are either less soluble and thus less likely to contaminate water, or that break down to harmless products, are required. There is also a need for better targeting than the current tendency towards insurance use. With these concerns in mind we suggest the following:

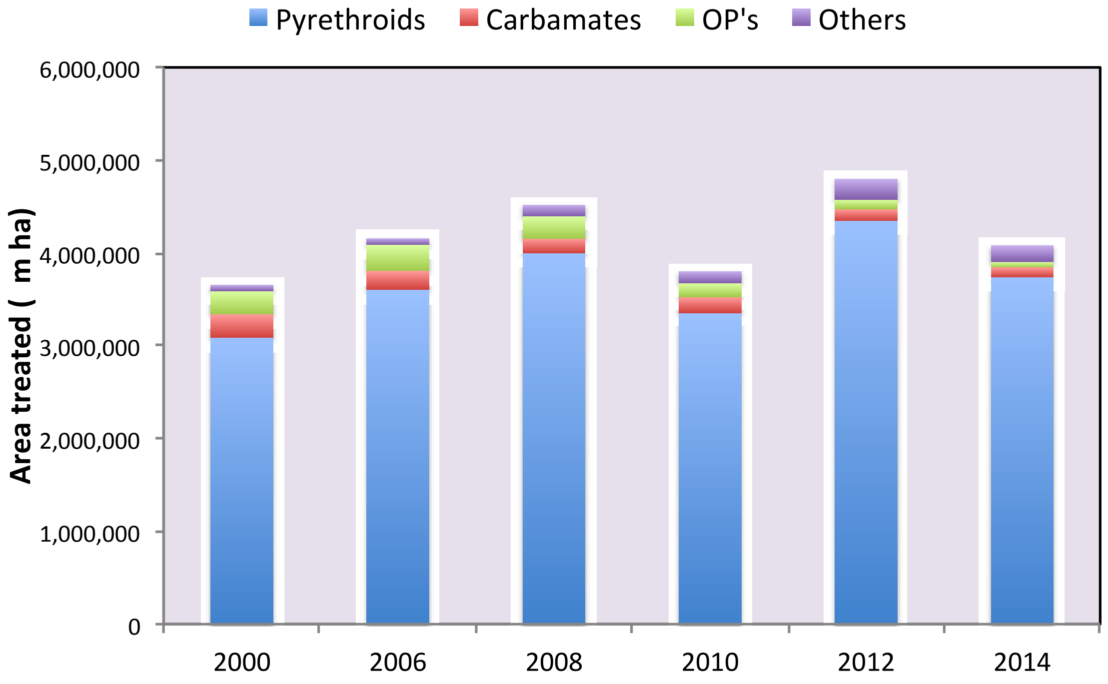
1. Assessment of ferric phosphate pellets on a wider scale than has currently been done, focussing on plant damage rather than just on slug mortality.
2. Formulation of metaldehyde and other slug pellets so that leaching of active ingredient is reduced.
3. Assessment of spray treatments, specifically those that are less soluble and confer greater persistence than metaldehyde (e.g. abamectin, caffeine, slow release metaldehyde).
4. Identification and development of repellent seed treatments in wheat that confer some control of slugs (why are barley and oat seeds less attractive to slugs?).
5. Provision of a forecasting scheme based on local trapping, and wide-scale models that have already been developed.
6. In light of the lack of published demonstrable yield benefits from slug control, the use of increased seed rates to compensate for slug damage in both oilseed rape and wheat should be investigated.

Some of these recommendations have already been suggested by Defra (2010).

4. Pesticide usage in UK arable crops

4.1. Spray treatments

Before considering specific research needs specifically in cereals and oilseeds it is useful to examine current practice, at least in terms of pesticide use. The Defra Pesticide Usage Survey in 2014 (the most recent available) showed that over 4 m hectares (spray hectares) of arable crops were treated topically (i.e. not including seed treatments) with insecticides, a slight decrease compared with the previous survey in 2012 (Table 12 in Garthwaite et al., 2015; Fig. 1). Most of the area was treated with pyrethroids (92%), followed by carbamates (2.6%), organophosphates (OPs) (1.4%) and others (4.4%). Examination of the crop-specific data showed that most insecticides were applied to wheat (39%), followed by oilseed rape (32%), winter barley (8%), potatoes (6%) and beans (6%); other crops made up the remainder (Garthwaite et al., 2015; Fig. 2). Wheat and oilseed rape, both mostly winter sown, comprised the majority of land that received insecticides to control pests.



Source: Defra Pesticide Usage Surveys of Arable Crops 2010, 2012 and 2014; Garthwaite et al, 2011; 2013; 2015

Figure 1. Insecticide use in the UK 2000–2014: total insecticide use (not including seed treatments). OP's = organophosphorous insecticides

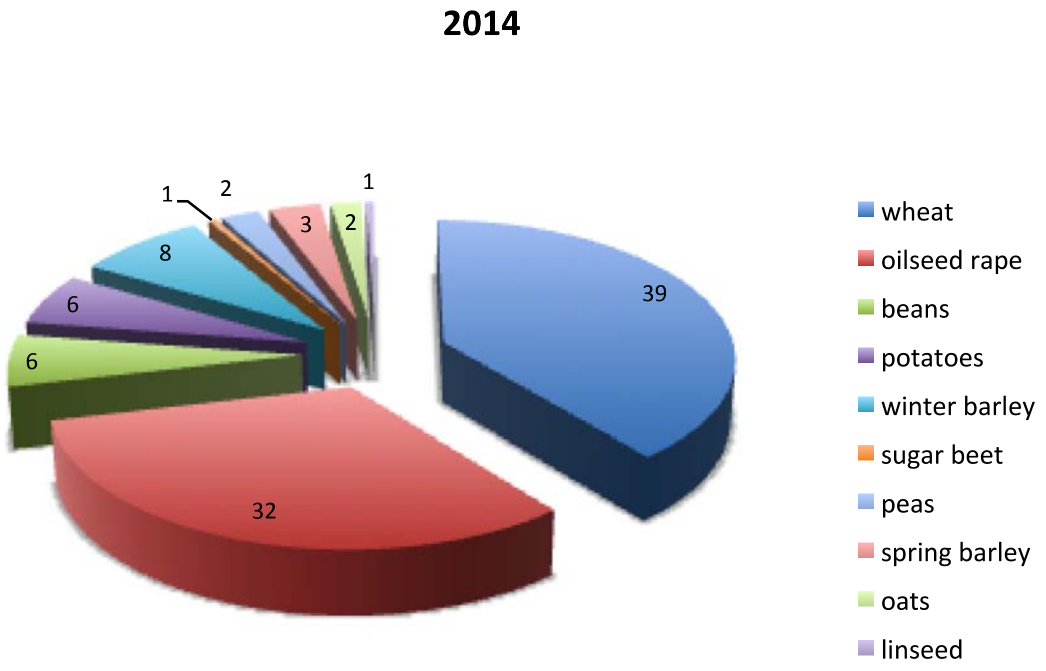


Figure 2. Insecticide use in arable crops in the UK 2014 (not including seed treatments): % of total area treated. Source: Defra Pesticide Usage Survey of Arable Crops 2014; Garthwaite et al., 2015.

5. Pesticide use in cereals

5.1. Spray treatments

Of the 3.2 million hectares of cereals grown in the UK in 2014, winter barley received the most insecticides, with 67% of all crops treated with at least one insecticide spray; of the other cereals, 61% of wheat (both winter and spring), 20% of spring barley and 50% of oats were treated (Table 4). Rye and triticale are included for completeness.

Of the insecticides listed, pyrethroids were the most heavily used, the most popular of which were lambda-cyhalothrin (38%), cypermethrin (32%), esfenvalerate (10%), zeta-cypermethrin (7%) and alpha-cypermethrin (6%) (Table 4). Of the other insecticide classes, the OP, chlorpyrifos, comprised 2.5% of total usage, probably to control wheat bulb fly and/or orange wheat blossom midges, and pirimicarb comprised only 1.1%, against aphids. None of the others individually comprised more than 2% of the total. Chlorpyrifos has now been withdrawn for use in the UK, and the future of pirmicarb is also being re-assessed by the EU at the time of writing.

5.2. Seed treatments

5.2.1. Active ingredients available

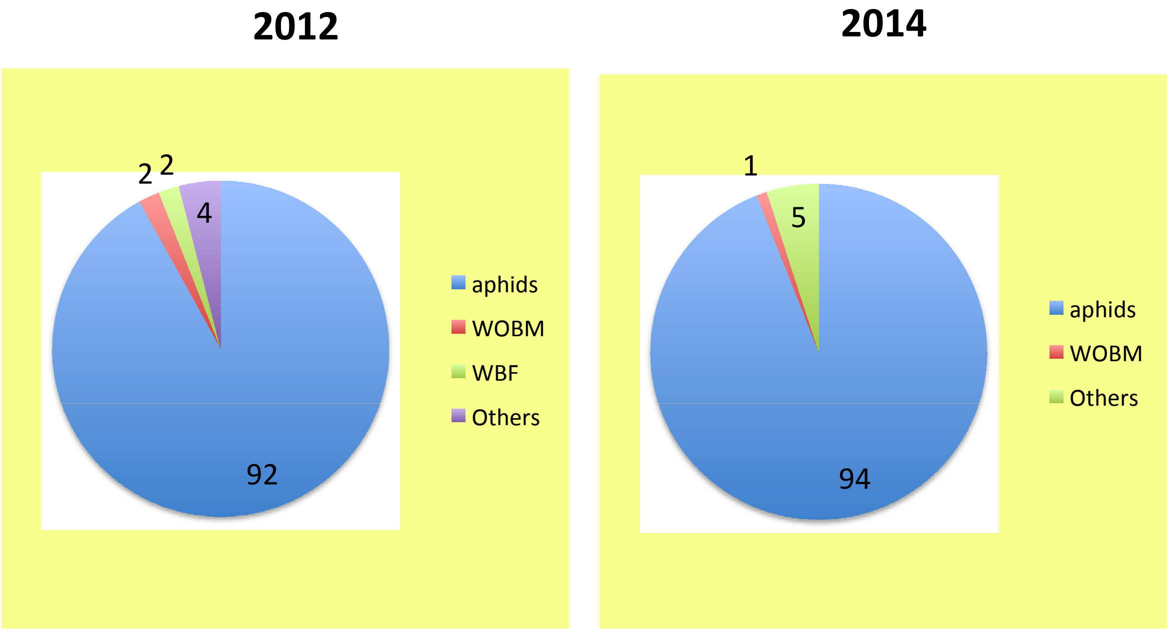
After the demise of gamma HCH as a seed treatment in 1999, it was replaced by imidacloprid (Sibutol Secur or Baytan Secur from Bayer). In 2006, imidacloprid was supplanted by clothianidin plus a fungicide (as Redigo Deter from Bayer), although it is still available under a different brand name (Tripod Plus from Mahkteshim). Other active ingredients available include the pyrethroids, tefluthrin (as Austral Plus from Syngenta) and more recently, cypermethrin (Signal from Chemtura), specifically for control of wheat bulb fly and wireworms.

5.2.2. Area treated

Survey results in 2014 show that wheat has been the main recipient of insecticide seed treatments in cereals. Only one insecticide active ingredient was used in sufficiently large quantities to merit being listed in the survey on wheat – clothianidin (Meredith et al., 2002; Ohkawara et al., 2002) - which was used alone but mostly in combination with a prothioconazole fungicide on 721872 ha - 37% of the total area grown; this represents a substantial increase compared with the 2012 survey, in which only 26% of the total area was treated (Garthwaite et al, 2013, 2015). In 2010, no insecticide actives were listed for winter barley, spring barley, or rye, but 22% of winter barley, 1% of spring barley, 8% of oats and 26% of rye were all treated either with with clothianidin alone or in combination with prothioconazole in 2014. Surprisingly there was no record of tefluthrin use on the major cereals in either 2010 or 2012, but 58 ha of triticale was treated with this insecticide in combination with fludioxonil fungicide in 2010 (Garthwaite et al., 2011; 2013; 2015).

Table 4. Area of cereals (spray ha) treated with insecticides in 2014

Insecticide	**wheat**	**%**	**winter barley**	**%**	**spring barley**	**%**	**oats**	**%**	**rye**	**%**	**Total cereals**	**% of total**
lambda-cyhalothrin	611713	138.0	107589	33.0	54361	40.8	30081	39.6	6470	52.5	810214	37.5
cypermethrin	532230	33.0	112707	34.6	19882	14.9	29768	39.1	2672	21.7	697259	32.3
esfenvalerate	134700	8.4	53841	16.5	16514	12.4	1207	1.6		0.0	206262	9.6
zeta-cypermethrin	110397	6.9	16190	5.0	8650	6.5	12012	15.8		0.0	147249	6.8
alpha-cypermethrin	105229	6.5	22901	7.0	9252	6.9	112	0.1		0.0	137494	6.4
tau-fluvalinate	32814	2.0	398	0.1	923	0.7	0	0.0		0.0	34135	1.6
chlorpyrifos	31514	2.0	636	0.2	19578	14.7	2045	2.7		0.0	53773	2.5
pirimicarb	21409	1.3	84	0.0	0	0.0	61	0.1	3173	25.8	24727	1.1
deltamethrin	18973	1.2	3759	1.2	2589	1.9	210	0.3		0.0	25531	1.2
others	12149	0.8	7848	2.4	1381	1.0	555	0.7		0.0	21933	1.0
Total area sprayed	1611128	100	325953	100	133130	100	76051	100	12315	100	2158577	100
Area grown (ha)	1935737		429023		650803		136807		10967		3163337	
% area treated*	**60.8**		**67**		**19.5**		**49.6**		**78.5**			
Actual area treated	1176928		287445		126907		67856		8609		1667745	
Sprays/crop	0.8		0.8		0.2		0.6		1.1			
Sprays/treated crop	1.4		1.1		1.0		1.1		1.4		1.3	



Source: Pesticide Usage Surveys in Arable Crops: Garthwaite et al., 2013 and 2015

Figure 3. Target pests for insecticides in winter wheat in the UK

6. Target pests in cereals

Across all the cereals surveyed by Defra, aphids were by far the most frequently recorded target pest in wheat winter and spring barley. In wheat aphids comprised over 79% of the records in 2010, 92% in 2012 and 94% in 2014 (Fig. 3; Table 5). However, orange wheat blossom midge and wheat bulb fly were also identified as significant targets in 2010 and 2014. In winter barley, frit fly was considered to be important on 9% of the treated area in 2010, but thereafter, aphids were cited for 98% of insecticide targeting. In spring barley, leatherjackets were treated on 16% of the area in 2010, and 20% in 2014, presumably in fields sown after grass.

Table 5. Target pests (when given) in cereals (% area treated)

Pest	Wheat			Winter barley			Spring barley		
	2010	2012	2014	2010	2012	2014	2010	2012	2014
Aphids	79	92	94	88	98	98	83	78	72
Aphids/frit fly	-	-		9			-	-	
Orange wheat blossom midge	9	2	1	-			-	-	
Wheat bulb fly	4	2		-			-	-	
Leatherjackets	-	-		-			16	-	20
Others	8	4	5	3			1	22	8

6.1. Aphids

Aphids are the most important pests of cereals around the world. Six species are predominant, of which three (the bird–cherry oat aphid, *Rhopalosiphum padi,* the green bug, *Schizaphis graminum,* and the Russian wheat aphid, *Diuraphis noxia*) are listed as global challenges to wheat production (Porter et al., 2009). In the UK and central and northern Europe the grain aphid, *Sitobion avenae*, the rose grain aphid, *Metopolophium dirhodum* and bird cherry–oat aphid, *R. padi,* cause most of the problems (Poehling et al., 2007). A sixth species, the maize aphid, *Rhopalosiphum maidis*, is relatively scarce in Europe, as are *S. graminum* and *D. noxia,* except in the warmer south (Kati et al., 2013). This section will focus on the three main European species.

6.1.1. Life cycles

The life cycles of these three aphid species are summarised by Blackman and Eastop (2007); more detail on life cycles of aphids is available in Williams and Dixon (2007).

The grain aphid, *S. avenae,* is a non-host-alternating (monoescious) species, being restricted in its host preference to grasses and cereals. It is the main pest of cereals, especially wheat, in the summer, but is also an efficient vector of BYDV, especially strains PAV and MAV, the former of which is the most widespread strain of BYDV in Western Europe (Henry et al., 1993; Plumb, 1995). *Sitobion avenae* is often assumed to be anholocyclic through UK winters, but sexuals, males and oviparae, can be produced in the autumn by holocyclic clones; after mating, oviparae lay their eggs on Poaceae, including young cereal seedlings (Dewar and Carter, 1984; Hand, 1980). They can also have two other reproductive modes: androcyclic clones, which produce parthenogenetic females and males, and intermediate clones which produce parthenogenetic females, males and oviparae (Dedryver et al., 1998; reviewed by Helden and Dixon, 2002). The tendency to produce sexuals is greater in the north of the UK than in the south, thought to be due partly, but not exclusively to temperature-determined mortality of anholocyclic clones (Helden and Dixon, 2002; reviewed by Loxdale and Lushai, 2007). Similar observations have been made in France with 600 clones collected from six regions with different climates (Dedryver et al., 2001). This is an important consideration, as it is the anholocyclic clones that cause the greatest spread of BYDV in mild winters, overwintering as active individuals, whilst those overwintering as eggs (a) do not spread virus and (b) cannot do so until they feed on infected plants after hatching in spring, as BYDV is not transmitted through the egg stage (Plumb, 1990). Such late infections do not damage yield as much as early infections at the seedling stage.

The rose–grain aphid, *M. dirhodum*, is primarily thought to be a holocyclic species host-alternating between rose, especially dog-rose, *Rosa canina,* and grasses including cereals. However, anholocyclic parthenogenetic specimens have been recorded on grasses and cereals during the winter in the UK (Dean, 1974;).

The bird cherry–oat aphid, *R. padi* is also regarded as a host-alternating holocyclic species, but can equally well be described as an anholocyclic parthenogenic species, especially where the primary host, bird–cherry, *Prunus padus*, is scarce (e.g. in southern England). In this form, *R. padi* is the most important vector of BYDV in Europe (Dedryver and Harrington, 2004; Fabre et al., 2006).

6.1.2. Damage

A comprehensive review of damage caused by cereal aphids is given by Dedryver et al., 2010.

Summer aphids

In Holland and Oakley's (2007) review, 1975 was regarded as the year with the last widespread damaging epidemic of aphids of any species in summer, but there have been quite a few mini-epidemics of *S.avenae* since then in some parts of the UK, especially in East Anglia (Bell et al., 2015). Epidemics of *M. dirhodum* are rare, but one such occurred in 1979 following a very cold winter (Dewar et al., 1980, 1984).

Direct feeding by aphids on cereals during the summer can decrease root proliferation, and affect the size and quality of the grains, due to interruption of the grain-filling process (reviewed by Poehling et al., 2007; Quisenberry and Ni, 2007). In Europe, Wellings et al. (1989) suggested that direct feeding damage by aphids in summer resulted in losses of 700,000 t of wheat per annum, and Tatchell (1989) estimated losses of 10–13% in the same crop in the UK. Most of this damage would probably have been caused by the *S. avenae*, but losses due to *M. dirhodum,* and/or *R. padi* feeding on the leaves can still occur, although at half the rate per aphid compared to that attributed to *S. avenae* (Niehoff and Stäblein, 1998). Serious losses caused by *M. dirhodum* have been more commonly reported in South America (Sánchez Chopa and Descamps, 2012).

Autumn aphids

Damage by autumn aphids is almost exclusively due to the spread of infection by barley yellow dwarf virus, BYDV, or cereal yellow dwarf virus, CYDV (D'Arcy, 1995), which can cause almost total crop loss, especially in winter barley, if infection is very early (Miles et al., 2001; Dedryver et al., 2010). The B/CYDV complex includes members of the genera *Polerovirus* (CYDV-RPV and -RMV), *Luteovirus* (BYDV-MAV, -PAS and -PAV), and unassigned viral species (BYDV- SGV, -RMV and -GPV) of the family Luteoviridae but debate still rages about these classifications (Miller et al., 2002)). BYDV induces yield losses ranging from 5% to 80% with an average of 30% (Lister and Ranieri, 1995; Perry et al., 2000).

The bird cherry–oat aphid, *R. padi,* is the most important vector of BYDV in autumn-sown cereals in Europe (Dedryver and Harrington, 2004), but *S. avenae* can also infest cereals at this time of year and have been found overwintering on cereals in some years (Dewar et al., 1984; Dewar, 2014). *Metopolophium dirhodum,* despite its ability to overwinter in some locations, is very rarely found on cereals during the winter. Counter intuitively, and contrary to expectations, predictions of increases in cereal aphid epidemics following increases in temperatures due to global warming, and decreases in the severity of winters, suggest that the pest status of cereal aphids in general, and *R. padi* in particular, will significantly decline in Southern Britain by the end of this century (Newman, 2005). Since that prediction, few oubreaks have indeed been recorded.

These aphid species can each carry specific strains of BYDV that are not transmitted by the others. For example, *R. padi* can transmit the RPV and PAV strains, but not the MAV strain of BYDV; in contrast, both *S. avenae* and *M. dirhodum* can transmit MAV and PAV, but not RPV (reviewed by Irwin and Thresh, 1990; reviewed by Shah et al., 2012). The PAV strain was identified as the most likely cause of the mini BYDV epidemic in 2012/13 in the UK. PAV was also identified as the most prevalent strain (90%) in Western France in autumn and spring; the MAV strain was more associated with spring infections, while the RPV strain was relatively rare, and mostly found in the autumn (Leclerq-Le Quillec et al., 1995; 2000).

BYDV infection in autumn sown cereals can be acquired from infected grass weeds that have been ploughed in or inadequately controlled by herbicides prior to the sowing of a new crop but, in most cases in the UK, the virus is introduced by winged aphids migrating from an infected source outside the field (Plumb, 1976). In hard winters, the extent of infection is very much related to the level of primary infection (Plumb, 1983; Kendall et al., 1992) but, in mild winters, secondary spread is probably the main method of virus infection and is related to the influence of weather on the vectors and their natural enemies (Plumb, 1990) and can thus be modelled (Leclerq-Le Quillec et al., 2000).

6.1.3. Monitoring and forecasting

Rothamsted Insect Survey (http://www.rothamsted.ac.uk/insect-survey/) has been operating a suction trap network for 50 years (Bell et al., 2015), which monitors migrations of aphids throughout the country, and publishes bulletins weekly during the growing season, with details of 21 species at 16 sites throughout the country. The activities of some particular pest species are part funded by AHDB and published as “AHDB Aphid News” issued by AHDB through their web site. These weekly summaries include data and graphs of current pest activity, but also comparisons with the previous year, and also a 10 year mean. The Survey team recently celebrated their 50th anniversary since the commencement of the first traps in 1965, which is an immense acheivement for any monitoring scheme (Harrington, 2014).

In addition to information on migrations, forecasts for some species can be made at the beginning of the seaon based on correlations between activity and overwintering temperatures. The first flight of *S. avenae*, for example, is highly correlated with winter temperature, and also the mean April temperature (James Bell, pers. comm.). This does not necessarily predict populations of epidemic proportions, but it can guide growers and agronomists about when to start monitoring their crops.

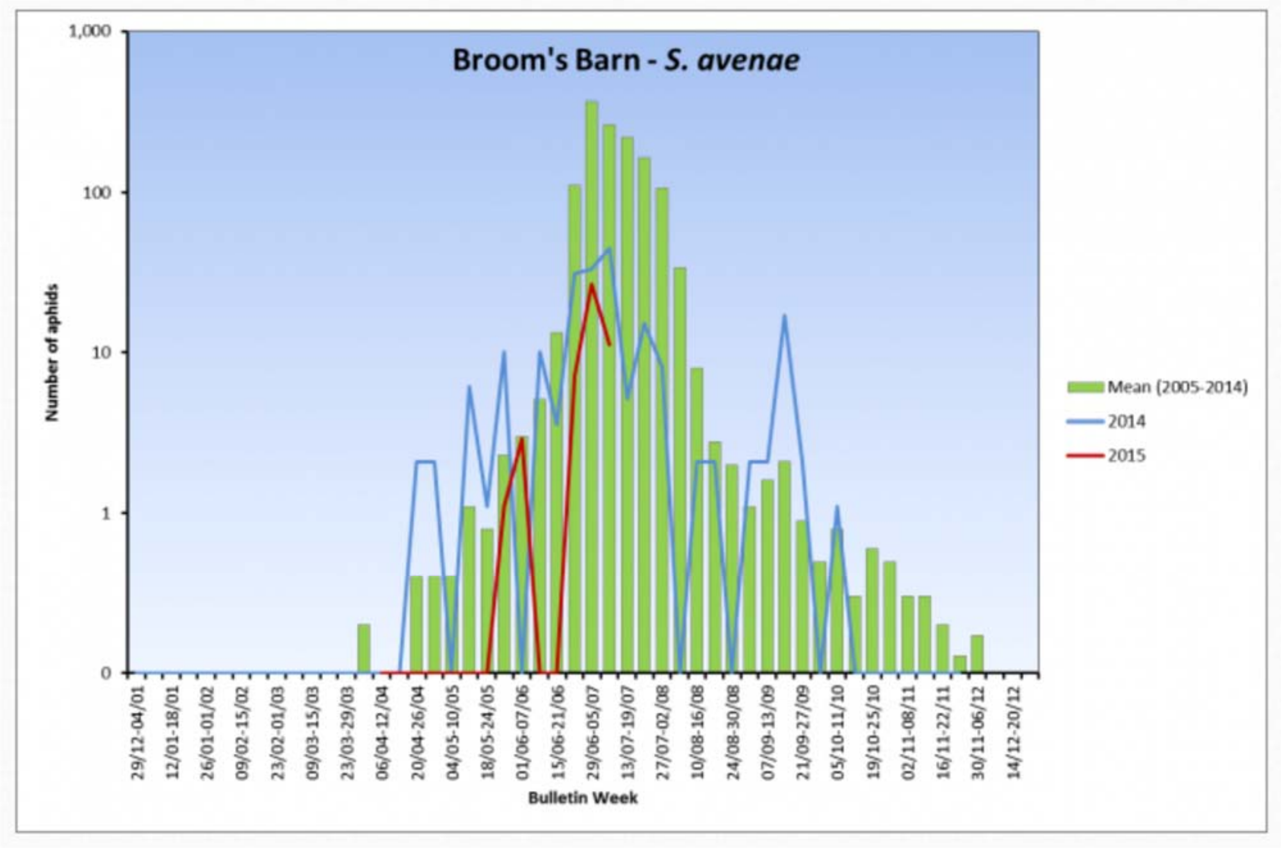


Figure. 4 Example of graphs produced from Rothamsted Insect Survey suction trap network: The grain aphid, *Sitobion avenae* in the Broom's Barn suction trap in Suffolk.

Attempts to forecast the population development of *R. padi* in autumn have been made in France, Australia and the UK to support decision making for control of BYDV in winter barley (reviewed in Dedryver et al., 2010). The French models (Leclerq-Le Quillec et al., 2000; Fabre et al., 2006) rely on an estimate of early infestation, followed by predictions of population growth affected by temperatures, the latter according to Bayesian principles. Validation of the forecasts in the Fabre et al., (2006) model using 20 year mean temperatures gave a good fit between observed and predicted values (R^2 = 0.85). Applying sprays according to model predictions suggested that 35% of treatments that might have been applied in a systematic control system (insurance sprays) were unnecessary and that 20% of costs could be saved annually (Dedryver et al., 2010). The model's predictions could be improved even more by taking account of the proportion of aphids carrying virus into cereal fields, which was shown to vary according to land-use at the regional scale (Fabre et al., 2006). However, these authors, and Ellis et al. (2009) made it clear that ”…labour intensive/expensive pest sampling/assessment techniques can easily make the use of thresholds uneconomic when the low cost of many insecticides [is] taken into account, thus providing an economic argument against threshold use…”.A change in the availability of chemicals and the price of new ones might change that calculation in the future, as will the evolution of resistance to the cheaper insecticides currently being used.

6.1.4. Thresholds for control

In Research Review 73 (Ellis et al., 2009), current thresholds for control of cereal aphids (grain and/or rose–grain aphids) with sprays in the summer were cited as follows: “if more than 50% of tillers were infested at or before GS61 (beginning of flowering), rising to 66% infestation between GS61 and two weeks before the end of grain filling” (Oakley and Walters, 1994). These levels equate to five aphids per ear (or tiller) at the beginning of flowering (George and Gair, 1979).

In the autumn, there are no thresholds for treatment in the UK. Advice is to spray if aphids are present (Ellis et al., 2009), irrespective of numbers or indeed whether they are carrying virus or not. As a consequence, it is likely that the majority of the area treated for aphids, as recorded in the Defra surveys (Fig. 3 and Table 5, above), represents insecticides applied in the autumn, often as insurance sprays because aphids, especially *R. padi*, are very difficult to find then, looking remarkably like specks of soil. The cheapness of pyrethroids has encouraged their indiscriminate use, sometimes at reduced rates, in tank mixes with herbicides and/or fungicides during other spray operations in autumn.

There are no thresholds to guide the use of seed treatments as they need to be ordered from suppliers long before any forecast scheme could be implemented (2–3 months) (Dedryver et al., 2010). Thus they are usually chosen as insurance treatments, based on previous history of damage in the location. For example, the large increase in use of systemic seed treatments in autumn-sown crops in 2012 and 2014 (see section 5.2.2) was a direct result of experience of the BYDV epidemic that became visible in spring 2012 in many areas of eastern England.

6.1.5. Control with sprays

Pyrethroids are by far the most commonly used products for controlling aphids in cereals in Europe, having supplanted OPs and pirimicarb in recent decades (Dedryver et al., 2010), and the same is true in the UK, as shown by the data collected in the Defra surveys in the last 10 years (Table 4)(Garthwaite et al., 2011, 2013, 2015). Much of this usage is in the autumn, and is targeted at aphid vectors of BYDV. As discussed above, usage is probably higher than is necessary in many years because treatments tend to be applied as insurance sprays due to the cheap cost of pyrethroid insecticides, especially cypermethrin, high management costs of monitoring aphid immigration and development, and the fact that aphids are difficult to see in the crop in the autumn.

Pyrethroids gave better control than OP's such as dimethoate and pirimicarb in early studies (Horellau and Evans, 1980; Kendall and Smith, 1982; reviewed in Schepers, 1989 and McKirdy and Jones, 1996). The new-generation pyrethroids such as apha-cypermethrin and beta-cyfluthrin gave good control of *R. padi* spreading BYDV in Australia (McKirdy and Jones, 1996) and well-timed sprays of pyrethroids in Ireland in both autumn and spring barley reduced the number of aphids, reduced BYDV, and resulted in better yields than use of OPs (Kennedy and Connery, 2005, 2012). Lambda-cyhalothrin gave a significant yield increase (9%) in winter barley in the mild winter of 2011/12 (Alan Dewar, pers. comm.).

Environmentally-friendly insecticidal approaches to aphid control include the use of essential oils. Components of these oils including alpha-phellandrene, 1,8-cineole and cis-ocimene extracted from the pepper tree (*Schinus areira*), rosemary (*Rosmarinus officinalis*) and marigold (*Tagetes terniflora*), respectively, have insecticidal effects on *M. dirhodum*, reducing colonisation, feeding and reproduction on wheat (Sánchez Chopa and Descamps, 2012). These offer a low toxicity alternative for management of aphids in cereals that would not be susceptible to the development of resistance due to their multiple sites of action (Tripathi et al., 2009; Rattan, 2010).

6.1.6. Control with insecticidal seed treatments

Currently, the only seed treatments that are capable of controlling sucking pests such as aphids belong to the neonicotinoid class of chemicals (Jeschke et al., 2011). Seed treatments containing imidacloprid, thiamethoxam or clothianidin give good control of aphids as soon as the seedlings emerge from the soil and for 4–6 weeks after sowing, before their systemic activity ceases (McKirdy and Jones, 1996; Miles et al., 2001; Meredith et al., 2002; Adam and Hopkinson, 2006; reviewed by Dewar, 2007). Consequent reductions in BYDV infection were demonstrated in some studies, resulting in significant increases in yield in both barley and wheat (McKirdy and Jones, 1996; Adam and Hopkinson, 2006; Kennedy and Connery, 2012).

Currently only clothianidin and imidacloprid are available to farmers in the UK for this purpose and their use is now restricted by the EC due to their perceived adverse effects on bees, especially when used on oilseed rape, maize and sunflowers (see section 7.1).

6.1.7. Resistance of aphids to insecticides

Until recently there were no reports of the development of resistance in cereal aphids. However, diagnostic studies following control failures after application of pyrethroids against *S. avenae* in 2011 and 2012 have demonstrated the presence of genes that are almost identical to those conferring resistance to pyrethroids in *Myzus persicae* (Foster et al., 2012). Subsequent bioassays in the lab showed a 40-fold tolerance to lambda-cyhalothrin and field trials have shown variable control by several pyrethroids with poorest control provided by cypermethrin (Dewar, 2014; Dewar et al., 2014). Reports from Germany and Denmark suggest that this resistance may be quite widespread (Thomas Thieme, pers. comm.; Ghita Cordsen Neilson, pers. comm.). So far in the UK resistance is only of the heterozygous form, which suggests that resistance levels are lower than they might be if homozygous forms were found (Foster, per. comm).

6.1.8. Cultural control

Changing the sowing date to avoid the main migrations of aphids is one obvious way of reducing the risk of aphids spreading BYDV in the autumn, but this can also reduce the potential yield of later-sown cereals. Moreover, this may not always fit in with the cultivation programme on the farm, especially if the weather deteriorates as the autumn progresses, as happened in autumn 2012. Later sowing dates, can also make cereal crops more vulnerable to migrations of summer aphids the following year if crops mature later and are thus exposed to more aphids at earlier, more vulnerable growth stages. Spring-sown wheat crops for example may have higher populations of aphids in June than early-sown winter ones.

Cultivation can have effects on aphid numbers in autumn-sown winter cereals. The numbers of aphids in wheat and barley were smaller under minimum cultivation compared to conventional ploughing in two out of six seasons between 2001 and 2006 in Ireland (Kennedy and Connery, 2012), presumably due to the adverse effects of conventional cultivations on predators such as carabid beetles (Holland, 2004; Kromp, 1999). However there is a danger that, following minimal cultivation, a 'green bridge' of volunteers and weeds that could increase the risk of virus transmission from infected volunteers and weeds to the newly emerging crop. Control of weeds and volunteers in this situation would be essential.

6.1.9. Conservation biological control

Cereal aphids are prey to a wide range of natural enemies from different taxa and these have been thoroughly reviewed in AHDB Cereals & Oilseeds RR64 (Holland and Oakley, 2007). For indigenous pests, including the majority of cereal aphids in the UK, there are two approaches to exploiting biological control. These are 'augmentation' and 'conservation' of resident natural enemy species, the latter being termed conservation biological control (Eilenberg et al., 2001). Blackshaw and Kerry (2008) proposed a useful method for selecting the most appropriate biological control approach based on consideration of the traits and population dynamics of the targeted pest: pests that are non-dispersive, reaching locally high populations, would be susceptible to augmentation biological control (e.g. slugs, craneflies, wireworms, leatherjackets in this review), whereas species that are highly dispersive in the agroecosystem (though often also patchily distributed, e.g. midges, stem-borers, the weevils and other beetles in this review, and aphids) are more suitable for conservation biological control approaches. This theory is supported for cereal aphids by the fact that there are no reported cases of significant commercial control following natural enemy augmentation in cereals (Dedryver et al., 2010), although Levie et al. (2005) did succeed in reducing cereal aphid numbers to below the economic threshold by releasing thousands of adults of the parasitoid *Aphidius rhopalosiphi* in experimental fields, albeit at an uneconomically high cost. Conservation approaches do not release mass-produced enemies but rather provide an environment that favours the reproduction and survival of existing natural enemies, often through non-crop habitat management, thereby increasing their population sizes and impact.

In the following paragraphs we will provide some general background information on conservation biological control by habitat manipulation. Much background research has been done in relation to aphids but, as many enemies are generalists and have the potential to control a range of pests, it is relevant to the majority of the pest species described in this review. Where specifically relevant to cereal aphids, this will be highlighted.

Effective conservation biological control requires an underpinning ecological understanding of the pests and enemies concerned and the resources (hosts, nectar, pollen, shelter) they require within the context of the wider agricultural landscape (Griffiths et al., 2008; Gurr et al., 2003; Landis et al., 2000; Pell, 2007; Pell et al., 2010; Rusch et al., 2010; Shah and Pell, 2003; Tscharntke et al., 2007). In the UK and elsewhere, the introduction of habitat management options within agri-environment schemes (AESs) designed to address declines in farmland biodiversity (Anon 2009), represent a potential tool for use in conservation biological control strategies. Recent reviews find that there is generally a positive relationship between the heterogeneity of a landscape (i.e. proportion of semi-natural habitats, field margins, woodland etc) and pest control in associated crops. However, research results are variable, demonstrating that the outcome is context- and species-dependent and that a better understanding of the local mechanisms driving the general relationship is required if the data are to underpin the development of habitat manipulation for conservation biological control (Rusch et al., 2010; Veres et al., 2013).

The design of AESs have largely focused on resource provision for pollinators and birds (e.g. Chiverton and Sotherton, 1991; Decourtye et al., 2010; Pywell et al., 2005), with only beetle banks designed specifically to encourage predatory beetles (Collins et al., 2002). However, several management options do coincidentally support large numbers of other natural enemies, including enemies of cereal aphids, and can improve cereal aphid control in associated crops (Baverstock and Pell, 2011; Holland et al., 2012, 2014; Plecas et al., 2014; Rusch et al., 2013; Storkey et al., 2014). Furthermore, they have the potential to be further optimised and to be particularly effective in landscapes typical of intensive arable farmland, where habitat heterogeneity supporting natural enemies is otherwise low (Chaplin-Kramer and Kremen, 2012; Wratten et al., 2012).

It is possible to design multifunctional margins and these could represent 'added value' for the same area of land used. For example winter bird-food habitats also provide hosts, prey and floral resources for natural enemies of cereal aphids and oilseed rape pests (Baverstock and Pell, 2011; Cook et al., 2016). However, it is important to select plants carefully. Pollen and nectar-providing plant mixes for long-tongued bees do not provide nectar that is accessible to most natural enemies and suitable plants are less likely to be found by natural enemies if they are planted in a mixture (Campbell et al., 2012). The flowering season may not be early enough or long enough to support enemies at critical periods (Baverstock and Pell, 2011). Natural enemies vary both in their preference for different flowers (e.g. Sivinski et al., 2011) and in how important the different nutrients provided by different floral resources are for survival, maturation of eggs and parasitism rates (reviewed in Rusch et al., 2010; Carrie et al., 2012). Consideration must also be given to the relative benefits provided to pests, natural enemies and hyperparasitoids by the sown plants to ensure a balance favouring the enemies (reviewed in Rusch et al., 2010; Carrie et al., 2012; Rand et al., 2012; Winkler et al., 2010). For specialist natural enemies, however, sown plants must support some pests to allow reproduction of the enemy (i.e. acting as 'banker plants'); for such natural enemies, providing floral resources alone is unlikely to be sufficient to provide control. Some natural enemies, particularly cereal aphid parasitoids, are more reliant on aphid honeydew for nutrition than nectar (Baverstock and Pell, 2011; Vollhardt et al., 2010). Ultimately it may be necessary to have a range of habitats to address all these issues, although it is important that they are practical for farmers to implement and relevant to the entire arable rotation. Some of these aspects are being addressed in the recently completed Defra-funded project IF0122 (Cook et al., 2016).

It is important that the habitats are sources, not sinks, of natural enemies that actually move into the crops and do so in sufficient numbers to deliver pest control and influence yield (yield has rarely been measured in conservation biological control research, although it is the ultimate measure of effectiveness). Insect movement is notoriously difficult to measure directly but it is important to understand the scale over which particular enemies are likely to be active and also the quantity and distribution of habitats required (Holland et al., 2014; Schellhorn et al., 2014; Storkey et al., 2014). Similarly, given that natural enemies interact with each other in positive and negative ways, the appropriate diversity necessary to deliver effective control is a subject of active research and discussion. In general it is considered that (a) the greater the diversity of enemies conserved (predators, parasitoids and pathogens), the more likely that long-term and resilient control will result and that (b) it is more likely that a diversity of natural enemies will be maintained if there is a diversity of habitats for them to utilise (reviewed in Rusch et al., 2013). These are huge areas of study with innumerable interactions to consider and so mechanistic models, such as the one recently published by Jonsson et al., 2014, will be useful tools to test management scenarios *in silico* and to identify particular scenarios for field evaluation of the relationships between habitat diversity, natural enemy diversity and pest control. However, modelling approaches are only possible with the empirical baseline data on the biology and ecology of the species concerned, as described above.

6.1.10. Plant breeding for resistance to aphids

In a review of 'pre-breeding' attempts to identify resistance genes against cereal aphids, Crespo Herrera (2012) concluded that breeding for resistance and deployment of resistant wheat cultivars has mainly concentrated on the two most noxious cereal aphid species, *S. graminum* and *D. noxia*, neither of which are serious pests in central and northern Europe (Blackman and Eastop, 2007). This status might change if global warming changes the climate in favour of these aphid species.

With regard to the other aphid species, no commercial wheat or barley variety has been bred to be resistant to *S. avenae, R. padi or M. dirhodum* in Europe to date, in spite of intensive research (Dedryver, 2004; Dedryver et al., 2010). This is probably due to the need to resist at least three species of aphid, all with different niche preferences for feeding. However, substantial research has been done to examine various resistance mechanisms (reviewed by Van Emden, 2007). For example, volatile chemicals, such as methyl salicylate (extracted from the tree *Prunus padus,* the primary host of *R. padi*) that might affect olfactory responses by colonising aphids, have been shown to be repellent to *S. avenae, R. padi* and *M.dirhodum* as well as the black bean aphid, *Aphis fabae* (Hardie et al., 1994; Pettersson et al., 1994; Pickett and Glinwood, 2007). Methyl salicylate also acts as a damage-induced plant signal that changes the colonising behaviour of *R. padi.* Another plant volatile, *cis*-jasmone, exhibited repellent activity against *S. avenae, R. padi* and *M. dirhodum* on previously-treated wheat and also had a negative effect on aphid growth whilst enhancing predator or parasitoid numbers (Birkett et al., 2000; Bruce et al., 2003). Effects were much greater in the laboratory than in the field. Similar effects were noted on these aphids and other herbivores, such as thrips and orange wheat blossom midge, when wheat was sprayed with *cis*-jasmone (El-Wakeil, et al., 2010b). Later studies showed that *cis*-jasmone also induced selective production of secondary metabolites e.g. DIMBOA and HBOA) that are capable of reducing development of pests (Blassioli Moraes et al., 2008). Methyl jasmonate and salicylic acid-induced defences (reviewed by Antico et al., 2012) affected the colonisation and feeding behaviour of *S. avenae* in wheat, but, in contrast to the Rothamsted studies above, ultimately had no significant effect on this aphid's fecundity and breeding performance (Cao and Liu, 2013).

Post-landing colonisation behaviour of aphids can be affected by the physical structure of the plant tissue they have landed on. Differences in host acceptance by *R. padi* were attributed to the pubescence (hairiness) of wheat leaves in one study in the USA (Roberts and Foster, 1983), but another study in Hungary suggested that varietal differences in the extent of infestation was not generally attributable to leaf pubescence (Papp and Mesterházy, 1993).

Resistance in the form of antibiosis has been shown frequently with *S. graminum* and *D. noxia* but less so with other cereal aphid species (Crespa Herrero, 2012). Hydroxamic acids have often been associated with antibiosis to *M. dirhodum, S. avenae* and *R. maidis* in cereals (Givovich et al., 1994; Givovich and Niemeyer, 1995; Cambier et al., 2001; Hanson, 2006; reviewed in Van Emden, 2007). Changes in the nutritional status of plants can sometimes affect aphid performance, which needs to be taken into account when interpreting varietal influence. For example, highly significant negative correlations were found between the *rm* values and concentrations of the allelochemicals L-DOPA ($r = -0.937$) and ornithine ($r = -0.907$), but not with GABA ($r = -0.363$) in wheat varieties purporting to be resistant to *S. avenae* (Ciepiela et al., 2001). The influence of non-protein amino acids in plant defense against insect herbivores, including aphids has been extensively reviewed by Huang et al. 2011.

Resistance to *R. padi* was recorded in triticale that was also resistant to *D. noxia* (line N1185), and in crosses between the resistant line and wheat cultivars, suggesting that this line of triticale may be a source of resistance for small grain breeding programmes (Hesler et al., 2007). Antibiosis in wheat cultivars in Germany showed changes in susceptibility to aphids with the age of the plant; cultivar Hybnos I showed excellent antibiosis to both *S. avenae* and *M. dirhodum* apterae at the seedling stage (GS13) but this did not persist after stem extension (GS30–32) (Klueken et al., 2008). Other varieties showed different degrees of attractiveness to alate aphids that were released over trial plots, suggesting variation in antixenosis (for definition see Van Emden, 2007). However, differences between cultivars were marginal over the whole season, which concurred with previous studies (Havlickova, 2001).

Some evidence of resistance has been shown in a cultivar of the Einkorn ancient diploid wheat *Triticum monococcum* (line TM44), on which the fecundity of *S. avenae* was reduced 10-fold (Caillaud et al., 1994) and in which the transmission of BYDV was also reduced in comparison to conventional hexaploid conventional varieties (Tanguy and Dedryver, 2009). This effect was specific to *S. avenae* as other species were not affected. Similar results were observed in Canada (Migui and Lamb, 2004). Unfortunately, resistance genes from *T. monococcum* have been difficult to incorporate into hexaploid wheats. Other resistance genes from *Aegilops neglecta* and *Triticum araraticum* conferring antibiosis to aphids are available and could be used to develop multiple aphid resistance in winter wheat cultivars (Arzani et al., 2004; Smith CM et al., 2004b).

In wild barley, *Hordeum sponateum*, some negative associations were found between the presence of several amino acids and the performance of *R. padi* (Weibull, 1994). Unfortunately, segregating offspring of crosses with cultivated barley showed no similar effects. It is likely that resistance associated with nutritional factors will vary in its integrity according to environmental conditions such as soil type and fertiliser regimes (Van Emden, 2007).

6.1.11. Plant breeding for tolerance to aphids

Tolerance of plants to aphids, as opposed to resistance to their colonisation, is often regarded as another form of resistance (e.g. Leimu and Koricheva, 2006; Mauricio et al., 1997; Stowe et al., 2000; Strauss and Agrawal, 1999; Tiffin, 2000). However, unlike truly resistant plants, tolerant ones do not exert any selection pressure on the insects. They just seem to endure the damage caused by the pest, but still manage to reproduce successfully. Tolerance to cereal aphids, particularly *S. graminum* and *D. noxia*, has been demonstrated in many studies (reviewed by Crespo Herrera, 2012), but few have shown similar effects against the main cereal aphid species in Europe. Exceptions to this are the studies by Hesler (2005) and Hesler et al. (1999) on *R. padi.*

Detection of plant growth responses is one of the difficulties associated with assessing varietal tolerance to aphids in the early stages of growth, especially with species that do not cause many or any symptoms of damage. Significant effects have been measured in gas-exchange and in chlorophyll fluorescence in some tolerant varieties (Franzen et al., 2008) but generally biomass measurements are required at some point, which is time consuming and laborious. However, rapid phenotypic differentiation methods have been devised for *R. padi* on wheat at the seedling stage (Dunn, et al., 2007, 2011). The latter study identified 17 cultivars from 4000 wheat accessions that showed no dramatic decreases in root and shoot growth. Care needs to be exercised in extrapolating from this to other aphid species that infest plants at later growth stages, as varietal tolerance can change with maturity (Migui and Lamb, 2004; Kleuken et al., 2008).

6.1.12. Genetic sources of resistance/tolerance

As has already been mentioned, some genetic sources of resistance have been obtained from triticale and rye (*Secale cereale*) (Hesler et al., 2007) but the genus *Aegilops* has also provided some resources. Most studies have been done on *S. graminum,* in which 14 genes conferring resistance have been reported, and *D. noxia*, in which 11 resistance genes have been reported (reviewed by Crespo Herrera, 2012). Reported resistance to the three main European species have often, but not always, been spin-offs from studies on the other two more globally important species and none have so far been incorporated into commercial wheat cultivars (Porter et al., 2009).

For example, Migui and Lamb (2003) evaluated aphid resistance in 19 graminaceous species related to wheat, and found that species with low ploidy levels were more frequently resistant. However, no single accession carried resistance to all three aphid species tested; they were either resistant to the combination of *S. graminum* and *R. padi* or to the combination of *S. graminum* and *S.avenae*. More appropriately, Smith et al. (2004b) evaluated 21 accessions from six species of *Aegilops* and one accession of *Triticum araraticum* that were previously identified to be resistant to *R. padi*; they found antibiosis effects on *S. avenae* and *M. dirhodum* in *A. neglecta* accession 8052, so this accession is reported to be resistant to three aphid species. Both tolerance and antibiosis to *R. padi* was found in *T. araraticum,* accession 168.

More focused studies on *R. padi* alone identified antibiosis effects in perennial grasses including *A. elongatum*, *A. intermedium*, *A. repens* and *Elymus angustus* and hybrids of these perennials with wheat (Tremblay et al., 1989). With *S. avenae,* only one resistance gene has been mapped so far, in durum wheat line C273 (Liu et al., 2011). Few studies on genetic sources have been done for *M. dirhodum,* although variation in resistance has been found in common wheat (Havlickova, 1997, 2001; Lamb and McKay, 1995). However, nothing commercial has resulted from the research so far. Indeed, this is the message that comes from this literature survey. Lots of research has been done on the three main aphid species in Europe but none of it has been introduced into commercial varieties. This is probably due to the laborious techniques required to identify antibiosis in segregating populations, especially under field conditions (Crespo Herrera, 2012).

A novel approach to aphid resistance involves the introgression of a gene (using GM technology) that stimulates plants to produce an insect pheromone that affects colonization behaviour, while at the same time attracting predators and parasitoids to the crop (Beale et al., 2006). The philosophy behind these novel approaches is described in the review papers of Birkett and Pickett (2014) and Pickett et al., (2014). The sesquiterpene (E)- β-farnesene (Eβf) expressed in spring wheat has been evaluated in the field for its potential to reduce colonisation by the grain aphid, *S. avenae*. Unfortunately results from these field trials were disappointing, showing that the GM wheat did not repel aphids as had been demonstrated in the laboratory (Bruce et al., 2015) (http://www.rothamsted.ac.uk/news-views/scientists-disappointed-results-gm-wheat-field-trial).

6.1.13. Breeding for resistance to BYDV

Controlling aphids using host plant resistance is one method for reducing the spread of virus infections by aphid vectors but this does not prevent the impact of BYDV on the originally infested aphid-resistant plants. On these plants, adverse effects of the virus on yield can still be expected as the virus(es) will have been transmitted even if the aphids were killed in the process. Breeding for resistance to the disease is also required to minimise the physiological effects of the aphid/virus complex.

Breeding for resistance to BYDV has been the goal of CIMMYT (International Maize and Wheat Improvement Center) for many years, and a major review of progress was published in 2002 (Henry and McNab, 2002). Tolerance to BYDV has been found in several wheat lines, including those developed by CIMMYT itself (Singh et al., 1993; Ayala et al., 2001; Weisz et al., 2005), but true resistance (a reduction in virus concentration) has not been found in the wheat primary gene pool, despite thousands of accessions being tested (Qian et al., 1993; Li et al., 1998; Francki et al., 2001; Henry et al., 2002). However, resistance has been found in wheat relatives (perennial *Triticinaeae*) such as *Thinopyram intermedium* and has been introgressed into bread wheat by several groups (e.g. Banks et al., 1995); two lines, Zhong ZH and TC14, are now commercially available (reviewed by Chain et al., 2005; 2007). However their durability in the face of ever-mutating strains of virus has been placed in doubt and their use in breeding programmes should be approached with caution (Chain et al., 2007; reviewed by Gomez et al., 2009). These two genes were combined in one single genotype (line ZT) using GISH (genomic *in situ* hybridisation). Exposure to five different strains of BYDV-PAV confirmed the resistance of TC14 and ZH and revealed an additive effect of the two sources of resistance in ZT. The resistance of line ZT was characterised by a proportion of infected plants that was significantly lower than in the parental lines TC14 and ZH (42% *vs*. a mean of 76% for the parents) and a very low virus titre (area under the virus concentration progress curve of 1·2 *vs*. a mean on 6·3 for the parents) (Jahier et al., 2009). Genotypes carrying both genes for resistance to BYDV-PAV from Z6 and TC14 should delay infection and reduce transmission from plant to plant in the field.

6.1.14. Recommendations for research

The main threats to current practices are from the development of resistance to pyrethroids in *S. avenae* and the withdrawal of neonicotinoids, the latter being especially useful as seed treatments. Thus the recommendations are as follows:

1. Continuation of the monitoring and forecasting scheme operated by Rothamsted Insect Survey and delivered through AHDB Aphid News, but perhaps with some consideration to using modern diagnostics to include information about the proportion of migrating aphids carrying BYDV in the autumn. Even if this is uniformly low each year, it would still provide a base-line measurement in the event that changes occur in the future, for example due to global warming.
2. Monitoring of the spread of resistance to pyrethroids in *S. avenae* across the country using vial test kits, backed up by DNA probes available at Rothamsted Research. Monitoring

should be extended to the other species, especially *R. padi,* which is subjected to the same selection pressure as *S. avenae* from over-use of pyrethroids.

3. Investigation of alternative insecticides for control of *S. avenae*, especially bearing in mind the current restriction on neonicotinoids, and the imminent withdrawal of pirimicarb for use in cereals due to continual reviews within the EU.
4. Investigation of the effect of synergists on performance of insecticides, and the potential for reducing dose rates, or overcoming resistance in the target insects.
5. Investigation of the potential for repelling aphids (and attracting natural enemies) through introgression of genes that stimulate alarm pheromone release by the plants.
6. Continue research on how to best conserve natural enemies for cereal aphid management within the wider arable crop rotation and how this could be achieved through non-crop habitat manipulation options within agri-environment schemes.
7. Consider modelling approaches for research to promote conservation biological control.
8. A full review of the potential of host-plant resistance genes that have been derived from research on other aphids, such as *D. noxia* and *S. graminum*, and might be useful against the three most common species in Europe.
9. A fresh look at the genetic potential of genes available through breeding programmes elsewhere in the world for tolerance of or resistance to BYDV in European varieties.

6.2. Wheat blossom midges

Two species of wheat blossom midge occur in the UK, the orange wheat blossom midge (OWBM), *Sitodiplosis mosellana*, and the yellow (or lemon) wheat blossom midge (YWBM), *Contarinia tritici* (Jones and Jones, 1984). They are common, although sporadic, in the northern hemisphere wherever cereals, particularly wheat, are grown (Jones and Jones, 19784. The OWBM is the most economically important, causing severe yield losses in years when infestation reaches outbreak levels. For example, in the UK, crop losses in the outbreak years of 1993 and 2004 cost £30 million and £60 million, respectively (AHDB, 2016a; Oakley, 1994; Oakley et al., 2005). Elsewhere similar losses have been reported in outbreak years (e.g. Olfert et al., 1985 [Canada]; Volkmar et al., 2008 [Germany]; Wu et al., 2008 [China]; reviewed in Gaafar et al., 2011). In recent years the incidence of OWBM has been decreasing, though it remains a serious pest and YWBM has only been reported once (ADAS Reports 2009, 2010, 2011, 2013).

6.2.1. Life cycle

As you would expect from their common names, the two midge species can be distinguished at all life stages based on their colour. Their life cycles are similar, as described below with particular reference to OWBM, but they have some key differences that influence their pest status and so these are highlighted. This description is a summary of information from a number of publications (Bayer Pest Spotter, 2014; Dow Webpage 2014; Dow Information Leaflet 1, 2014; Ellis et al., 2009a, b; AHDB, 2016a, 2009; Hao et al., 2013; Jones and Jones, 1984; Lamb et al., 2002; Oakley, 1994; Oakley et al., 1998; Pivnick and Labbé, 1993).

Adults are small slender flies 2–3mm in length that mate at the emergence site; males only fly to find females on the first evening after their emergence, and thereafter they die. Females spend much of their time deep within the crop canopy but are stimulated to move up the plants and fly to find oviposition sites during calm evenings (<10km/h wind speeds) when air temperatures are warm (generally exceeding 15°C but as low as 11°C) and light levels fall below 18,000 lux; on sunny days they fly later into the evening than on overcast days. Recent studies have shown that flight may be influenced by humidity more than previously realised, as flight was severely reduced when humidities fell to 35%. Only females fly between fields and they can travel up to 3km (potentially further if they are carried in air currents), generally at the height of the crop or a little above it, in search of ears of wheat at the right stage for oviposition.

For OWBM, eggs are laid exclusively at night (most within the first 2h of darkness) inside the florets of emerging ears and, therefore, only mid-ear emergence stages GS53 – GS59 are vulnerable. In contrast, YWBM emerge and are active approximately 2 weeks earlier in the season, laying their eggs in the florets of stage GS51 – GS55 plants; they will not lay eggs once the florets have hardened. OWBM females lay an average of 80 eggs in total (their lifetime is approximately 7 days and most eggs are laid on day 3), generally laying 1–2 eggs per floret. YWBM females lay several batches of approximately 15 eggs per floret, of which 4–15 per floret are likely to survive.

Depending on temperature, eggs hatch within 4–10 days and the resulting larvae crawl down to the developing grain, burrowing between the lemma and palea of the wheat ear, and begin to feed. OWBM larvae feed directly on developing grain, using enzymes to convert the starch of the grain to sugar that they then utilise. In contrast, YWBM larvae feed on the anthers; their eggs must hatch before pollination occurs to ensure that flower development is arrested, retaining the anthers on which the larvae feed.

After 2–3 weeks OWBM larvae become immobile and fall from the ear to the soil. They burrow into the soil, spin a cocoon and overwinter as larvae in diapause within the cocoon. OWBM are univoltine with one generation a year; conditions of 70 days at < 10°C are necessary to break larval diapause and, if these conditions are not achieved, larvae can survive in diapause for more than 10 years. A recent global transcriptome analysis of OWBM has identified a number of genes regulating diapause and metamorphosis; insights from this study could one day lead to practical ways to disrupt diapause and aid OWBM control (Gong et al., 2013). In contrast to OWBM, some larvae of YWBM can pupate and emerge as adults almost immediately after entering the soil and this partial second generation can lay eggs on couch grass; YWBM larvae in diapause can survive for up to 3 years in the soil.

Once activated, larvae move towards the soil surface to pupate in spring, requiring wet soil (to a depth of 10 mm) and temperatures above 13°C; if these conditions are not achieved, they can return to a state of diapause. They spend 2–4 weeks as pupae, depending on temperature, finally emerging as adults in early summer to repeat the cycle. Adult emergence is particularly stimulated by rising temperatures followed by rainfall, air temperatures above 15°C being particularly favourable.

6.2.2. Damage

Larval feeding on developing grain by OWBM causes grain shrivelling, premature sprouting in the ear, a reduction in the Hagberg Falling Number, and can also facilitate secondary invasion by fungal plant pathogens such as *Fusarium graminearum* and *Septoria nodorum* when conditions are damp (DOW Webpage, 2014; Oakley, 1994). Once plants reach growth stage GS61 they are less susceptible to damage because larvae cannot digest the hardening seed coat (Bayer Pest Spotter, 2014). Typically one larva feeding on a grain will reduce yield by 30% but if two or three larvae feed per grain site, yield loss can be as much as 75% or even higher if ear emergence is late (DOW Webpage, 2014). In the U.S. there are also reports of OWBM vectoring wheat scab and glume blotch (Knodel and Garichiarachchi, 2008). As YWBM arrest flower development and prohibit pollination, their presence can lead to blind ears with the potential for a greater negative impact on yield compared with OWBM; however, if pollination is successful the grain develops normally (Bayer Pest Spotter, 2014). Both midges can occur together. The damage to yield and quality is often underestimated because of the difficulty in detecting them on the crop (see below for further discussion).

6.2.3. Thresholds for control, monitoring and forecasting

The likelihood of an OWBM outbreak occurring is strongly linked to climatic conditions during winter and spring, particularly temperature and moisture of both the soil and the air. These factors influence several attributes of the midge: the activation of larvae in the soil, the rate of pupation/ adult emergence and adult flight/ oviposition ability. They also influence attributes of the cereal host plant such as timing of the susceptible ear emergence stage, which also varies amongst varieties (Bruce and Smart, 2009; Ding and Lamb, 1999; Hu et al., 2005; Oakley et al., 1998, 2008). Unless midge emergence occurs in synchrony with ear emergence, an outbreak is unlikely to happen – but this timing is difficult to predict and the window of opportunity for an insecticide application, should it be required, is reduced by the fact that only the eggs and adults are likely to be controlled, while larvae, buried within the ear, are cryptic and escape applications (Bruce and Smart, 2009; Ellis et al., 2009a). The use of degree-day accumulations to predict emergence and flight activity are used in Canada but have proved unreliable in the UK (Elliott et al., 2009; Oakley et al., 1998). The development of effective and easy monitoring methods and of effective thresholds to indicate when a control measure is necessary have therefore been considered essential and been the subject of much research and development (Ellis et al., 2009b).

The sex pheromone of the OWBM has been identified as (2S,7S)-nonadiyl dibutyrate and a single isomer of it, the SS-stereoisomer, used as a lure in OWBM monitoring traps has been sold commercially in the U.S (Gries et al., 2000). The sex pheromone is used by male midges to locate females and is specific to OWBM. However, preliminary experiments in the UK found that too few midges were captured using this trap/ lure to establish a reliable threshold and it was necessary to identify an optimal pheromone blend specifically for use in the UK (Bruce et al., 2007). The most effective pheromone blend contained a mixture of isomers and captured more male OWBM than any one of the individual isomers when placed in sticky traps and evaluated in the field (Bruce et al., 2007).

The most appropriate way to deploy pheromone traps as a monitoring tool was determined in field trials done between 2005 and 2008 at a number of sites across UK. Starting before ear emergence (susceptible stage), pheromone-baited sticky traps (specifically capturing male OWBM) and un-baited yellow sticky traps (capturing female OWBM and other insect species) were placed in first and second wheat crops and also in adjoining crops in fields that had had wheat crops in the previous year. Catches were recorded twice a week and OWBM numbers were compared to the damage levels found at the end of the season. The pheromone traps were highly sensitive and only captured OWBM, making assessments of counts very easy and fast. It was also clear that they were a very good measure of OWBM emergence and flight activity in fields that had been in wheat the previous year. Furthermore, infestation levels in first wheat crops were well predicted by pheromone trap catches in neighbouring 'source' fields with second wheat or with crops following wheat. While counts of females on sticky traps were a good indication of infestation in the field where the trap was placed, these traps were less sensitive and were indiscriminate, capturing many other species and making the identification of the OWBMs a more difficult task, requiring training and time (Bruce and Smart, 2009; Ellis et al., 2009a).

Taking this information together it was possible to devise a simple decision support model based on a stepwise decision tree, involving yes/ no answers to questions, that was practical for farmers growing OWBM-susceptible wheat varieties (the majority) to use in spray decision-making, and as such, is advocated by AHDB (AHDB, 2016a). Nationally, the number of pupae and larvae in the soil is assessed at a number of sites and warnings of imminent hatch provided via DOW Pestwatch (www.dowagro.com/uk/cereal/pests.htm); OWBM damaged grain found at the previous harvest will also indicate to the farmer a level of local risk and the need for vigilance. However, decisions on whether to spray or not can only be made reliably in response to whether the numbers of OWBM captured in pheromone traps (two per field) **during the period of risk**, exceed threshold levels (Fig. 4). If traps capture fewer than 30 OWBM/day, then no action other than continued trap monitoring is necessary. If more than 120 OWBM/ day are captured then the farmer is advised to spray infested and surrounding wheat fields as soon as possible (Threshold from Ellis et al., 2009a). If between 30 and 120 OWBM/ day are captured then crop searches for the number of adult OWBM actually visible on the crop is advised and if there is more than 1 adult OWBM per 3 ears of feed wheat or 6 ears of milling/ seed wheat, then spraying is advised (Threshold from: Kurppa and Hursburg, 1989; Larsson, 1992; Pivnick and Labbé, 1993; Oakley et al, 2005). AHDB (Information Sheet 53) also advise using yellow sticky traps (two per field) prioritising milling/ seed wheat and sheltered crops/ second wheat, although being indiscriminate they do require accurate identification.

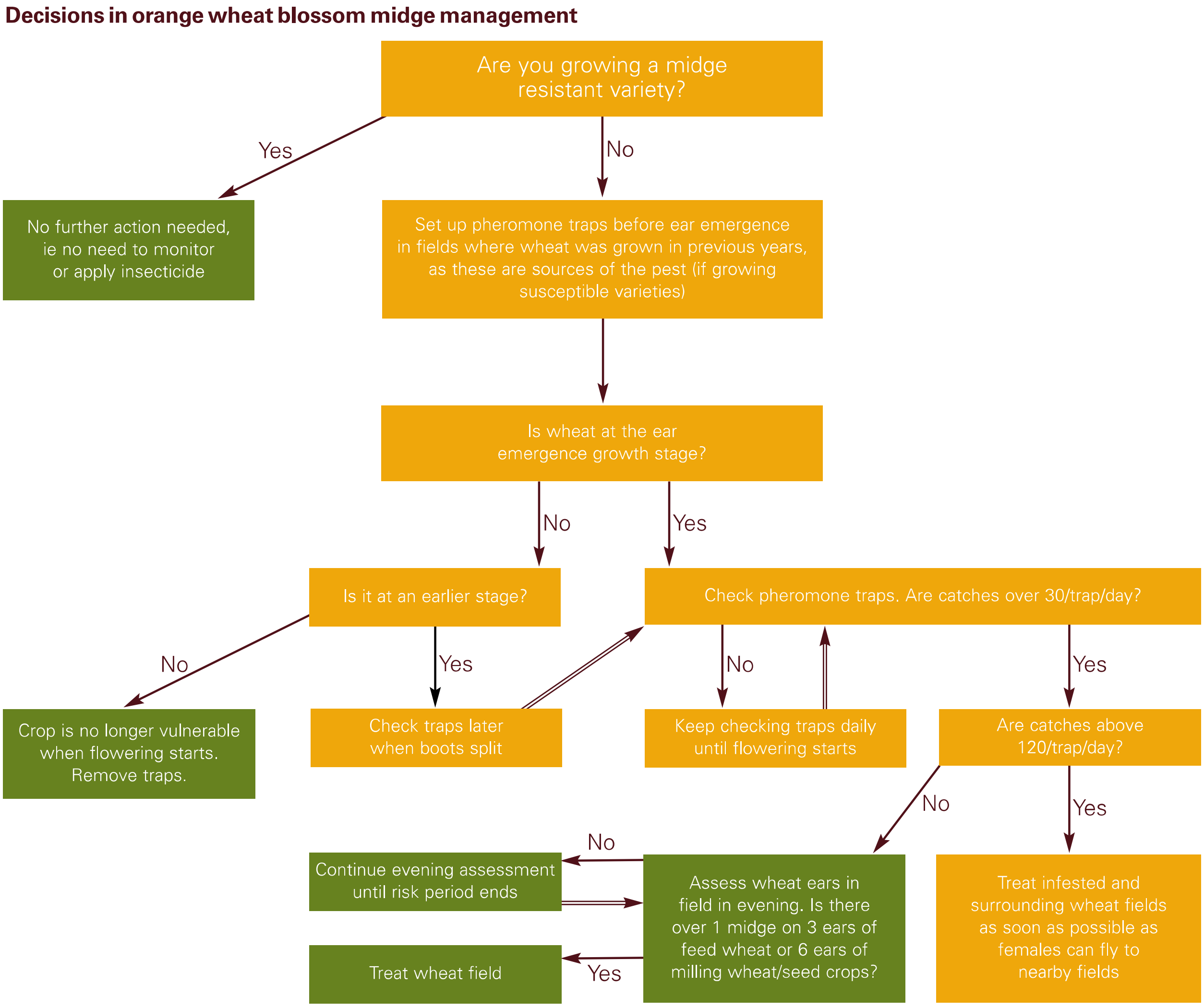


Figure 4. Decision tree to determine whether insectidies are necessary to control orange wheat blossom midges in wheat. (Ellis et al, 2009b)

The methods for determining population threshold levels used in this decision-support system are relatively simple, quick and easy to use, particularly using the pheromone traps. This is important for farmer uptake and confidence in the recommendations ultimately provided, which is essential to decrease the likelihood of prophylactic spraying based only on perceived, rather than real, risk (Ellis et al., 2009b). There remain some issues with the monitoring techniques available: it is still considered that, in practice, observing the number of adult OWBM per ear is very difficult; the use of yellow sticky traps does require time and training; and there is an issue with the pheromone traps only catching males (Ellis et al., 2009b). However, the latter issue is greatly outweighed by the sensitivity and specificity of the pheromone and the clear correlation between numbers of male OWBM trapped and infestation risk (Bruce and Smart, 2009). Farmers are generally confident of the results from pheromone traps (Ellis et al., 2009b). Some recent work suggests that the colour and height of sticky traps can influence their trapping efficiency but it is unlikely that specificity will be improved (Li et al., 2012). Attempts have been made to use odours that attract female OWBM, such as the volatiles emitted from panicles of wheat at the ear emergence stage (Birkett et al., 2004). These volatiles were certainly very attractive to female OWBM under laboratory conditions but less effective in the field, perhaps due to competition with natural background odours or due to incorrect release rates (Bruce et al., 2007; Oakley et al., 2005).

It is also the case that the pheromone traps only capture OWBM and not YWBM. Although YWBM has not become a significant problem in UK, there are reports of it becoming increasingly important in some regions and this may increase if host-plant resistance to OWBM (which does not affect YWBM) leads to fewer insecticide applications that currently deliver incidental control of YWBM (Impey, 2009; Lehmhus and Heimbach, 2012; Oakley, 2008). It is thought that YWBM may become an increasing problem with continued climate change and may become more difficult to control without host-plant resistance or an effective monitoring system for it (Oakley, 2008). Given that monitoring traps based on specific sex pheromones have been successfully developed for a number of cecidomyiid midges (Hall et al., 2012), it should be possible to do the same for YWBM.

6.2.4. Control with insecticides

While many insecticides have been developed and used for OWBM control in the past (Oakley, 1994), only three active substances are now available for OWBM control: the pyrethroids, beta-cyfluthrin (Gandalf) and lambda-cyhalothrin (e.g. Hallmark Zeon), and the neonicotinoid, thiacloprid (Biscaya) (AHDB, 2016a). Chlorpyrifos (e.g. Dursban WG), which was approved until March 2016 when it was withdrawn, killed adults, eggs and larvae when they were on exposed florets, but lambda-cyhalothrin only killed adults on the crop at the time of spraying and not eggs, making the timing more critical. No chemical can kill larvae once they have moved down into the ear, emphasising the need to use monitoring to time spraying effectively (AHDB, 2016a). As all the insecticides available are broad-spectrum chemicals, it is essential only to apply them when thresholds have been exceeded, in order not to kill beneficial natural enemies that could also be present in the crop (AHDB, 2016a). When considering the quantity of cereals grown and their placement, it is also important for the farmer to match this to spraying capacity, as it is likely that if a requirement for spraying is identified, then it will need to be done across the entire cereal acreage within 4 days (AHDB, 2016a). Some studies have considered the potential of plant extracts such as the botanical NeemAzal T/S for OWBM control but, while they reduced OWBM populations, they were not as effective as pyrethroids (Karate) or neonicotinoids (Biscaya) (El-Wakeil et al., 2013). In a small-scale field experiment using extracts from the plant *Tasmannia stipitata*, containing the antifeedant polygodial, there was a trend towards fewer OWBM on treated wheat, but the results were not conclusive (Bruce et al., 2002). There are no reports of insecticide resistance in OWBM.

6.2.5. Cultural control

Overall, cultural control methods appear to be less well accepted for OWBM control in UK than in Canada where, for example, rotation and planting of alternative, more resistant crops is encouraged when larval populations are high (Elliott et al., 2011). In the UK, rotation has little effect on the risk of OWBM and it is principally a tool for disease management (Glen, 2000), although block cropping may make monitoring and control easier in current crops and reduce future risk (AHDB, 2016a). Ryegrass is a very good host plant for OWBM and so should be avoided on arable farms (Holland and Oakley, 2007). The presence of straw residues can reduce the incidence of OWBM, but can also encourage slugs (Glen, 2000).

Deep ploughing used to be advocated for OWBM control but, as the larvae are mobile in the soil, it has been suggested that they may still be able to find their way to the surface and so the emergence period may simply be extended (Oakley, 1994). Moreover, deep ploughing is not in-keeping with the trend towards low-tillage methods and its associated environmental advantages, including the conservation of natural enemies that also overwinter in the soil (Glen, 2000). Nevertheless, recent comparisons of the effect of different tillage practices on occurrence of OWBM do confirm that the more aggressive tillage methods cause the greatest reductions in OWBM numbers (Zhang et al., 2012).

The later flowering of spring-sown varieties can reduce their risk of infestation and in most years spring-sown crops are not attacked; moreover, their inclusion can spread the demand for monitoring time (AHDB, 2016a). Careful selection of variety for very early or very late flowering time, in conjunction with very early or late sowing, can increase the chance that the emergence of the midge and the susceptible stage of the ear do not coincide. However, this can be difficult to put into practice as climate/ weather conditions will also influence plant and midge development time and may affect the ability of the farmer to sow during the selected optimal period (Barnes, 1956; Oakley, 1994). Also, what may favour OWBM control, may exacerbate other pests. For example, early sown winter crops are at greater risk of attack by gout fly compared with later sown crops. As some cultural control options are associated with both benefits and drawbacks it is necessary to assess the balance of risks and benefits for each farm.

6.2.6. Biological control

The predominant natural enemies of OWMB are chalcid parasitoid wasps, particularly *Macroglenes penetrans*. The female wasps lay their eggs individually inside the eggs or larvae of the midge. The parasitoid hatches after 5–10 days and develops within the midge, overwintering as a 2nd instar larva inside its diapausing host. Once midge diapause is broken, the parasitoid consumes its host, killing it in the process. It then pupates and emerges as an adult a little later than un-parasitised midges and begins the cycle again (Affolter, 1990; Doane et al., 1989). In this way damage is not reduced in the current year but pest populations are reduced in the following year, having a long-term cumulative effect in the absence of insecticides, which kill the parasitoid (Elliott et al., 2011).

Parasitism rates of 40%, 40% and 75% have been reported in UK, Canada and Switzerland, respectively, making this species a very important potential natural control agent if it can be conserved and encouraged within the farmed environment (Oakley, 1994; Olfert et al., 2009). An estimate of the value of this parasitoid in terms of insecticide savings has not been made in the UK but in Saskatchewan it was estimated to be $248.3 million between 1991 and 2000 (Olfert et al., 2009). Another parasitoid, *Platygaster tuberosula*, was released as a classical biological control agent in eastern Saskatchewan in 1993 and 1994 to supplement natural control and it is thought to have become established (Olfert et al., 2003).

In the UK, parasitoid conservation and manipulation are more appropriate strategies for development than parasitoid augmentation. Parasitoids require hosts and floral resources, both of which can be provided by non-crop habitat manipulation (Holland and Oakley, 2007; Powell and Pell, 2007) and their behaviour can be manipulated using volatiles (Oakley and Smart, 2002). Recent advances demonstrating that habitat manipulation can conserve natural enemies within the arable landscape and, in some studies increase pest control in cereals, have potential for application to parasitoids regulating OWBM populations, and indeed other pests in the arable rotation (Bailey et al., 2009; Baverstock and Pell, 2011; Holland et al., 2012, 2013, 2014; Powell et al., 2004).

The importance of polyphagous predators in pest management has been widely accepted (Oakley, 1994). Exclusion studies in the UK showed that polyphagous predators had little effect on OWBM numbers prior to oviposition but may have reduced the number of larvae returning to the soil to diapause, thereby contributing to the prevention of population build-up in the soil (Holland and Thomas, 2003). Similarly, in a Canadian study OWBM larvae were susceptible to predation by carabid ground beetles when the larvae broke diapause and again when they left the plant and entered the soil (Floate et al., 1990). In another UK study, it was not possible to show an effect of predators on OWBM numbers but there was an effect of farming practice, there being fewer OWBM on wheat farmed following integrated farm practice compared to wheat farmed conventionally (Holland et al., 1996). It is possible that integrated farming practices encouraged the activity of a range of other natural enemies and it is widely accepted that supporting a diversity of enemies provides more resilient control in the long term (e.g. Pell, 2007).

6.2.7. Plant breeding for resistance

Natural variation between varieties in the level of susceptibility to OWBM infestation is evident, even when they have originally been selected for other traits (e.g. yield, drought resistance, disease resistance etc.) (e.g. Barker and McKenzie, 1996; Gaafar et al., 2011; Ellis et al., 2009c ; El-Wakeil et al., 2010a). Understanding the mechanisms of resistance, and how to select for it, have become increasingly important in the development of management tools for OWBM. If the crop is completely resistant to attack then there is no need for monitoring or for insecticide applications (AHDB, 2016a).

Oakley et al. (2005) defined a number of plant traits that conferred resistance to attack, tolerance to attack, or escape from attack. Resistant varieties either have elevated levels of defensive phenolic acids (*p*-coumaric and/or ferulic acid) at the susceptible ear stage, or induce these compounds more rapidly upon attack than do other varieties (Abdel-Aal et al., 2001; Barker and McKenzie, 1996; Berzonsky et al., 2003; Ding et al., 2000; McKenzie et al., 2002). These phenolic acids slow larval development and kill them before they reach 2nd instar (i.e. they act by antibiosis) and remain at high levels protecting the grain throughout the susceptible period. Insect damage induces these chemical changes as part of a defensive response orchestrated through the jasmonate signal pathway and can be induced in the absence of insect damage by spraying with synthetic jasmonic acid. In a field experiment, winter wheat crops sprayed with jasmonic acid had fewer OWBM and less damage (El-Wakeil et al., 2010b).

Tolerant varieties are attacked by similar numbers of OWBM as are susceptible varieties and the larvae survive, but fewer grains are damaged, the majority remaining a good size and not shrivelling (Barker and McKenzie, 1996; Kurppa, 1989). Varieties that escape attack (antixenosis) do so due to a number of different traits: they may be extremely early flowering, ensuring that the susceptible stage rarely coincides with OWBM emergence (Barnes, 1959; Kurppa, 1989); their flowering period may be very short ensuring the window of opportunity for OWBM attack (GS55-59) is also very short (Barnes, 1959); their head structure or other morphological attributes may deter oviposition, or they may be close-flowering, thereby limiting the ability of the OWBM to lay eggs inside the floret and forcing them to lay them in more exposed positions where mortality rates are higher (Ganehiarachchi and Harris, 2007; Gharalari et al., 2009a; Wise et al., 2001); alternatively they may produce fewer of the volatiles that OWBM use for host location, or indeed different volatiles that are unrecognisable to the OWBM (Birkett et al., 2004).

Canadian researchers identified that resistance (antibiosis) to OWBM through release of phenolic acids at the larval feeding site was controlled by a single gene, *Sm*1, located on chromosome 2BS (McKenzie et al., 2002; Thomas et al., 2005). They discovered this in winter wheat varieties from the USA and, through breeding, transferred it into susceptible Canadian spring wheat varieties, conferring resistance to them. This gene is selectable using the DNA markers WM1 (Thomas et al., 2005) and XBarc35 (Randhawa et al., 2013). Marker-assisted breeding (MAB) has made it easier for breeders to indirectly select superior genotypes for traits that are difficult to select directly, based only on phenotype, and facilitate pyramiding of desirable combinations of genes within a single variety. MAB has been used routinely in Canada to develop varieties resistant to plant pathogens and insect pests (DePauw et al., 2011; Randhawa et al., 2013). Thus a number of new OWBM-resistant varieties expressing the *Sm*1 gene (including high value bread-making varieties) have been developed and registered in Canada (DePauw et al., 2009, 2011; Humphreys et al., 2010). Double haploid technology (DH) has also increased the speed of varietal development (Randhawa et al., 2013).

Resistance to insect pests based on a single gene can be short-lived because it can be overcome by selection of resistant pest biotypes. Indeed, in Canada, Smith et al., (2007) consistently found small numbers of OWBM larvae surviving to maturity on *Sm*1-resistant wheat over a number of years. Although only a few matured and their mass and survival during diapause was low, this was consistent with the hypothesis that a virulence allele allowing adaptation to *Sm*1 was present in the population (Smith et al., 2007). To overcome the potential for evolution of resistance in OWBM and to preserve host-plant resistance, the use of varietal blends (i.e. with interspersed susceptible refuges for pests) has been evaluated and advocated (Smith MAH et al., 2004). Now all new resistant cultivars are released as a blend containing a ratio of 90% resistant seeds to 10% susceptible seeds. This ensures that sufficient numbers of susceptible OWBM survive on the susceptible variety to mate with any *Sm*1-resistant OWBM that may develop on the resistant variety, thereby diluting the resistant proportion of the OWBM population (Elliott et al., 2011). Using the seed blend also helps conserve populations of the OWBM parasitoid, *M. penetrans* (Elliott et al., 2011; Smith et al., 2004). A recent large-scale Canadian field evaluation over 4 years of four resistant varieties planted as blends showed that the blends yielded significantly more grain than pure susceptible varieties, especially in high infestation areas (Vera et al., 2013).

Improvement in European wheat varieties has paid less attention to the development of resistance to OWBM, or indeed any insect, than to the development of quality traits and resistance to pathogens and it has been supported largely with private rather than with public funding (Galushka and Gray, (2012); see WGIN Webpage, 2014). However, using the WM1 marker, Oakley et al. (2005) determined that the *Sm*1 gene was present in UK and European varieties although it was not always correlated with resistance, as some phenotypically susceptible varieties also had the gene. They concluded that although this marker band was diagnostic in a restricted gene pool, where the specific cross was known to segregate both for *Sm*1 and the marker band, it was not of general use in European germplasm. In a follow-on study to explore resistance and its patterns of inheritance, mapping techniques and several different markers were used on three phenotypically resistant varieties (Welford, Brompton and Carlton), three phenotypically susceptible varieties, their F1 crosses and subsequent selfed generations (Ellis et al., 2009a). All generations were also grown in the field and the OWBM infestation level was recorded, allowing correlations to be made between genetic and phenotypic resistance. Several genetic effects contributing to resistance were identified, the major one of which was *Sm*1 in all three resistant varieties. The mechanism of *Sm*1 resistance is related to the production of phenolic acids but the level of induction of p-coumaric acid in the variety Welford was insufficient to account for the large reductions in OWBM numbers observed, suggesting that other resistance mechanisms were also involved. A number of quantitative trait loci (QTLs) associated with resistant phenotypes (some on different chromosomes) were reported amongst the crosses but the attributes that these genes regulated were not known (Ellis et al., 2009a).

Although a full understanding of the mechanism of resistance remains elusive, it has led to the development of European OWBM-resistant varieties with the *Sm*1 gene (Oakley, 2008). The majority of these varieties (13 currently listed) have been lower value soft varieties for biscuit or cake making and for animal feed (Groups 3 and 4), but the AHDB Recommended list (2016) includes one OWBM-resistant bread-making variety ("Skyfall") from Group 1. These OWBM-resistant varieties are not resistant to YWBM (AHDB, 2016a).

While genetic control of antibiosis has been widely studied, the basis of antixenosis, is generally less well understood (e.g. Gharalari et al., 2009b), limiting a genetic approach to breeding for those traits. Smith et al. (2004) found that the *Sm*1-resistant cultivar they used also deterred midge oviposition, reducing egg densities by 65% compared with susceptible wheat, suggesting that although resistant varieties have primarily been selected for the presence of *Sm*1, antixenosis-related attributes are also present, under the control of other unknown genes. In another study it was found that oviposition deterrence was indeed controlled by a number of genes that were not linked to the antibiosis gene, *Sm*1 (Gharalari et al., 2009a). Also, in the study of Ellis et al. (2009a), comparisons with other known QTLs controlling ear emergence suggested that some QTLs linked with resistance were likely to be associated with flowering time (Griffiths et al., 2009). It is, therefore, possible that in resistant varieties from both Canada and Europe, overall resistance is a reflection of the expression of more than one gene. The multigenic nature of deterrence, flowering time etc. and the fact that these antixenosis attributes are heavily influenced by the environment, makes them challenging to incorporate into breeding programmes. Nevertheless, the wider use of genes controlling antixenosis would reduce the selection pressure for resistance to *Sm*1-based antibiosis in OWBM and these traits could be integrated with conservation of natural enemies.

6.2.8. Recommendations for research

1. A better understanding of the mechanisms of host-plant resistance in European cereal varieties is needed, particularly the relative contributions of antibiosis and antixenosis.
2. More varieties of OWBM-resistant wheat in Groups 1 and 2 are needed.
3. Blends of resistant and susceptible varieties to maintain *Sm1*-based antibiosis should be tested.
4. Keep a watching brief on the incidence and severity of OWBM and YWBM damage for any changing trend.
5. Assess the risk of insecticide resistance using the outputs of AHDB Cereals & Oilseeds project RD-2012-3780 ‘Combating insecticide resistance in major UK pests’ when available.
6. Monitor resistance status of the OWBM.
7. New and safe insecticide actives are needed for use when host-plant resistance is unavailable (Group 1 and 2 varieties).
8. Research is needed on how to conserve natural enemies, particularly parasitoids, for OWBM management and how this could be achieved through non-crop habitat manipulation options within agri-environment schemes.
9. It is essential to understand the relationships between natural enemies and host plant resistance if the two strategies are to be used together.
10. Investigate the potential for semiochemical-based monitoring traps for parasitoids, in addition to OWBM, to improve risk assessment.
11. Investigate why OWBM resistance does not confer resistance to YWBM.
12. Identify natural enemies of YWBM and determine whether they can be conserved alongside those of OWBM.

6.3. Wheat bulb fly

Wheat bulb fly (WBF), *Delia coarctata,* was once decribed as “probably the most serious insect pest of winter wheat in Britain” (Gratwick, 1992), and certainly caused serious crop losses in the 1960s (Raw, 1967). Gratwick’s statement may have been an overstatement at the time, and certainly is not true now, but it is still considered to be an important pest, although less than 4% of growers surveyed in 2010 and 2012 listed this pest as a target for insecticides, and it was sufficiently unimportant in the 2014 survey to be included in the ‘others’ category (Fig. 3; Table 5) (Garthwaite et al, 2011, 2013, 2015).

6.3.1. Description and life cycle.

Adults are similar to house flies in size and appearance. Males are dark brown and the females yellowish grey. These emerge from the soil in June and feed through the summer on fungal spores on the ears of wheat.

After mating, eggs are laid in bare soil following early harvest of crops such as peas and beans and onions, or in soil under the canopy of a root crop such as potatoes or sugar beet, especially if those crops are gappy, allowing access to the soil. In this respect wheat bulb flies are the ultimate gamblers, as they lay their eggs without knowing if suitable host plants to feed their offspring will be present at the time of egg hatch some 6–8 months later (Ellis, 2012; AHDB, 2016b). The majority of eggs are laid before the end of August (Bowden and Jones, 1979), but sometimes into September (Raw, 1967), especially in more northern areas such as Scotland (Rogers and Evans, 2014).

Unusually for flies, eggs hatch at the end of January, at least in eastern England, and burrow into neighbouring cereals or grass if present; if none are present, they die. Wheat, barley and rye can be colonised but not oats; their preferred wild host is couch grass, *Elymus (formerly Agropyron) repens* (Jones and Jones, 1984; Marriot and Evans, 2003). The basal development temperature for egg hatch is 0.5°C, so they are not adversely affected by low temperatures (Gratwick, 1992), although egg-hatch would be delayed in freezing conditions.

After hatching, the young larvae are especially vulnerable between egg hatch and colonisation of a wheat stem (Raw, 1967). As they have been laid in bare soil nowhere near an existing host plant, there first task is to find one. This is acheived in part by responding initially to the presence of enhanced levels of carbon dioxide associated with a growing host plant (Rogers et al., 2013), and then by attraction to secondary plant metabolites, including hydroxamic, syringic and vanillic acids, exuded by roots of young cereal or couch grass seedlings (Rogers and Evans 2013, 2014). Hydroxamic acids, at least, are absent from root exudates of oats, which might explain the immunity of oats to colonisation by WBF larvae (Hamilton, 1964 – reviewed by Rogers and Evans (2013)).

The young maggots that survive this hazardous journey are white, long and cylindrical, pointed at the front end but with a truncated hind end. They burrow into the shoot of young cereals just below ground where the ‘bulb’ is located, and feed there, moving from shoot to shoot, until they mature. They indergo three instar stages before they migrate back into the soil to pupate in late April or May. The puparium is a brown elongated barrel shape. Adults emerge about 5–6 weeks later to begin the life cycle again (Jones and Jones, 1984; Gratwick, 1992).

6.3.2. Distribution

Delia coarctata is widely distributed across Europe and Asia (CACI 1987), but seems to be of particular importance in the UK (Gratwick 1992), where it is most prevalent in the eastern side of the country in both England and Scotland. In England, surveys conducted by ADAS on behalf of AHDB show that wheat bulb flies are most prevalent in eastern England, the East Midlands and north-eastern England (AHDB, 2016b) in fields following fallow, potatoes, peas, sugar beet and oilseed rape (Young and Cochrane, 1993).

6.3.3. Damage

The maggots cause the death of the central shoot of the tiller it feeds on, resulting in classic ‘dead heart’ symptoms, in which the central leaf dies but can be surrounded by still-green leaves. When populations are high, serious damage to whole fields can occur.

The most serious damage is caused to late-sown crops (sown after mid November), which have not produced many tillers by the time of egg hatch, and will not have the time to compensate for damage by producing new tillers once the main shoots have been killed in February or March. Early-sown crops (e.g. in September/October the previous autumn) usually have sufficient tillers to tolerate moderate damage (Ellis et al., 2009b). Ironically, greater numbers of wheat bulb fly per hectare survive to adulthood on early-sown crops than on late-sown ones, probably due to the larger number of tillers available for colonisation (Raw, 1967).

6.3.4. Monitoring and Forecasting

Young and Cochrane (1993) reported a long term decline in its importance, possibly due to climate change, but more recently Holland and Oakley (2007) suggested an increasing number of fields above threshold levels in surveys. Ongoing surveys, conducted by ADAS with funding from AHDB Cereals & Oilseeds, involve sampling soil from a W-shaped transect (Ellis 2010; Evans 2003) or on the diagonal across the field (McKinley and Franklin, 1980), and extracting the eggs using soil washing procedures. It is very time-consuming and therefore prohibitively expensive (Ellis et al 2009b), but does give indications each year of the relative risks in known hot spots, and this can be used to advise on control measures that need to be applied before sowing e.g. seed treatments (see later section). Results from the surveys are published by AHDB every year in September to aid growers in decision making for comical control. A recent study on temporal variation in WBF infested fields suggested that sampling on a 50 by 50 m grid system may give a more accurate measure of egg populations due to aggregated ovipisition revealed by distribution maps (Rogers et al., 2014), but, of course, would also take longer and thus cost more.

The level of risk appears to fluctuate each season mainly due to rainfall and temperatures in July and August (Young and Cochrane, 1993), and harvest dates of previous wheat crops. Oakley and Green (2006) considered this to be related to the availability of saprophytic fungal spores on ripening wheat (greater in wet seasons) and the dryness of the soil at the time eggs are laid, which could also affect their survival. For example, in dry summers egg survival was thought to be greater under the canopy of root crops such as potatoes or sugar beet where desiccation was less likely; by implication, in wet summers egg survival might be as good in open bare fallow, although cool temperatures might also affect fly migratory activity.

6.3.5. Thresholds for control

The current threshold for economic control of wheat bulb fly is 2.5 m eggs per hectare for crops sown in September or October, but it can be less (1.25 m eggs/ha) for those sown late from November to March (Ellis et al, 2009b; AHDB, 2016b). These figures are based on old studies reported by Gough et al, (1961), and have not been updated since to take account of the differing attributes of modern wheat varieties. Nevertheless the figures were regarded with some confidence by the agricultural community in a recent survey on pest management practices (Ellis et al, 2009b).

6.3.6. Control measures

There is only one approache to the control of wheat bulb fly; the use of a seed treatment applied pre-sowing. Until 2016, an egg-hatch spray of chlorpyrifos could be applied at the end of January before damage was seen. A dead-heart spray was also an option until 2013 and was applied when damage symptoms could be seen in February/March.

Seed treatments

The most common seed treatment employed for control of WBF larvae is tefluthrin, applied in a formulated mixture with the fungicide fludioxinil (sold as Austral Plus by Syngenta) (Frost et al., 1994). Recently, a seed teeatment approved in 2012, containing cypermethrin (Signal from Chemtura), has shown some promise in trials conducted by ADAS. There have been no published papers on the relative merits of the latter seed treatments against WBF, so growers are reliant on anecdotal evidence and in-house company results. However, it is thought that such seed treatments will not be sufficiently persistent to last until egg hatch in January for crops sown in September/early October, so their use is recommened mainly for later sown crops. In any case, use of these seed treatments in recent years has not been high, and did not merit a mention in the 2012 or 2014 pesticide survey of seed treatments in wheat (Garthwaite et al, 2013, 2015).

Egg-hatch sprays

If egg numbers are known to be high, and concern is expressed that seed treatments might not be sufficiently persistent or have not been applied at all, then growers could, until March 2016, apply egg hatch sprays containing chlorpyrifos (e.g. Dursban) at the recommended rates (Harris & Thompson, 2012). Timing of sprays was guided by bulletins issued by AHDB and Dow Agrosciences on their respective websites following surveys done by ADAS on the progress of the egg hatch in different regions. It is probable that many crops will have many tillers by then and not require a protectant spray if numbers of eggs are moderate. Plants can tolerate some damage without yield loss (AHDB, 2016b). Since 1 April 2016 chlorpyrifos has been withdrawn from use in UK arable agriculture, and there are no alternative insecticides approved for use at this time and for this purpose (HSE, 2016)

Dead-heart sprays

Until 2013, dead heart sprays of dimethoate were recommended and approved for control of larvae after they had hatched. Such sprays do not, of course, protect the tillers that are already damaged, but do give some protection to unattacked tillers when the larvae move from one to the other (Gratwick, 1992). However, concerns have been expressed about the continued approval of dimethoate for certain purposes (EFSA, 2013b), and its use on cereals expires in September 2016 (https://secure.pesticides.gov.uk/pestreg/ProdSearch.asp).

6.3.7. Resistance to insecticides

There are no records of wheat bulb fly developing resistance to the insecticides currently used to control them.

6.3.8. Biological control

Survival of WBF larvae has been positively linked to the capacity for varieties to produce lots of tillers, but the proportion of tillers damaged was similar in all varieties. No variteies that are truly resistant to colonisation have been discovered to date. A research programme is currently under way at Nottingham University in collaboration with Rothamsted Research (http://www.rothamsted.ac.uk/wisp/resistance.html) to investigate varietal differences.

Activated charcoal interferes with normal host-seeking by larvae of theWBF, *Delia coarctata*, by adsorbing arrestant compounds exuded from the plants (Scott and Greenway, 1984). In laboratory tests, activated charcoal in soil surrounding one of two rows of wheat seedlings decreased larval attack on the treated row. Charcoal in soil above the level of the seeds decreased attack but had no effect when below the seeds.

Once inside the shoots of grasses and cereals larvae of WBF are largely protected from predation and parasitism, but outside the plant they are subject to these risks as eggs, as larvae while moving from egg to plant, or between plants, as pupae in the soil and also as adults (Jones 1975; Ryan 1975; Kendall, 2003). Egg predation by carabids is the most likely cause of mortality (Ryan 1973; reviewed in Rogers and Evans 2014), so events such as soil cultivations, that affect these will also affect the level of predation afforded by this trophic group (Holland 2007; Kromp 1999; Kendall 2003).

Parasitoids of wheat bulb fly have also been recorded. The main parasite found at Rothamsted farm was *Trybliographa spaniandra*, and this affected about 10 per cent, of the population in 1957 and about 5 per cent, in 1958. At Whittlesey and Peterborough, in 1959, parasitisation affected 5·5 and 13·7 per cent, of the populations, respectively. In this case, the two main parasitoids were *Aleochara bipustulata* (L.) and *A. inconspicua* Aubé (Coleoptera, Staphylinidae). *Phygadeuon trichops* Thoms. (Hymenoptera, Ichneumonidae) also occurred but was much less frequent (Dobson, 1961). Ryan (1975) found similar levels of parasitism by Hymenoptera from 1964-1966 at Rothamsted Research.

6.3.9. Cultural control

Given the capacity of wheat to tolerate damage by WBF, the obvious method of reducing risk to yields is to sow early with a reasonably high seed rate. However this may increase the pest burden in future years by encouraging successful survival of larvae, even if crop losses are reduced. Another strategy would be to avoid growing wheat on fields likely to be badly infested because they jave previously been fallow or were growing suceptible crops, as this would reduce the source of infestation for future years (Gratwick, 1992), However, there is a limit to how often growers can change their rotations for this purpose, and wheat is a good following crop after early harvested crops. One way to miminise carry over of WBF infestation from one year to the next in adjacent fields is to limit the area of bare land exposed to migrating flies by encouraging a full canopy in crops growing there at the time of egg-laying. The propensity for egg laying is hugely affected by the nature and structure of crops in the neighbouring fields in July and August (Raw, 1967; Young and Cochrane 1993). However this again is not possible with some of the crops that attract flies to egg laying sites.

6.3.10. Recommendations for research

1. Investigate the potential for some varieties to tolerate high infestations by overproducing tillers, and the consequences of this on future risk to less tolerant varieties
2. Investigate whether the gene(s) conferring immunity of oats and some grasses to attack by WBF larvae is (are) transmissible to wheat.
3. Establish a more scientifically robust control threshold for cereals taking into account seedling damage per larva, the crop's tolerance to seedling losses and ability to compensate for them, weather conditions and soil type

4. Develop modelling tools to predict the timing of WBF migrations at regional or more local scales using information on weather and soil type.
5. Studies on the identity, ecology and impact of invertebrate predators and parasitoids of wheat bulb fly larvae have been neglected. Their potential contribution to conservation biological control of WBF should be re-assessed.
6. More research on the chemical ecology of WBF larval host-finding and feeding in order to define host plant chemistry with potential to confer resistance in cereals, or to develop methods of disrupting host finding behaviour, thus increasing larval mortality prior to colonisation.
7. Encourage screening of breeders' lines of cereals for resistance to WBF
8. Investigate comparative efficacy in public-funded trials of existing approved and novel insecticide actives, both as seed treatments and as crop sprays.

6.4. Wireworms

Wireworms, the larvae of click beetles (Coleoptera, Elateridae), are an important generalist pests of crops. This is reflected in a large body of scientific literature published over the last 10-15 years. A review on management of wireworms in potato, commissioned by AHDB Potatoes, was published in 2010 (Lole, 2010b) and a major review of wireworm management was published by Barsics et al. in 2013. In the same year a special issue of Journal of Pest Science was devoted to the ecology and control of wireworms (Traugott et al., 2013). This review draws on these and other recent sources.

6.4.1. Description and geographic distribution

There are three common pest species of wireworm in the UK, *Agriotes lineatus, A. obscurus and A. sputator.* Older larvae are up to 37 mm long and slender with tough yellow skins, powerful jaws and three pairs of thoracic legs (Jones and Jones, 1984). The dull brown adult click beetles are 10-16 mm long and are named after their ability to right themselves through an interaction between two thoracic sternites that causes the beetles to spring into the air with an audible click.

Agriotes spp. are widely distributed pests across the UK, Europe and North America (Barsics et al., 2013; Jones and Jones, 1984). Different species may predominate in different regions of the UK (Jones and Jones, 1984; Parker and Howard, 2001). At a landscape scale their distribution is influenced by time and crop type, and at a field scale the distribution of adults and larvae is usually clustered (Benefer et al., 2010; Blackshaw and Hicks, 2013; Lole, 2010b; Toepfer et al., 2007).

6.4.2. Life cycle

Wireworms are polyphagous and primarily herbivorous, feeding on the subterranean parts of plants, and are best adapted to undisturbed permanent grassland (Barsics et al., 2013; Jones and Jones, 1984; Lole, 2010b; Traugott et al., 2008). The life cycle of wireworms varies greatly between species (Barsics et al., 2013) but in the three species most common in the UK it follows a similar pattern. Adults overwinter at their pupation site 5-30 cm below the soil surface and their peak emergence is between March and May. After mating, they lay eggs singly or in clusters below the soil surface, mainly from May to June, and most adults die by the end of July (Barsics et al., 2013; Jones & Jones, 1984; Oakley, 2003; AHDB Potatoes, 2011). In the UK, larvae hatch within 4-6 weeks (Barsics et al., 2013; Parker and Howard, 2001). Newly-hatched larvae are *c.* 1 mm long. They remain in the soil for 4-5 years, growing up to 37 mm long and moulting twice a year (Jones and Jones, 1984). They usually have two periods of more intense feeding activity between March and May and between September and October, when soil conditions are suitably moist and warm. Between these periods they migrate vertically within the soil according to soil moisture and temperature conditions and may spend the winter as deep as 60 cm (Barsics et al., 2013; Ellis JS et al., 2009b; Jones and Jones, 1984).

6.4.3. Damage and pest status

Wireworms feed by biting into the base of stems of cereals, leaving ragged holes. They bite into the hypocotyls of seedlings such as sugar beet and they burrow into the tissues of root crops. Cereals and root crops are particularly susceptible, whereas peas, beans, linseed and flax are resistant or tolerant (Blake et al., 2003; Jones and Jones, 1984; Oakley, 2003). Cereals are most susceptible at the seedling stage when damaged plants can break off at the soil surface, falling over and dying, and, typically, the damage continues along the row (Ellis JS et al., 2009b; Oakley, 2003). Both autumn and spring-sown cereals are at risk as the seedling stages coincide with seasonal peaks in wireworm activity. Heavy infestations can cause losses of up to 0.6 t/ha (Oakley, 2003). Damage to potatoes is most significant in the autumn when the wireworms burrow into the tuber, causing a reduction in crop quality rather than yield, and losses in the range 5-25% have been reported (Parker and Howard, 2001). The importance of wireworm damage to potatoes has been a significant driver of research into their ecology and management (e.g. Barsics et al., 2013; Ester and Huiting, 2007; Lole, 2010b; Parker and Howard, 2001; Sufyan et al., 2013). In contrast to their larvae, feeding by adult click beetles at the base of grass or cereal leaves does not cause significant damage (Jones and Jones, 1984; Oakley, 2003).

The pest status of wireworms in arable rotations has become more severe in recent decades and the reasons for this are not entirely clear (Holland and Oakley, 2007; Lole, 2010b; Oakley, 2003; Parker and Howard, 2001). In the past, wireworm problems were most severe in crops following long-term grassland, which can support up to 20 million wireworms per hectare, but were rarely serious in cereals in long-term arable rotations (Jones and Jones, 1984). It has been suggested that various changes may be responsible for increasing wireworm problems, including the switch to winter cereal cropping (providing a year-round supply of preferred monocot food), the inclusion of set-aside in rotations, the sowing of grassy margins (providing a reservoir for infestations to spread into the field), the adoption of reduced tillage, and the withdrawal of persistent organochlorine insecticides (Blake et al., 2003; Holland and Oakley, 2007; Lole, 2010b; Oakley, 2003; Parker and Howard, 2001).

In the years since the publication of AHDB Cereals & Oilseeds Research Reviews 51, 64 and 73 (Blake et al., 2003; Ellis et al., 2009a; Holland and Oakley, 2007) ADAS Pest, Disease and Weed Incidence Reports suggest that there has been no further increase in the incidence of wireworms in arable crops, there being few reports of wireworm damage in cereals and most occurrences probably being related to a site-history of grassland (ADAS, 2013; Lole, 2009; 2010a; 2011). This suggests that wireworm populations may have stabilised following the agronomic changes that led to their increase. This is consistent with Parker and Seeney's (1997) finding that wireworm populations tend to stabilise in permanent pasture 15 years after sowing.

The soil-dwelling nature and the long life cycle of this pest, its patchy distribution and its seasonal movement within the soil column present challenges to successful management (Benefer et al., 2010; Blackshaw and Hicks, 2013; Traugott et al., 2013). The long period that larvae spend in the soil dictate that crop rotation, the availability of food plants (grass weeds and/or crops) throughout the season, climatic and soil factors, including tillage, have major influences on populations and often operate at a small scale, producing distributions that are usually clustered and may differ between species (Barsics et al., 2013; Benefer et al., 2010; Benefer et al., 2013; Blackshaw and Vernon, 2008).

6.4.4. Thresholds for control

The control threshold for wireworms in cereals is based upon estimates of field populations from soil cores, which is a problematic and expensive monitoring technique (see below) and hence it is rarely done (Ellis et al., 2009a; Jones and Jones, 1984; Oakley, 2003). Seed treatment is recommended if populations exceed 0.75 million per hectare. It is advised that damage is likely, even with seed treatment, if populations exceed 1.25 million per hectare (Ellis et al., 2009a; Oakley, 2003), but there are no further insecticide treatments recommended for control of these pests, presumably because of the difficulty of hitting the target underground using sprays. The origin of the thresholds is uncertain and an internal ADAS report in 1990 expressed only moderate confidence in them (Ellis et al., 2009a. There may be scope to derive a more scientifically robust threshold for cereals by establishing the number of seedlings that can be damaged by a single wireworm and relating this to plant density and the tolerance of the crop to seedling losses (i.e. the minimum plant density needed to achieve full yield potential; Ellis et al., 2009a). However, any such threshold may also need to take into account the age structure and species composition of the wireworm population, soil type and weather conditions (Benefer et al., 2013; Jung et al., 2012).

In rotations that include potatoes, populations of wireworms must be maintained at lower levels because of the market's low tolerance of damage in that crop. However, the relationship between larval populations and damage levels has proved hard to establish and even numbers below the detection limit for standard soil sampling methods can cause economic damage to potatoes (Parker and Howard, 2001).

6.4.5. Monitoring and forecasting

The traditionally recommended method for assessing wireworm populations for control decisions is to take 20 soil cores over a W-shaped transect covering 4-10 ha and to send these to an accredited laboratory, such as ADAS Pest Evaluation Services or the Fera Plant Clinic, for wet extraction Ellis et al., 2009a; Jones and Jones, 1984; AHDB Potatoes, 2011). This has a number of drawbacks: it is time consuming, expensive, subject to large sampling errors (as a result of minimised sampling and the clustered distribution of larvae) and can fail to detect economically significant populations (Barsics et al., 2013; Benefer et al., 2013; Parker and Howard, 2001). In the light of this, Oakley (2003) advised that it was rarely justified for farmers to take soil cores to establish wireworm populations in cereal crops. Ellis et al. (2009b) suggested that regional or national surveys using soil cores are valuable to warn growers and advisers of the risk of wireworm attack and for product stewardship.

In an attempt to overcome the difficulties associated with soil core sampling, much effort has been devoted to studying the chemical ecology of adult click beetles and developing baited monitoring traps (Barsics et al., 2013; Parker and Howard, 2001). In locating their food plants in the soil, wireworm larvae have been shown to respond to the carbon dioxide released from plant tissues and this is the basis for the baiting of wireworm monitoring traps with plant material (Parker and Howard, 2001). Typically, traps consist of germinating cereal grains in a plastic pot pierced with holes and sunk 20 cm deep into the soil (Parker, 1994; AHDB Potatoes, 2011). These traps appear to be more sensitive indicators of the presence/absence of wireworms than soil core sampling but in general it has not been possible to relate the size of the trap catch to the degree of crop damage that can be expected (Barsics et al., 2013; Parker, 1996). More recently, the sex pheromones of *Agriotes* spp. that were identified in the 1980s have been used to bait monitoring traps to catch walking and flying adult males in the hope of relating trap catches to the risk of crop damage by their wireworm larvae (Barsics et al., 2013; Lole, 2010b; Parker and Howard, 2001). Pheromone-baited traps are recommended to potato growers in the UK for use as an early warning of the presence of click beetles, which can be followed up by sampling for wireworm larvae (AHDB Potatoes, 2011).

While pheromone traps may have value for indicating the presence/absence of click beetles, spatial studies suggest that there are several impediments to their ability to reflect populations of wireworms in the soil. Chief amongst these are that annual wireworm cohorts are not of equal size, adult male distributions do not relate to larval distributions, and activity/density relationships differ between species (Blackshaw et al., 2009; Blackshaw and Vernon, 2008). Moreover there is evidence that click beetles disperse more widely than previously thought and can be recruited from outside the field (Blackshaw Hicks, 2013; Hermann et al., 2013; Lole, 2010b). The monitoring potential of pheromone traps is therefore most likely to be of value in ecological studies of responses of click beetles to landscape elements and the development of landscape models to predict risk (Blackshaw and Vernon, 2006).

In conclusion, despite recent advances, the ability to assess the risk of wireworm damage remains disappointing. Further research is needed on the spatial ecology of individual *Agriotes* spp., taking advantage of recent advances in the molecular identification of species (Barsics et al., 2013; Benefer, 2011; Benefer and Blackshaw, 2014; Benefer et al., 2013; Ellis et al., 2009a) to explore spatial and temporal relationships of each species with refuges in the environment and between generations. Barsics et al. (2011) suggested that a large scale multivariate analysis of different farming systems might identify more factors that confer a predisposition to wireworm problems. Early attempts to use climate, soil type, cropping and cultivation history to model wireworm damage risk were largely unsuccessful (Parker and Howard, 2001). However, a recently developed model successfully predicted the degree of activity of wireworms in relation to soil moisture, temperature and soil type (Jung et al., 2012). With the appropriate biological information, modelling tools may have potential to estimate the timing of risk to crops at a regional scale or even at a field scale, if environmental data of sufficient resolution is available. Such a model could make use of GIS technology and could be incorporated into a web-based decision support system such as proPlant (Johnen and von Richthofen, 2013; Parker and Howard, 2001).

6.4.6. Control measures

Given the interrelationships between cropping history, crop type, damage tolerance and the severity of wireworm damage, the sequence of cropping has an important influence on wireworm populations and can be manipulated for their management (see the section on cultural control below for further discussion of this).

Chemical control of any soil pest is difficult due to the mass, physical properties and biological activity of the soil they inhabit. This is particularly so for wireworms as they have a multi-year life cycle and migrate vertically within the soil. Nevertheless, insecticides are the second mainstay of their management.

Given that cereal crops are chiefly vulnerable at seedling stage, seed treatment with the pyrethroid tefluthrin, or with the neonicotinoids imidacloprid or clothianidin have been sufficient to manage moderate attacks (Oakley, 2003) and have been used increasingly for early season aphid/virus control (Lole, 2009; 2010a; 2011; Nicholls, 2013). Significant wireworm damage to oilseed rape is not common (Alford et al., 2003b) but a degree of protection to seedlings was likely to be conferred by seed dressings containing neonicotinoids or pyrethroids for flea beetle control. Maize crops are most commonly treated with the carbamate, methiocarb, which is unlikely to control wireworms at the rate it is applied; neonicotinoids, imidacloprid and clothianidin are only used on 9% of the seed treated area (Garthwaite et al., 2014), to protect against wireworms and other pests. Several insecticides, including tefluthrin and imidacloprid, have been shown to be repellent to wireworms and this may be part of the mode of action by which seed treatments protect seedlings from attack (Barsics et al., 2013; Van Herk et al., 2008).

As a result of a recent EU-wide restriction, the option to use neonicotinoid seed treatments in any oilseed crop or maize crop, or in cereal crops sown between January and June has currently been removed (Nicholls, 2013). It is fortunate that this restriction does not affect winter cereals. However, any restriction on the ability to manage wireworms risks reducing rotational choices and the ability to manage wireworm populations down to levels suitable for the inclusion of high value but vulnerable crops such as potatoes (Parker and Howard, 2001; AHDB Potatoes, 2011). Potato growers use organophosphate insecticides incorporated to the soil at planting to provide a degree of protection against wireworms until late in the life of the crop but there is a lack of suitable new and effective insecticide chemistry with soil persistence and an acceptable environmental profile (AHDB Potatoes, 2011). The restriction on neonicotinoids places more pressure on the remaining compounds used to treat this pest, risking the development of insecticide resistance and increasing the urgency to seek new actives for management of this difficult-to-target soil pest.

6.4.7. Evolution of resistance to insecticides

There appears to be no evidence for insecticide resistance in wireworm pests in the UK, even though the life cycle of a wireworm is long enough to expose them to insecticides on multiple occasions. However, resistance in other wireworm species was reported in the USA in the middle of the last century (Harris, 1972) and in Australia in the 1980's (Gunning and Forrester, 1984). Although seed dressing insecticides used on cereals were thought to be less persistent than in those reports, a recent survey by Fera showed that some e.g, imidacloprid could still be detected in soil three years after its use (Jones et al., 2014), although other studies suggested that field degradation rates of thiamethoxam were faster than demonstrated in the laboratory, and that it would not accumulate in the soil with repeated use (Hilton et al., 2015). Studies on clothinaidin in maize fields also suggested that this insecticide does not accumulate with repeated use (Xu et al., 2016). Nevertheless, a risk of resistance development is likely to remain where a restricted range of actives is used intensively and over long periods. This risk may be greatest in rotations that include potatoes for which more persistent actives, such as ethoprophos and fosthiazate, are available (AHDB Potatoes, 2011). The current restriction on the use of neonicotinoids leaves fewer actives available for spring-sown cereals, oilseed crops and maize and so may exacerbate the risk of resistance. New insecticide actives are needed to reduce the risk of resistance development.

6.4.8. Biological control

There is rather little published information on the predators, parasitoids and pathogens of wireworms and click beetles. Some carabid and staphylinid beetles and the larvae of therevid flies have been reported to prey on wireworms (Buchs and Alford, 2003; Fox and MacLellan, 1956) as do various vertebrates (Holland and Oakley, 2007; Parker and Howard, 2001). Oakley (2003) stated that parasitoids were among their main natural enemies, but according to Kuhar et al. (2003) they have few predators or parasitoids.

Recently, entomopathogenic fungi have been sought that would be suitable for use as biological control agents of wireworms through inundative release or as seed treatments. Isolates of *Metarhizium anisopliae* and *Beauveria bassiana* have been identified that show great promise in the laboratory and cause significant mortality in field trials (Ansari et al., 2009; Barsics et al., 2013; Kabaluk et al., 2007), but results are not consistently positive (Lole, 2010b) and this is probably due to a complex interaction between environmental and behavioural factors that influence the infection process (Kabaluk and Ericsson, 2007). Interestingly, there appears to be synergy between entomopathogenic fungi and insecticides concurrently applied (Barsics et al., 2013; Butt, 2011; Ester and Huiting, 2007). The reasons for this are not entirely clear.

Tests of strains of the entomopathogenic nematodes *Steinernema feltiae*, *S. glaseri*, *S. carpocapsae*, *Heterorhabditis bacteriophora* and *H. megidis* have shown promise for wireworm biocontrol in the laboratory but results have not always been positive, either in the lab or field (Ansari et al., 2009; Barsics et al., 2013; Lole, 2010b; Toba et al., 1983). Some strains of bacteria pathogenic to wireworms also show potential for exploitation in biological control (Barsics et al., 2013). More research is needed on interactions between biological control agents, the soil environment and the behavioural ecology of the pest if the potential of artificial release of biological control agents is to be realised. More information is needed on the mortality factors affecting eggs and early instars (Parker and Howard, 2001).

6.4.9. Semiochemical-based control strategies

At present the development of viable semiochemical-based control strategies for wireworms in cereal crops does not appear to be imminent. Identification of the female sex pheromones of *Agriotes* spp. offered potential for management of the adult pest by mating disruption or by mass trapping. Results from tests of both these strategies have not proved promising, at least in part because of the short range of action of the pheromone which would necessitate an uneconomically dense array of traps, except perhaps in very high value crops (Sufyan et al., 2011; Sufyan et al., 2013; Vernon et al., 2014). Moreover, click beetle adults disperse widely and are recruited from outside the crop (Blackshaw and Hicks, 2013), therefore mass trapping is unlikely to succeed in reducing wireworm populations if conducted at a small scale.

A number of plant volatiles have been tested for their repellence to wireworms and it has been suggested that they may have a role in push-pull strategies (Barsics et al., 2013; Waliwitiya et al., 2005). Intercropping with a more attractive ‘trap crop’ has also been tested but there is a risk that such an arrangement of the trap crop simply attracts higher infestations (Barsics et al., 2013; Cook et al., 2007; Landl and Glauninger, 2013).

6.4.10. Cultural control and conservation biological control

Crop rotation

The sequence of cropping has an important influence on wireworm populations given the interrelationships between cropping history, crop type, damage tolerance and the severity of wireworm damage. Rotations can thus be manipulated for their management. Crops are at most risk when they follow within two years of long-term grassland, when the abundance of preferred food-plants and the lack of soil disturbance encourages egg-laying and larval survival (Barsics et al., 2013; Blake et al., 2003; Jones and Jones, 1984; Oakley, 2003; AHDB Potatoes, 2011). Rotations predominantly of winter crops, particularly cereals or crops with grass weeds present, are at risk for the same reasons and there is evidence that long-term set-aside also provides a suitable habitat for wireworms (Blake et al., 2003; Oakley, 2003; Parker and Howard, 2001). To ameliorate or avoid these problems the grower can consider sowing resistant/tolerant crops, such as linseed, flax or peas, and including a spring crop in the rotation, which allows winter cultivations or spring cultivations that expose vulnerable eggs and larvae to desiccation (Blake et al., 2003; Furlan, 2007; Oakley, 2003). Susceptible crops may be protected by avoiding drilling them during the peaks of wireworm activity in spring and autumn, when seedlings would be most vulnerable (Furlan, 2007).

Tillage

There is evidence that the adoption of inversion ploughing in wheat disrupts wireworm populations and causes them to decline, whereas survival of wireworms in wheat with minimum tillage is as high as in plots sown with grass (Lole, 2010b). Click beetle eggs and young wireworms are vulnerable to desiccation and therefore, in extreme cases, ploughing in spring and leaving fallow over summer can be used for control (Blake et al., 2003). Consolidation of the seedbed following drilling restricts wireworm movement (Oakley, 2003).

Biofumigants

Recently the effect on wireworms of ‘biofumigation’, using fresh plant material or defatted seed meal from mustard species broadcast or incorporated to the soil, has been tested in the laboratory and field with conflicting results (Furlan et al., 2010; Lole, 2010b). It is likely that the success of this technique is sensitive to the conditions at the time of application (Barsics et al., 2013).

Margin management

Grassy margins offer stable refugia for wireworms and the dispersal abilities of click beetles probably make them a significant source of invasion into fields (Blackshaw and Hicks, 2013; Hermann et al., 2013; Lole, 2010b; Parker and Howard, 2001). However, field margins are also refugia for natural enemies, no doubt including those of wireworms. Further research is needed to establish the influence of field margin management on the spatial and temporal population dynamics of wireworms and their natural enemies and on crop damage (Griffiths et al., 2008; Hermann et al., 2013).

Genetic resources

Research interest in the development of wireworm resistant potato cultivars (Kwon et al., 1999; Parker and Howard, 2001; AHDB Potatoes, 2011) does not seem to have been replicated in cereal crops. It is thought that the resistance or tolerance of other crop species may in part be related to the size of their seeds and seedlings or to the population density at which they are sown (Jones and Jones, 1984). Unfortunately seed size is not a very tractable character and routinely increasing the sowing density of cereals would be expensive and may simply increase the food supply for wireworms, postponing the problem. However, further research on host-plant chemicals released into the soil that are used by wireworms in host-location, recognition and feeding, might lead to the development of less susceptible cultivars for use in wireworm management (Barsics et al., 2013).

6.4.11. Factors potentially influencing future risk

The need for the use of insecticide seed dressings is accentuated by the increase in wireworm problems in arable rotations in recent decades. At the same time, a loss of available insecticide actives puts greater pressure on the existing range of chemistry. Although some insecticides used in seed dressings on cereal crops are of lower persistence than historically, others may not be (Jones et al., 2014), and the potential for multiple exposure to insecticides, when several crops may use the same actives during the 4/5-year life of a wireworm in the soil, means that the risk of resistance development cannot be ignored.

The activity of wireworms is strongly influenced by weather, their spring and autumn feeding periods being governed by the periods when the upper soil layers are both sufficiently moist and sufficiently warm (Barsics et al., 2013; Ellis et al., 2009a; Jones and Jones, 1984). Any change in climate that extends or reduces the period of optimal conditions for wireworm activity could have a substantial effect on the severity of this pest. Staley et al. (2007) found a marked increase in populations of *A. lineatus* larvae in grassland plots in the UK that had had ten years of artificially enhanced summer rainfall. By contrast, a comparison of 17 fields in four regions of Croatia found that the abundance of *A. lineatus* adults in sex pheromone traps was less in the warmer and drier east of the country, the numbers caught being negatively correlated with temperature (Kozina et al., 2013).

6.4.12. Recommendations for research and other actions

- Keep a watching brief on the incidence and severity of wireworm damage for any changing trend. Consider annual national or regional surveys based on soil core samples or pheromone traps to monitor abundance trends.
- Assess the risk of insecticide resistance using the outputs of AHDB Cereals & Oilseeds project RD-2012-3780 'Combating insecticide resistance in major UK pests' when available.
- Monitor resistance status of wireworms.
- Consider clarification of advice on any control measures to be taken when wireworm populations exceed 1.25 million per ha in cereals.
- Establish a more scientifically robust control threshold for cereals taking into account seedling damage per wireworm, the crop's tolerance to seedling losses and ability to compensate for them, weather conditions, soil type, and wireworm age-structure and species.
- Develop modelling tools to predict the timing of wireworm activity at regional or more local scales using information on weather and soil type. Consider delivering resulting advice to growers through a web-based DSS such as proPlant.
- Further research is needed on the spatio-temporal dynamics of *Agriotes* species and their natural enemies in the landscape in relation to crop and field margin management and crop damage. This could contribute to the development of field-specific risk advice and the better interpretation of pheromone trap catches.
- Studies on the identity, ecology and impact of invertebrate predators and parasitoids of wireworms and click beetles have been neglected. Their potential contribution to conservation biological control of wireworms should be assessed.

- More research is needed on interactions between microbial control agents, the soil environment and the behavioural ecology of the pest if the potential of artificial release of these biological control agents is to be realised.
- Observed synergies between biological control agents and insecticides should be better understood if they are to be fully exploited.
- Research is needed on the chemical ecology of wireworm host-finding and feeding in order to define host plant chemistry with potential to confer resistance in cereals.
- Screening of breeders’ lines of cereals for resistance to soil pests should be encouraged.
- New and safe insecticide actives are urgently needed.

6.5. Leatherjackets

Leatherjackets are the larvae of craneflies (daddy long-legs) and, while there are a number of species in the UK, only *Tipula paludosa* (the marsh cranefly) and *T. oleracea* (the cabbage cranefly) are regularly reported as pests. *Tipula paludosa* is the most abundant and widespread while *T. oleracea* occurs more sporadically and usually under specific circumstances (Blackshaw and Coll, 1999; Coll et al., 1993a). The two species are difficult to distinguish morphologically and so many studies just report results for *Tipula* spp. without distinguishing between them, which has led to some confusion concerning their respective life-cycles and whether crop damage is due to one species or the other, or indeed due to a complex (Blackshaw, 2009; Blackshaw et al., 1996; Humphreys et al., 1993). They are both temperate European species but have spread to the USA and Canada where they are a particular problem in amenity grass such as golf courses and in turf production (e.g. Byers and Arnaud, 2011; Peck et al., 2010; Petersen et al., 2011; Taschereau et al., 2009).

In the UK leatherjackets (in the broadest sense but likely to be predominantly *T. paludosa*) have historically been considered as major pests of grassland (permanent grassland, amenity grassland, grass/clover leys). Consequently they were also pests of spring cereals (particularly barley) that followed grass or a grass ley because their numbers build up to high levels in the ley and then easily transfer to the subsequent cereal. However, their economic importance in arable farming declined when agricultural intensification removed the need for fertility-building grass leys and more autumn-sown crops were grown that are not at a susceptible stage in spring when larvae are most active (Blackshaw, 1988; Blackshaw and Kerry, 2008). With growth in organic farming, which requires more fertility-building grass/clover leys than conventional farming, they again became a focus of attention (Blackshaw, 2009; Blackshaw and Kerry, 2008). Despite this, they are only a sporadic pest and, while numbers did increase in response to damp autumns from 1992 - 2006 (Holland and Oakley, 2007), recent ADAS Reports suggest that since 2007 numbers have been generally low and below the threshold level that could cause harm in cereal crops, confirming them as a relatively minor pest on the majority of arable farms (e.g. ADAS Reports 2009, 2010, 2011, 2013).

6.5.1. Life-cycle

Tipula paludosa is univoltine and is closely associated with stable grassland habitats where its numbers build up. Adults emerge between the months of June and September, depending on regional differences in temperature, from pupae that can be found close to the soil surface. Emergence is at dusk. Females are gravid when they emerge and mating occurs quickly. Three quarters of their eggs are laid before daybreak the following day and all are laid within 36 hours of emergence. Females are very poor fliers until they have laid their eggs. For this reason, eggs are laid close to the emergence site, usually in a single batch on soil amongst the herbage, and populations remain localised, increasing year on year if unchecked. Each female lays between 200 and 300 eggs and, where possible, selects damp swards of moderate height. Pale sandy-grey coloured larvae hatch within approximately two weeks and immediately begin feeding within the top 3 cm of soil, on the bases and roots of cereals and/or grasses, passing through the first two instars relatively quickly and generally overwintering as third instar larvae. They remain active and able to feed while temperatures exceed 5 °C and become particularly active as fourth instar larvae during spring when temperatures rise. It is the fourth instar that causes the greatest damage and is coincident with small seedlings of spring-sown cereals, affecting establishment. They are well adapted to wet situations and more common in regions with higher rainfall. Eggs and early instar larvae can be susceptible to desiccation when rainfall is abnormally low during September. However, desiccation may not be the only mechanism for the population crashes that are observed during dry weather; larvae can migrate within the soil to find locations with optimal moisture levels and during dry periods they can become concentrated into any remaining moist locations leading to mutual aggression and cannibalism. Even under optimal conditions of moisture, high-density populations may be regulated by cannibalism because larvae are more likely to come into contact with each other than in low-density populations. Larvae can also be susceptible to extended periods of flooding. Fully-grown larvae are greyish in colour, tough-skinned and can reach 3-5 cm in length. They diapause in an inactive non-feeding pre-pupal stage within their burrows from June to August (again depending on temperature), before moving to the soil surface to pupate. Larvae spend at least nine months in the soil. They remain as pupae for a further two weeks before emerging as adults and beginning the cycle again.

While similar in many respects, *T. oleracea* is far less common than *T. paludosa* and does not have such strong associations with grassland. In fact, in a survey of larvae in grasslands in northern Britain (in which the two species were identified using isoelectric focusing), *T. oleracea* was rare in comparison with *T. paludosa*; it follows that the majority of damage in spring cereals following a ley can therefore be attributable to *T. paludosa*. *Tipula oleracea* also develops faster than *T. palidosa* and has no diapause period, meaning that it has the potential to be bivoltine in years when climatic conditions allow. In these circumstances one adult generation emerges in spring/summer, overlapping with *T. paludosa* emergence, and a second generation emerges in autumn/winter. Females of *T. oleracea* are able to fly when gravid and lay several batches of eggs further away from the emergence site than *T. paludosa* is able to do. They are also thought to have a wider host range than *T. paludosa*, and so reports of leatherjackets attacking non-graminaceous plants are probably more likely to be *T. oleracea* than *T. paludosa*. This means that populations of *T. oleracea* are generally distributed over a larger area and at lower density than those of *T. paludosa* and that large localised populations and consequent damage are rarely associated with *T. oleracea*.

These life cycles are summarised from a number of references (Bayer Pest Spotter, 2014; Blackshaw, 1999, 2009; Blackshaw and Coll, 1999, and references therein; Blackshaw and Petrovskii, 2007; Blackshaw and Kerry, 2008; Blackshaw and Hicks, 2013; Blackshaw et al., 1996; Blake et al., 2003; Coll et al., 1993a,b; DOW Information Leaflet 3, 2014; Humphreys et al., 1993; Jones and Jones, 1984; Meats, 1970; Milne et al., 1965; Petersen et al., 2013).

6.5.2. Damage

The majority of damage caused by leatherjackets, predominantly *T. paludosa*, is in undisturbed leys, pastures and amenity grassland where numbers build up over years, resulting in insidious yield losses and, in the latter, economically important cosmetic damage (Blackshaw, 1983, 1991; Blackshaw and Coll, 1999; Blackshaw and Kerry, 2008; Peck et al., 2010).

In arable crops, the greatest threat from both species has always been in relation to cereal establishment rather than debilitation of plants and yield loss through root feeding; however, root feeding can lead to yield losses without visible signs of infestation and will be considered further below (Blackshaw and Coll, 1999; DOW Information Leaflet 3, 2014).

Spring-sown cereal seedlings drilled after a ley are most susceptible to attack, although there are reports of other crops such as brassicas being at risk following a ley (Blackshaw and Coll, 1999; Blackshaw and Hicks, 2012; Ellis et al., 2009b; AHDB, 2014c). Drilled seed can be hollowed out, but the greatest damage is due to the voracious fourth instar larvae moving along the rows, feeding at night at the soil surface and cutting through cereal shoots. Feeding below the soil surface makes the stems at the surface appear ragged and they are vulnerable to breaking. The first symptoms are yellow, wilting plants and this can lead to plant loss and the appearance of bare patches in the crop when populations are high (Bayer Pest Spotter, 2014; Blake et al., 2003; AHDB, 2014c). Negative impacts on the establishment of spring-sown crops could be due to feeding by either or both species (fourth instar larvae of both can be present at this time) but are likely to be predominantly due to *T. paludosa* because this is the most widespread and abundant species and is more likely to establish locally-damaging populations (see life-cycle above). Despite the long association between leatherjackets and establishment problems in spring-sown crops, figures for associated yield losses are rare (Blackshaw and Coll, 1999).

When autumn-sown cereals first became more common, there were sporadic reports of leatherjacket feeding damage causing establishment problems during October and November; this is in stark contrast to the usual observation that such problems occur only in spring, in spring-sown crops. The larvae causing autumn damage included fourth instars at a time when *T. paludosa* larvae could only have reached the second instar, indicating that they were in fact the first generation of the faster-growing *T. oleracea* (Blackshaw and Coll, 1999). What is more, damage in winter cereals due to *T. oleracea* was strongly associated with a preceding crop of oilseed rape. This was believed to be because, emerging during May and June into an established oilseed rape crop, *T. oleracea* were unable to escape the canopy and disperse as they would normally do, and were thus forced to lay their eggs in high concentrations around the emergence site, much as *T. paludosa* normally does. These eggs hatched and, unlike *T. paludosa*, had reached the most damaging fourth instar when the subsequent winter cereal was at its most susceptible stage (Coll and Blackshaw, 1996; Coll et al., 1993a). Consequently, while establishment damage to spring-sown crops is most likely to be due to *T. paludosa*, establishment damage to autumn-sown crops is more likely to be due to *T. oleracea* and is exacerbated in winter cereals following oilseed rape, because populations were unable to disperse from the latter.

Although establishment losses can be devastating when they occur, they are generally localised and, to an extent, predictable because they are most commonly associated with wetter regions and with crops following a grass/clover ley (see below).

6.5.3. Thresholds for control, monitoring and forecasting

Before the ban of chlorpyrifos, nationwide monitoring of leatherjacket populations in grassland was done annually; some regions are more prone to problems than others due to climate and agriculture type and useful regional information on 'hot-spots' is provided for farmers (DOW Cereals Pestwatch, 2014; Ellis et al., 2009b). However, because problems can be very localised, even in high-risk areas, field-level information on thresholds is essential for informed spray decisions to be made on a field-by-field basis.

Treatment thresholds have been devised for fourth instar larvae monitored in spring cereals. The currently available thresholds to prevent establishment losses are either five leatherjackets per m length of row, as determined by 'row scratching', or 50 leatherjackets per m^2 as determined by 'brine flotation' (AHDB, 2014c, 2003; Ellis et al., 2009b). These thresholds are much lower than the equivalent for grassland because plant density is so much lower in a cereal crop than in a ley or grassland (Blackshaw and Coll, 1999).

No threshold has been established for *T. oleracea*-related establishment damage in winter cereals although it is likely that lower values would be appropriate because winter cereals are less able to compensate for damage (Blackshaw and Coll, 1999; Blackshaw et al., 1994; Coll et al., 1993b). Neither do thresholds exist for small root-feeding *T. paludosa* larvae present during winter in autumn-sown crops as they are difficult to quantify because of their small size. These younger instars do not prevent establishment but can contribute to yield loss through root feeding. (Blackshaw and Coll, 1999). Farmers have to use risk indicators based on local knowledge to determine whether they should consider treating during autumn/winter. These include whether the crop is a cereal or a less susceptible crop, whether they are in a predominantly grassland area, whether they have had a history of problems and what the autumn weather has been like. The lack of thresholds for winter cereals might be expected to lead to a risk of unnecessary prophylactic spraying but all treatments may be hampered during winter by difficulties in accessing wet land (Blackshaw and Coll, 1999).

The origins of the ‘row scratching’ technique are unclear but it is a well-established method described by Blackshaw et al. (1996). Briefly, a number of 30 cm drill lengths are taken diagonally across a field and in each one the soil is disturbed, or scratched, to root depth and any larvae revealed counted. The threshold is reached if there are 15 larvae found in ten such samples (approximately equal to five per m length of row) although this number should be adapted in relation to drill width (DOW Information Leaflet 3, 2014). Commercially available ‘brine flotation’ kits have been adapted from the DIY kits of Stewart and Kosicki (1987) and Blackshaw, (1990a) as described in Blackshaw et al. (1996). Briefly, each DIY kit is a 30 cm length of 10 cm diameter pipe that is sunk into the ground to a depth of 5 cm and then filled to within 5 cm of the top with brine. The salt causes the leatherjackets to move to the soil surface, enter the brine solution and float to the top where they can be counted. If five leatherjackets are captured in 12 of these pipes placed in different areas in the crop, then this is equivalent to 50 per m^2 (AHDB, 2014c). While the brine flotation method is more effective (Blackshaw et al., 1996) it is rarely used, even with the improvements of Blackshaw (1990a), because it is time-consuming, requires transport of a lot of brine to the field, and the pipes can drain too fast in some soil types or if installed soon after cultivation (Ellis et al., 2009b). This means most farmers rely on the ‘row scratching’ method in combination with local knowledge such as any previous problems (if they are on damp or heavy soils that favour leatherjackets or in a predominantly grassland region), cropping history (e.g. a recent ley) and autumn weather (e.g. a dry September might desiccate and kill eggs and early instars).

In the hope of being better able to predict high-risk regions or years and better forecast populations of leatherjackets, a number of modelling studies have investigated the biotic and abiotic factors arable crops, particularly for *T. paludosa* (Blackshaw, 1990b, 2009; Blackshaw and Hicks, 2013; Blackshaw and Moore, 2012; Blackshaw and Petrovskii, 2007; Blackshaw and Perry, 1994; driving their within- and between-generation population dynamics and distribution in grassland and McCracken et al., 1995; Petersen et al., 2013). These studies made use of the substantial amount of experimental and field data available from the numerous annual surveys of leatherjackets that have been made in grassland. While these studies are informative and potentially very useful for grassland management, because of the localised nature of this pest, arable farmers will still need to inform spray decisions with local information and sampling in relation to thresholds.

Simulation modelling has also allowed the *in silico* testing of different management strategies to identify combinations and timing of control approaches that are most likely to be effective (Blackshaw, 2009). This study focused on organic systems with grass leys in the rotation and included the use of a biopesticide. While the outputs of such studies need to be confirmed by field experimentation, they offer opportunities to identify knowledge gaps and best management practices for leatherjackets that are relevant more widely. They can also be used to build decision trees for practical use by farmers.

6.5.4. Control with insecticides

On conventional arable farms, control is usually attempted by remedial application of insecticides once damage is noticed because leatherjackets are only regional and sporadic pests (Blackshaw and Kerry, 2008). Chlorpyrifos was the only approved treatment for leatherjackets and had proven efficacy (Blackshaw and Coll, 1999; AHDB Cereals & Oilseeds, 2003). Its use was only recommended in spring cereals and when the damage threshold was exceeded. For autumn-sown crops, unless they were at high risk, a spray was not necessary nor recommended (DOW Information Leaflet 3, 2014). However, the recent withdrawal of chlopyrifos for use in agricultural situations in the UK has removed this option (HSE, 2016). It is worth noting that in recent studies in the US a number of insecticides were found to be effective against leatherjackets in turf but they achieved better ‘preventative’ control in autumn against earlier instars than ‘curative’ control in spring against later instars (Peck et al., 2008; Petersen et al., 2011; Stahnke et al., 2005). Seed treatments are not thought to be effective against leatherjackets on sugar beet in the UK (Dewar et al., 2000). To our knowledge there are no reports of insecticide resistance in leatherjackets in the UK or elsewhere.

In leys left for long periods before cultivation or in permanent grassland it has been suggested that insecticide treatments every 3-5 years would be useful to stop leatherjacket population build up and protect subsequent crops (Blackshaw and Coll, 1999). However, farmers are more likely to apply a fertilizer than an insecticide to ensure the grass grows away from damage and, as leatherjackets are important prey within the grassland ecosystem (e.g. for birds), this also has benefits that should be considered (Blackshaw and Coll, 1999; Blackshaw and Moore, 2012). Relationships between the number of larvae in the ley and likely damage in the first subsequent crop suggest that populations in the ley would need to be in excess of 1.7×10^6/ha to make a pre-cultivation insecticide treatment worthwhile (Blackshaw, 1988).

6.5.5. Cultural control

Crop rotation

As numbers of leatherjackets can be very high in a ley, the first crop following it will be at risk. Populations of leatherjackets take 3-7 years to reach peak levels in a ley (Kell, 1988). Based on these data and predictions from simulation modelling (Blackshaw, 2009), it has been suggested that limiting leys to two years would help prevent leatherjacket damage in subsequent crops. Effects on the fertility-building value of a short ley and other unforeseen costs would also need to be considered in choosing this strategy.

Tillage

Soil cultivation reduces the numbers of leatherjackets significantly. In cropping systems that use fertility-building grass leys, the ploughing up and cultivation of the ley prior to drilling with a spring cereal can reduce populations by up to 70% but it is advisable to plough as early as possible (July) and bury herbage well to limit carry-over and prevent egg laying by the current year’s generation of adults (Blackshaw, 1988; AHDB, 2014c). With repeated annual cultivation, populations are reduced to low levels within two years (Blackshaw, 1988).

Farming is now moving away from regular ploughing to no and low-till systems for the cost and environmental benefits accrued and for the preservation of natural enemies. In the context of this strategy, ploughing for leatherjacket control could be limited according to an assessment of risk, i.e. used only in the years after a ley or where significant populations have been found in previous years.

Straw disposal

Chopping followed by spreading, or baling and removal of oilseed rape straw, is beneficial in situations where leatherjackets (*T. oleracea*) have emerged into oilseed rape and laid their eggs into the standing straw, with the potential to damage the subsequent cereal crop (ADAS Report, 2010). Predicting the need for this can only be based on local knowledge as there is very little known about the pest status of *T.oleracea* in winter wheat (Blackshaw and Coll, 1999).

Drainage

Leatherjackets flourish in moist ground and so drainage has also been suggested as a control method, certainly in grassland (Maercks, 1941), and may be appropriate under some extreme circumstances on arable land (Blackshaw and Coll, 1999). Certainly targeted drainage and/or withholding irrigation until after egg laying have proved to be effective ways to impose desiccating conditions and thereby leatherjacket control in turf production in the US (Petersen et al., 2011). However, in one study comparing four drainage systems in the UK, differences in populations were detected but could not be related to soil moisture (Kell and Blackshaw, 1988). Furthermore, as Blackshaw and Coll (1999) point out, in some very wet areas regular flooding may actually contribute to leatherjacket population regulation in grassland and any drainage could make the problem worse. Interestingly, in peatland, which is a natural habitat of high conservation value, past drainage is associated with reduced populations of cranefly prey important in the diet of birds of conservation concern; blocking the drains increased populations of craneflies, although there was variability between years (Carroll et al., 2011).

6.5.6. Biological control

Leatherjackets are attacked by a wide range of natural enemies: predators, pathogens and parasitoids. Predatory beetles actively take eggs and young larvae; birds (including species of conservation concern in farmland) feed on large larvae and, as such, are good indicators of the presence of leatherjackets; parasitoids have been reported and there are numerous pathogens (virus, fungi, bacteria and nematodes) (Blackshaw and Moore, 2012; Blackshaw et al., 1996 and references therein; Chapman, 1994; AHDB Cereals & Oilseeds, 2003; Holland and Oakley, 2007). Some of these natural enemy species have the potential to be encouraged within biological and integrated control strategies but for many others little is known of their biology and ecology and so it is not known how their impact can be optimised (Blackshaw and Coll, 1999; Blackshaw et al., 1996, for a comprehensive list and associated references; AHDB Cereals & Oilseeds, 2003; Holland and Oakley, 2007).

Blackshaw and Kerry (2008) categorised soil pests into a number of groups based on their biological traits. Leatherjackets (and wireworms) fell into Group 1: these are species that increase in numbers within a field over years so that when a crop is planted there is a resident, potentially damaging, population already present. These species are also usually linked to grass rotations providing a stable ‘source’ habitat free of cultivation-induced mortality. In their study they suggested that, because of these traits, Group 1 species would be better targeted by augmentative biological control strategies and that conservation biological control approaches that would be more applicable to the more mobile species in other Groups (Blackshaw and Kerry, 2008). Augmentative biological control is indeed the approach that has received most attention in relation to the microbial control of leatherjackets by entomopathogenic nematodes, *Bacillus thuringiensis* subsp. *israelensis* (Bti) and *Beauveria bassiana*. Although the focus has been on leatherjacket control in turf and in organic systems, where they are the most significant pests, the principals are relevant to conventional arable systems (e.g. Ansari and Butt, 2012; Blackshaw, 2009; Ehlers et al., 2010; Oestergaard et al., 2006; Peck et al., 2010; Peters and Ehlers, 1994; Simard et al., 2006; Waalwijk et al., 1992).

Field trials of augmentative biological control of leatherjackets have mainly been done in turf grass. Good control (80% mortality, which is comparable to insecticides) of early instars of *T. paludosa* present in the autumn and winter has been achieved with both with Bti and the entomopathogenic nematode *Steinernema carpocapsae* but control dropped to below 40% against the later, more damaging instars present in spring; the success of *S. carpocapsae* was dependent on temperatures being >2C (Oestergaard et al., 2006). In the USA, Peck et al. (2010) reported good control with *B. bassiana* applied against early instars of *T. paludosa* in autumn. Granular formulations of Bti have also been effective in European trials (Ehlers et al., 2010). However, results from other trials have been more variable and it is clear that further refinement is required (Petersen et al., 2011).

For leatherjacket control to be most effective in relation to the spring cereal crops that are most at risk, it is necessary to treat autumn populations beforehand, but unfortunately population estimates (and risk) are most difficult to determine in the autumn (Blackshaw and Coll, 1999; Blackshaw and Kerry, 2008). Moreover, autumn treatment would constitute a paradigm shift from waiting for damage to be observed in spring before considering a treatment. The use of a biological control agent in autumn (when it is most effective) could prevent yield loss due to early instar leatherjackets in winter crops and establishment problems caused by larger instars in spring crops. It would also be more environmentally acceptable than an autumn insecticide application that could damage natural enemies and for which the need cannot currently be determined against a genuine threshold. There are still issues of cost associated with the augmentative release of biological control agents (Blackshaw and Kerry, 2008) but they could be very useful in targeted high-risk situations.

6.5.7. Plant breeding for resistance

To the best of our knowledge there have been no studies on resistance of cereal varieties to leatherjackets. The only published studies have been on differences in susceptibility between grass varieties or between grass and clover in leys (Dawson et al., 2002; Pesho et al., 1981; Petersen and Peck, 2013). For example, larvae were larger when feeding on *Trifolium repens* than on *Lolium perenne* (Dawson et al., 2002) and ryegrass supported fewer larvae than bentgrass and bluegrass (Pesho et al., 1981). In the most recent study, different grass genotypes differed in their tolerance to larvae and in their effect on the physiology of the larvae, and endophytes had sublethal effects on larval fitness (Petersen and Peck, 2013). Understanding the effects of host plants on larval survival and fitness could lead to the identification of traits useful not only in breeding for crop plant resistance but also in selection of grasses for field margins that support beneficial species but not pests such as leatherjackets.

6.5.8. Recommendations for research

1. Keep a watching brief on leatherjacket population densities and damage, especially in high-risk areas and given the potential for warmer and wetter winters under climate change.
2. Monitor resistance status of leatherjackets.
3. Establish appropriate treatment thresholds in winter cereals for (a) establishment damage by *T. oleracea* and (b) yield losses due to root damage, together with practical sampling methods to assess the larvae responsible.

4. Appropriate methods for management of leatherjackets in grass prior to cereals are required but should take into account the value of leatherjackets as food for farmland birds.
5. Practical and economic optimisation of microbials for environmentally acceptable autumn treatments deserve attention as they have the potential to provide a sustainable alternative to pesticide applications and are also relevant for organic production where leys continue to be required.
6. Studies on the biology, ecology and impact of natural enemies of leatherjackets have been neglected. Their potential contribution to conservation biological control of leatherjackets should be assessed.
7. Experimental testing of optimised management strategies predicted by simulation modelling would be valuable.
8. Screening of breeders' lines of cereals for resistance to soil pests should be encouraged.
9. New and safe insecticide actives are urgently needed.

6.6. Gout fly

Although widespread, the gout fly, *Chlorops pumiliones*, was traditionally only considered as an occasional pest in southern England, but it has increased in incidence and in geographic range as far north as Northumberland and Yorkshire, west to Worcestershire and east to Lincolnshire (Bryson et al., 2005; AHDB Cereals & Oilseeds, 2005d). There are a number of contributory factors but increasingly early sowing of winter cereals, milder autumns and winters and negative effects of autumn insecticide applications on parasitoid natural enemies are considered the most important (Bryson et al., 2005; Holland and Oakley, 2007). Gout fly has been reported as a pest in recent years but never in sufficient numbers to influence yield (ADAS Reports 2009, 2010, 2011). However, a local epidemic of gout fly in spring wheat in Suffolk in 2014, where over 50% of tillers were affected, is likely to have had a substantial effect on yield (Dewar per. comm).

6.6.1. Life cycle

There are two generations a year and the first generation of adults emerge during May and June. They are small flies (5 mm in length) with a distinctive black and yellow striped thorax. They lay their eggs, usually singly, on the upper surface of the unfurled leaves of cereal plants, often near the central shoot. The white eggs are 3-4 mm long, cigar shaped and hatch within 7-10 days. The larvae crawl down within the leaf sheath feeding on the sheath and the central shoot beneath the ear. Fully-grown larvae pupate on the plant in grooves on the stem, carved out by feeding activities. They emerge as the second generation of adults in August, prior to harvest. These adults shelter in woodland and hedgerows, again laying eggs on cereal plants (and also grasses such as couch grass); the eggs hatch into larvae that feed on the plant, overwintering there and beginning the cycle again in the spring. This life cycle description is summarised from a number of references: Bayer Pest Spotter, 2014; Bryson et al., 2005; DOW Webpage, 2014; AHDB Cereals & Oilseeds, 2003; Jones and Jones, 1984.

6.6.2. Damage

Wheat, barley, rye and triticale are all susceptible to attack, but oats and maize are immune (Bayer Pest Spotter, 2014; AHDB Cereals & Oilseeds, 2003). The type and degree of damage differs depending on the fly generation responsible for it. Autumn attacks result in swelling/ stunting of the affected shoots (dead hearts) with other shoots on the plant senescing and dying in the spring; in severe cases the whole plant may be lost but generally autumn damage can be compensated for by subsequent plant growth (Bryson et al., 2005; AHDB Cereals & Oilseeds, 2003). Spring attacks target the stem beneath the ear and, as the stem extends, feeding damage is evident as a distinctive groove. Spring attack is more damaging as restricted stem extension caused by larval feeding can prevent ear emergence from the sheath; grain size and number are reduced and yield can be depressed by over 30% (Bryson et al., 2005). Swollen shoots can be apparent in both autumn and spring attacks, though they are most evident in autumn attacks, and have a ‘gouty’ appearance, giving the fly its common name (DOW Webpage, 2014; Holland and Oakley, 2007). The earliest crop to emerge in a local area attracts most flies and sheltered fields near to woodland are more prone to attack (Bryson et al., 2005). In some high-risk areas farmers choose not to grow spring wheat at all (AHDB Cereals & Oilseeds, 2005).

6.6.3. Thresholds for control, monitoring and forecasting

The current threshold for control in winter crops is the presence of eggs on more than 50% of plants at GS12, although there is little practical evidence to support the usefulness of this threshold (Ellis et al., 2009b). Even if the threshold is exceeded, an autumn spray for gout fly is not recommended (see below for further discussion) unless it is necessary for BYDV vector control (Ellis et al., 2009b; AHDB Cereals & Oilseeds, 2003; AHDB Cereals & Oilseeds, 2005e). There is no known threshold for spring crops (Ellis et al., 2009b) although such a threshold could potentially be useful as spring crops are at greater risk of economic damage. Examining the crop for gout fly eggs is relatively quick and easy but determining the level of infestation does require the ability to recognise them.

6.6.4. Control with insecticides

Damage due to autumn infestations of gout fly generally have little effect on yield as the plant compensates for the damage, and so for yield benefits alone, insecticide treatments are rarely required (Ellis et al., 2009b). However, infested autumn crops can represent a source of gout fly for the more susceptible spring-sown crops, which is of greater concern. Autumn sprays are not recommended because the only foliar insecticides available for use in autumn are broad spectrum pyrethroids that would also kill the beneficial natural enemies of gout fly (Bryson et al., 2005; AHDB Cereals & Oilseeds, 2005d). Furthermore, they require critical timing, because larvae are protected once they are inside the stem, and do not result in yield benefits. The latter was demonstrated in a UK study comparing the relative efficacy of seed and foliar insecticide treatments in autumn sown crops. Regardless of product, foliar applications were only effective in reducing numbers of gout fly if used early, at GS 11-12 rather than 10 and 20 days after this, and even when applied in the correct window there was no concomitant increase in yield (Bryson et al., 2005). The issue of critical timing of sprays was mirrored in similar studies in Poland on spring-sown crops (Kaniuczak, 2008).

Bryson et al. (2005) showed that neonicotinoid seed treatments targeted at control of BYDV vectors, also controlled gout fly numbers and resulted in higher yields because the virus vectors were more effectively controlled than would have been possible with sprays; direct in-field effects on natural enemies were also minimised (Bryson et al., 2005). In the AHDB Cereals & Oilseeds Topic Sheet No 87 (2005e) developed from this study, farmers were therefore recommended to rely on seed treatments in autumn crops for incidental gout fly control, with subsequent protection of more susceptible spring crops, and only to use an additional autumn pyrethroid spray if necessary for BYDV vector control (e.g. if weather conditions meant vector transmission could continue for longer). The current EU ban on neonicotinoids does not apply to seed treatments on autumn-sown cereal crops and so gout fly control, and more importantly BYDV-vector control, is unlikely to be affected (AHDB Cereals & Oilseeds Handout, 2014; Nicholls, 2013), unless the ban is extended to all crops including those are not attractive to bees.

The potential of plant extracts for use in gout fly control is being tested in small-scale field trials. Wheat treated with extracts from the plant *Tasmannia stipitata*, containing the antifeedant polygodial, had significantly fewer larvae of gout fly than untreated wheat plants, suggesting potential for gout fly control; there was also a trend (though not significant) for reduced populations of OWBM (Bruce et al., 2002). RNA interference technology is also being evaluated for control of gout fly and other dipteran pests. This involves the development of novel fly-specific actives that, when ingested by fly larvae, selectively knock-down essential genes resulting in larval death; to the best of our knowledge, there are currently no published outputs from this project (DEFRA Project PS2136).

6.6.5. Biological control

Gout fly are attacked by two species of parasitoid wasps, the pteromalid *Stenomalina micans* and the braconid *Coelinus niger* (Bryson et al., 2005; Kearns, 1931) but, because so little work has been done on biological control, the number of natural enemies contributing to gout fly population regulation is likely to be under-reported. In recent UK studies the number of adult parasitoids captured in sticky traps placed in winter wheat were relatively low, although comparable to the number of gout flies also captured in the traps (a mean of 0.075, 0.07 and 0.065 individuals of gout fly, *S. micans* and *C. niger* per day, respectively). As parasitoid numbers increased, gout fly populations decreased (Bryson et al., 2003). In very early studies, before synthetic insecticides were widely available, there are records of 68% of the larval population being parasitised in summer, of which 45% was attributable to *S. micans*, suggesting the potential of parasitoids to control populations, if encouraged (Kearns, 1931).

6.6.6. Cultural and conservation biological control

Early-sown winter crops and late-sown spring crops are most at risk and so, in areas where damage is prevalent, coincidence of the most susceptible growth stages with the peak oviposition period can be avoided by sowing spring cereals as early as possible and before mid-April, and by sowing winter cereals as late as possible and after mid-September (AHDB Cereals & Oilseeds, 2005d). Furthermore, in sheltered fields near woodland, where risk is greatest, wheat and barley should only be sown after late September (AHDB Cereals & Oilseeds, 2005d). An early nitrogen application can encourage tillering to compensate for damage (AHDB Cereals & Oilseeds, 2005d).

Conserving and enhancing natural enemies through habitat manipulation has proved useful in cereal aphid control and could be applied to gout fly control with a greater understanding of the life cycles and resource requirements of both the parasitoids and the gout fly host. For example both gout fly and its parasitoids use pollen and nectar of plants in the family Apiaceae (Holland and Oakley, 2007) but there may be other plant species that only favour the parasitoids and could be incorporated into field margin mixes.

6.6.7. Plant breeding for resistance

The development of resistant cultivars has received very little attention. When a low-tillering (Napier) and a high-tillering (Consort) variety of winter wheat were compared in UK, more gout fly eggs were laid on Consort but ultimately the proportion of plants infested was similar (37 - 46%) and there were no effects of infestation on expected yield. While these two varieties were similar it is possible that other varieties may differ in their traits and one might expect that, while high-tillering varieties may be more attractive (more stems), they may also have a greater capacity for compensatory growth. Field trials in Poland have shown variability in susceptibility to gout fly amongst varieties of spring wheat and triticale. Overall, spring wheat was more susceptible than triticale (41.6% damage *vs*. 8.9% respectively) but a number of cultivars with lower susceptibility could be identified. This suggests that in spring-sown crops, where the greatest economic damage occurs, there may be opportunities for improving tolerance to gout fly through breeding (Kaniuczak, 2011). Transgenic wheat with resistance to powdery mildew had no cross-resistance to gout fly or to cereal leaf beetle (Von Burg, 2011).

6.6.8. Recommendations for research

1 Keep a watching brief on the incidence and severity of gout fly damage for any changing trend.

2 New and safe insecticide actives are needed with benign profiles in regard to natural enemies. This need will be accentuated should the restriction on use of neonicotinoids be extended to autumn-sown cereals.

3 There is a need to understand more about the natural enemies of gout fly and how they might be conserved and encouraged in the agro-ecosystem.

6.7. Frit fly

Frit fly, *Oscinella frit*, can attack all cereals and, of all the dipteran stem borers, it is the only one that attacks oats, which are very susceptible and a preferred host plant along with Italian ryegrass (Blake et al., 2003; Jones and Jones, 1984). It is largely considered as a pest of grassland and turf because grasses are the natural habitat and ryegrass leys can represent a reservoir for the species from where they can infest cereals (Bayer Pest Spotter, 2014; Holland and Oakley, 2007). Consequently, cereal crops are at greatest risk in areas where grassland predominates, at less risk in mixed arable and grassland areas and at least risk in fully arable areas (DOW Information Leaflet 2, 2014). However, in recent years it has rarely been reported as a pest in the UK (ADAS Report 2010).

6.7.1. Life cycle

There are three generations a year in most of England and Wales and two in the north and in Scotland), all of which occur on grasses, particularly ryegrass and in cereals in risk areas. Adults are small (2-3 mm long) black flies. The first generation emerges in April/ May and migrates to find oviposition sites. The size of the emerging adult population varies enormously between years (Lindblad and Sigvald, 1996; Lindblad and Solbreck, 1998). First generation adults lay their cream-coloured eggs in small groups at the base of shoots of young late-sown spring cereal plants and grasses, often on the underside of the first leaf sheath. Cereals at GS 11-12 (one and two-leaves unfurled) are most susceptible. Susceptibility decreases at GS13 (unless populations are high) and seedlings become largely resistant by the time the seedling reaches the four-leaf stage (oats, wheat, barley) or the five to six-leaf stage (sweetcorn and maize). Egg-laying does not occur below daily maximum temperatures of 15°C and is not influenced by sunshine and wind conditions. Larvae bore into the central stem where they feed and ultimately pupate at the base. The larvae are white, reaching 5-6mm in length and the pupae are dark or reddish brown. The second generation of adults emerge in July and this generation lay their eggs in the spikelets of the panicle of the developing cereal or grass; the second generation of larvae hatch from these eggs and feed on and pupate inside the grain. Adults of the third generation emerge from the grain, sometimes after harvest, and lay their eggs on the undersides of leaf sheaths at the base of young, early-sown winter crops, volunteer cereals, or grasses, particularly ryegrass. As in the first generation, hatching third generation larvae bore inside the central shoot; they feed throughout the winter at the base of the shoot and ultimately pupate there (Feb-March) to emerge as adults in May. Larvae can move from tiller to tiller and between plants across the soil if necessary. This life cycle is summarised from a number of references (Bayer Pest Spotter, 2014; DOW Webpage, 2014; El-Wakeil and Volkman, 2011; AHDB Cereals & Oilseeds, 2003; Jones and Jones, 1984; Lindblad and Sigvald, 1999; Plantwise Technical Factsheet, 2014).

6.7.2. Damage

Here we focus on damage to cereals and not to grass leys and turf. In the UK, late-sown spring oats and winter wheat following a ryegrass ley are considered the crops most at risk from the first and third generations of frit fly, respectively. Late-sown spring oats are a highly attractive crop that is at the susceptible growth stage during peak oviposition of the first generation, whereas winter wheat following a ley is faced with a reservoir of frit fly from the previous crop (AHDB Cereals & Oilseeds, 2003). Crops with a high burden of grass weeds are also at risk as frit fly may preferentially lay eggs on the grass, but larvae can then move to the cereals. Frit fly populations build up in ryegrass leys and reach a peak at the end of the second year when leys are often ploughed out (parasitoids appear to suppress populations in older leys). For this reason, winter wheat drilled into the same land where a two-year-old ley has just been ploughed out is considered at particular risk of heavy attack because of the large populations of frit fly larvae searching for new host plants as the ley dies (Blake et al., 2003).

Frit fly stem mining damage produces typical ‘dead heart’ symptoms with a yellow central leaf that can be easily pulled away from the surrounding green leaves and can be severe (Bayer Pest Spotter, 2014; AHDB Cereals & Oilseeds, 2003). Larvae can move between tillers increasing the level of damage, particularly in small plants. If attacks are very severe then the entire crop may need to be re-drilled (Bayer Pest Spotter, 2014). The appearance of the damage is similar to that caused by other dipteran stem borers (wheat bulb fly, gout fly, yellow cereal fly) and so dissection would be necessary to categorically identify the species responsible (Jones and Jones, 1984). Third generation flies that emerge from harvested grain can be a temporary nuisance in grain stores (AHDB Cereals & Oilseeds, 2003). Surviving plants produce smaller panicles, mature later and have reduced yield (Lindblad and Sigvald, 1999).

6.7.3. Thresholds for control, monitoring and forecasting

In the UK, the widely accepted threshold for treatment in cereals is 10% of shoots damaged per m^2 at the 1-2 leaf stage, above which a treatment is required to ensure the crop establishes (AHDB 2014c). A treatment at this stage would not save the damaged plants but should protect against further damage. This threshold was not, however, mentioned in the 2003 AHDB Cereals & Oilseeds Guidelines or in the recent review on thresholds by Ellis et al. (2009b) and its origins are unclear. As with other cereal stem borers, it is likely that frit fly is incidentally controlled in winter wheat (though not in spring oats) by neonicotinoid seed treatments for BYDV vector control. The likelihood of serious damage is also very closely related to: cropping in the wider locality (presence of grassland reservoirs); the previous crop (especially if a ley) and the interval between its ploughing-up and the drilling of the current crop; the interaction between weather and variety (which affects the synchrony of frit fly emergence with the susceptible stage of the crop) (Blake et al., 2003; El-Wakeil and Volkman, 2011; AHDB Cereals & Oilseeds, 2003). Most of these influences are susceptible to cultural management.

Some organizations offer a trapping service that monitors the emergence of frit flies from grassland. This gives an indication of `unseasonable` frit fly activity in high-risk areas based on comparisons with previous seasons, and thereby the potential risk of crop damage (Bayer Pest Spotter, 2014). Significant research effort in Sweden has been directed to developing methods to predict spring emergence based on preceding population size and weather data to determine how best to protect valuable spring oat fodder crops. Using more than ten years of suction trap data and meteorological data they were able to determine that the spring population size could not be explained by previous years catch sizes but was best explained by weather conditions in the previous year; spring migration from grassland into oats also finished earlier if the preceding autumn had been warm (Lindblad, 2001; Lindblad and Solbreck, 1998). The arrival of spring migrations could be predicted from spring temperatures using a day-degree model (Lindblad and Sigvald, 1996). Such predictions may be feasible in the UK although our climate and cropping systems are different. With the appropriate biological information, modelling tools have potential to estimate the timing of pest risk to crops at a field scale and could be incorporated into web-based decision support systems such as proPlant (Johnen and von Richthofen, 2013). Studies in northern England have already determined the day-degrees above 5°C required for first and 50% emergence of first generation frit flies (Umuru et al., 1990).

6.7.4. Control with insecticides

Neonicotinoid seed-treatments of autumn sown crops targeted at BYDV vector control also provide efficient incidental control of frit fly in autumn sown crops (Bayer Pest Spotter, 2014). Recent studies in Poland confirmed that neonicotinoid-treated seed provided protection against frit fly damage in maize (Beres, 2011). As the ban on neonicotinoids does not apply to seed dressings of autumn-sown cereals (AHDB Cereals & Oilseeds Handout, 2014; Nicholls, 2013) this incidental control will continue. Contact insecticides such as chlorpyrifos and pyrethroids can also be effective and increase yield, but should only be used at the 1-2 leaf stage and if the threshold has been exceeded (Bayer Pest Spotter, 2014; Clements et al., 1990; DOW Leaflet 2, 2014; El-Wakeil et al., 2009; French et al., 1988; AHDB Cereals & Oilseeds, 2003; AHDB 2014c; Larsson, 1984). However, chlorpyrifos has now been withdrawn for use in arable agriculture in the UK, and so this option is not available. To our knowledge, there are no reports of insecticide resistance in frit fly.

6.7.5. Cultural control

Ryegrass is very attractive to frit fly and so its use in tracks and field margins should be avoided on arable farms as it could act as a reservoir (Holland and Oakley, 2007). Interestingly, in Sweden, while ryegrass is still a good host, more frit flies are found in permanent grassland than in ryegrass leys (Lindblad, 1999). Early sowing of spring oats is advised to ensure the crop has reached the resistant GS13 or beyond by mid-May when egg-laying generally begins (Blake et al., 2003). Early sowing of autumn crops can also reduce damage by frit fly. In a Bulgarian study on triticale, late September and early October sowings had fewer frit fly than late October sowings (Krusteva and Karadjova, 2011). Early ploughing after a ley and lengthening the time between ploughing and drilling helps to ensure that any larvae in the soil are likely to be dead before the new crop reaches a susceptible stage (Blake et al., 2003). Recommendations on the period of time between ploughing-out a ley and drilling a cereal are 5, 6 and 10 weeks depending on the source of the recommendation but one must assume that, in the absence of volunteers, the longer the time, the greater chance that all larvae will be dead (Bayer Pest Spotter, 2014; DOW Leaflet 2; AHDB Cereals & Oilseeds, 2003; AHDB, 2014c). Clements et al. (1990) suggested that a pre-ploughing glyphosate application was beneficial in reducing frit fly numbers by quickly destroying the remains of the earlier sward.

6.7.6. Biological control

Numerous parasitoids attacking frit fly have been recorded (Holland and Oakley, 2007) but the predominant ones in both cereals and grassland are *Rhoptomeris heptoma*, *Haticoptera circulus* and *Trichomalus nanus*; additionally, *Chasmodas apterus* is found in grassland but not in cereals (Lindblad, 1997, 1999; Nordlander, 1978 a,b; Umuru, 1993). These parasitoids lay their eggs onto or into the larvae of the frit fly, paralysing them immediately before feeding on them or killing them when they reach the pupal stage. Parasitism has been reported to reach high levels in the first generation (40-50%) but the second generation largely escapes (Nordlander, 1978 a,b). Parasitism rates in grassland varied greatly between years in UK (3.9 – 56.4%; Umuru, 1993) but rates were more consistent between years in Sweden where the greatest variation was between ryegrass swards (37%) and pastures (14%) (Lindblad,1999).

Rain can dislodge frit fly eggs onto the ground where carabid beetles, such as *Bembidion lampros* and *Trechis quadristriatus* have been reported to feed on them (Nordlander, 1978b). All stages of frit fly are likely to be prey to a number of generalist predators (Holland and Oakley, 2007).

In a recent study by El-Wakeil and Volkmar (2013) the efficacy against frit fly of commercially available entomopathogenic nematodes and the pyrethroid lambda-cyhalothrin were compared in field plots. While the pyrethroid performed better overall, the use of nematodes also resulted in significant reductions in frit fly larvae and significant increases in yield compared to controls. These results are very promising, although the economics of using nematodes in broad-acre crops will need to be considered.

6.7.7. Plant breeding for resistance

It is known that there is variability amongst varieties in susceptibility to frit fly. Some varieties are resistant because they grow faster, reducing the likelihood of the susceptible growth stage coinciding with fly activity (El-Wakeil and Volkmar, 2011; El-Wakeil et al., 2009; Jonasson, 1978). However, no varieties, including spring oat varieties, are specifically identified as resistant to frit fly in the AHDB Recommended List (2016) and no rigorous breeding programme has been undertaken.

6.7.8. Recommendations for research

1. Keep a watching brief on the incidence and severity of frit fly damage for any changing trend.
2. Consideration should be given to validating the currently accepted control threshold.
3. Develop modelling tools to estimate the timing of pest risk.
4. Routine screening of breeders' lines for pest as well as for disease resistance should be encouraged.
5. Assess the risk of insecticide resistance using the outputs of AHDB Cereals & Oilseeds project RD-2012-3780 'Combating insecticide resistance in major UK pests' when available.
6. There is a lack of knowledge about the relationships between crop and grassland populations of natural enemies of frit fly and how they might be conserved and encouraged.
7. New and safe insecticide actives are needed with benign profiles in regard to natural enemies. This need will be accentuated should the restriction on use of neonicotinoids be extended to autumn-sown cereals.

6.8. Cereal leaf beetle

Although widely seen in cereal crops, particularly oats, the cereal leaf beetle, *Oulema melanopus*, rarely causes economic damage in the UK (Bayer Pest Spotter, 2014). Their presence in crops has been reported in recent years but in insufficient numbers to require specific treatment and with no documented effect on yield (ADAS Reports, 2009, 2010, 2011). In Eastern Europe and the Balkans, outbreaks do occur in some years and can result in high levels of damage (Kaniuczak, 2013; Kher et al., 2011, and references therein; Tanaskovic et al., 2012). In the USA and Canada the cereal leaf beetle is an invasive species and is a much more significant pest; consequently there has been a greater research focus on this pest and its control in North America than in the UK (e.g. Dosdall et al., 2011; Kher et al., 2011; LeSage et al., 2007; Philips et al., 2011).

6.8.1. Life cycle

Adults are elongate chrysomelid beetles, 4 – 5 mm in length and striking in colour, with black head, red thorax, red/ orange legs and metallic blue wing cases. Cereal leaf beetles are univoltine and adults emerge from overwintering sites (often leaf litter in woodland areas) from April onwards, when temperatures exceed 14 °C. They feed on the leaves of cereal crops before mating and egg-laying begins in May. Eggs are cylindrical, 1 mm in length and yellow in colour although they darken as they age; they are covered in a glutinous secretion that hardens on contact with the air and are laid singly or in groups of two or three (100 - 400 per female) on the upper surfaces of cereal leaves near to the midrib. The larvae hatch from eggs within 5 -14 days depending on temperature. Larvae are ‘slug-like’ in appearance with yellow bodies, brown heads and three pairs of thoracic legs; however, they are camouflaged by a covering of mucous and excreta giving them a black, shiny appearance. Larvae pass through four instars over a period of approximately three weeks, depending on temperature, reaching a maximum length of 4 - 6 mm. Mature larvae then fall from the plant and burrow into the soil to a depth of 5 - 8 cm and pupate. Pupae are formed within a transparent membrane and are initially yellow but rapidly darken to the same colour as the adults. New adults emerge within a month in late summer, depending on temperature, and feed on grasses prior to overwintering. This life cycle is summarised from a number of references (Bayer Pest Spotter, 2014; Jones and Jones, 1973; Philips et al., 2011; USDA – APHIS Pest Assessment, 2003)

6.8.2. Damage

Both adults and larvae feed on leaves, thereby damaging them. Adults tend to feed between the veins of the leaf and entirely perforate the leaf, leaving conspicuous slits. Larvae do not fully perforate the leaf, feeding on the upper surface only. In the USA, adult feeding rarely has any effect on yield but larval feeding does because long strips of the parenchyma tissue are removed, decreasing the plant’s ability to photosynthesise; in very heavy infestations the crop appears ‘frosted’ (Philips et al., 2011). Yield losses in the USA vary depending on infestation level, crop type and region but are typically 10 - 20% and can be as high as 40% which is often attributed to unnecessary or poorly-timed applications of insecticides that disrupt natural enemies (Buntin et al., 2004; Herbert and Van Duyn, 2009; Philips et al., 2011). There are reports that cereal leaf beetle transmits cocksfoot mottle and phloeum mottle viruses in the UK (Jones and Jones, 1984).

6.8.3. Thresholds for control, monitoring and forecasting

To the best of our knowledge there are no current UK thresholds for control (Ellis et al., 2009b). In the USA, treatment thresholds vary depending on state and region but are being promoted as part of IPM strategies that enhance biological control and reduce prophylactic sprays (Philips et al., 2011). For example, for Virginia and North Carolina, the treatment threshold is 25 eggs and larvae per 100 tillers based on scouting, particularly in field centres, the favoured location of the beetle which are patchily distributed (Herbert and Van Duyn, 2009; Reay-Jones, 2012). To ensure that any necessary spray is effective, the proportion of larvae in the population sample counted should be more than 50% (i.e. <50% eggs) and they should be small larvae rather than large larvae – if this is the case then a single spray is all that is required because the beetle is univoltine. Philips et al. (2012) have used the fact that temperature drives egg and larval development to build day-degree models capable of predicting egg peaks (and therefore larval peaks) to within 3 days of the observed calendar date. Use of these models could significantly improve scouting efficiency and convince USA farmers that using thresholds within an IPM approach is a reliable and economically efficient alternative to prophylactic spraying that can also be economically efficient. Currently in the USA, IPM of cereal leaf beetle provides environmental benefits but, depending on region, not always economic advantages. Thus farmers are tempted to make prophylactic sprays (sometimes ineffective because of poor timing) that disrupt natural enemies (Reisig et al., 2012). The aggregation pheromone of the cereal leaf beetle has been identified and may have potential as a monitoring tool in the future as it attracts both sexes (Rao et al., 2003).

6.8.4. Control with insecticides

Treatment is not normally necessary in the UK and it is thought that natural enemies generally maintain populations at low levels, but if flag leaves are being badly grazed a suitable insecticide may be necessary. If the presence of cereal leaf beetle coincides with the more important pest, OWBM, then treatments for OWBM will also be effective against the cereal leaf beetle (Bayer Pest Spotter, 2014). Sprays of pyrethroids and organophosphates are more effective than seed treatments with neonicotinoids but can have negative effects on natural enemies (Coats et al., 1979; Kher et al., 2011; Tanaskovic et al., 2012; Tharp et al., 2000).

6.8.5. Cultural control

In the USA, farmers in some states are advised to avoid drilling autumn-sown crops too late, to use lower seed rates and to manage for thick-planted/ tillered wheat, although the supporting evidence for these approaches is contradictory (Herbert and Van Duyn, Kher et al., 2011; Philips et al., 2011). Mixed cropping of oats and barley in Poland lowered yield losses (Piesik and Piesik, 1998). Applications of nitrogen and potassium fertilizer in spring wheat can aid control by increasing plant vigour and reducing palatability to beetles (Dimitrijevic et al., 1999).

6.8.6. Biological control

Numerous parasitoids have been reported from the cereal leaf beetle in the UK and in Europe in general, including the larval parasitoid, *Tetrastichus julis*, and the egg parasitoid, *Anaphes flavipes*, and it is likely that generalist predators are also important; cereal leaf beetle populations are generally well regulated in the UK (Jones and Jones, 1973; Kher et al., 2011). These parasitoids were also mass produced in ‘field nurseries’ and released as part of classical biological control programmes in the USA and Canada; they have established widely and generally provide good control, maintaining populations below threshold levels (Dosdall et al., 2011; Evans et al., 2006; Kher et al., 2011; LeSage et al., 2007; Philips et al., 2011).

Tetrastichus julis is host specific, bivoltine and lays 4 - 6 eggs in each larva, preferring young larvae, and overwinters underground within the pupal cell of its host. It has been the most successful parasitoid released as it is highly synchronised with its host. However, warm spring temperatures in the USA (which are increasingly common) affect the phenology of the beetle and the parasitoid differently, resulting in increased asynchrony between their populations and reduced parasitism (Evans et al., 2013). In the USA, strategically timed sprays of sucrose did provide resources for *T. julis* and parasitism was increased substantially (Evans et al., 2010). Provision of floral resources through agri-environment schemes in the UK could provide similar resources. *Anaphes flavipes* has also established in the USA but is less successful due to its asynchrony with the peak egg-laying period of the beetle. It lays a maximum of eight eggs inside each beetle egg.

Recent laboratory and field studies in Slovenia have shown that entomopathogenic nematodes applied as foliar sprays were effective in controlling cereal leaf beetle and reduced yield losses, even at low application rates (Laznik et al., 2010, 2012).

6.8.7. Plant breeding for resistance

In the UK there have been no cereal breeding programmes targeted at resistance to cereal leaf beetle and there are no varieties listed in the AHDB Recommended List (2016) with specific resistance to the cereal leaf beetle. However, host plant resistance associated with leaf trichome density (antixenosis) has been found in wheat and studied extensively in USA, Canada and eastern Europe (Kher et al., 2011 and references therein) and new varieties continue to be identified and evaluated (e.g. Hoffman and Rao, 2011; Konyspaevna, 2012; Micu et al., 2013; Rouag et al., 2012). Varieties with dense trichomes on their leaves deter feeding and/ or oviposition (Kher et al., 2011) but, unfortunately, are generally low yielding (Kostov, 2001). Nevertheless, they have a role to play in IPM (Kher et al., 2011). Recently, varieties have been selected where the mechanism of resistance is antibiosis and these are now available to be incorporated into breeding programmes with the potential to deliver high yielding varieties with resistance to cereal leaf beetle (Kher et al., 2013). Genetically modified maize expressing *Bacillus thuringiensis* cryotoxins also has resistance to cereal leaf beetle (Meissle et al., 2012). Recent studies on induced resistance, e.g. through the application of synthetic cis-jasmone, show the potential to induce repellence to both sexes of cereal leaf beetle in treated plants, but this requires more research before practical uptake (Delaney et al., 2013; Piesik et al., 2011, 2013).

6.8.8. Recommendations for research

1. A watching brief should be maintained on prevalence of cereal leaf beetle in UK. There is a risk that climate change could encourage asynchrony with natural enemies
2. More research to understand the biology and ecology of cereal leaf beetle natural enemies and how they can be promoted would help to future-proof against problems associated with climate change.

6.9. Saddle gall midge

Recent mini-epidemics of the saddle gall midge, *Haplodiplosis marginata* (syn. *H. equestris*) have been recorded in the last couple of years in central England, especially Buckinghamshire, Bedfordshire, Warwickshire, Worcestershire and Suffolk (Allison, 2010; Case, 2011; http://farmingforum.co.uk/forums/showthread.php?t=35126; http://www.syngenta-crop.co.uk/sm/blogview.aspx?blogid=25&groupid=11). This pest is very sporadic in the UK. Previous epidemics were reported in 1968 and 1969 (Golightly and Woodville, 1974; Woodville, 1968, 1970, 1973) but since then saddle gall midge has remained below economically damaging levels until recently. The recent epidemics have raised its profile once again, stimulating renewed interest in its ecology and methods of control. Because of its sporadic nature, few ecological studies have been conducted and, of those, most have been done in continental Europe (e.g. Censier et al., 2012, 2015). This review draws heavily on recent reviews by Dewar (2012) and Rowley et al., (2016).

6.9.1. Description

As its name suggests, the saddle gall midge is a fly. It belongs to the same family (Cecidomyiidae) as the orange wheat blossom midge and is not unlike it in appearance, females ranging in size from 2 to 5.5 mm and being larger than males. Both are dark reddish in colour. The eggs are blood red and the larvae are initially whitish green but turn orangy-red as they grow larger

6.9.2. Life cycle

The adults emerge from their pupation sites in the soil from late May onwards (Gratwick, 1992; Skuhravy et al., 1983) although, if spring weather is unusually warm, it can appear as early as late April, as was reported in 2011 (Censier et al., 2015). Males tend to emerge first, followed 3-5 days later by females; the latter predominate towards the end of the migration period (Skuhravy et al., 1983). Emergence is influenced by temperature and moisture conditions, with warmer temperatures stimulating earlier migration and dry conditions prohibiting it. After mating, females lay their eggs in a long thin raft on the upper or lower surfaces of cereal or grass leaves when plants are at the stem extension stage (GS 31-39; Zadoks et al., 1974). Each female has about 100 eggs in her ovariole, (range 14-250 eggs, depending on her size). The eggs hatch within 1-2 weeks and the young larvae move down the leaf to feed on the stem under the protection of the leaf sheath.

The larvae achieve full size by mid-July, when they fall to the ground in search of shelter in the soil, sometimes reaching densities as high as 6,400-30000 /m^2 (Popov et al., 1998; Censier et al., 2015). They spend the rest of the year, and overwinter, as larvae in diapause in small mud cells in the soil. Thus soil types that encourage cell formation (e.g. with some clay content) are preferred. The larvae pupate in the following spring and emerge again as adults in May. If weather conditions are dry and inhospitable (at least to the midge) some larvae will remain in diapause for another year, emerging when conditions may be more favourable. Even where weather is suitable, about 20% of larvae may still remain in the soil in diapause but this can rise to over 75% in dry conditions (Popov et al., 1998).

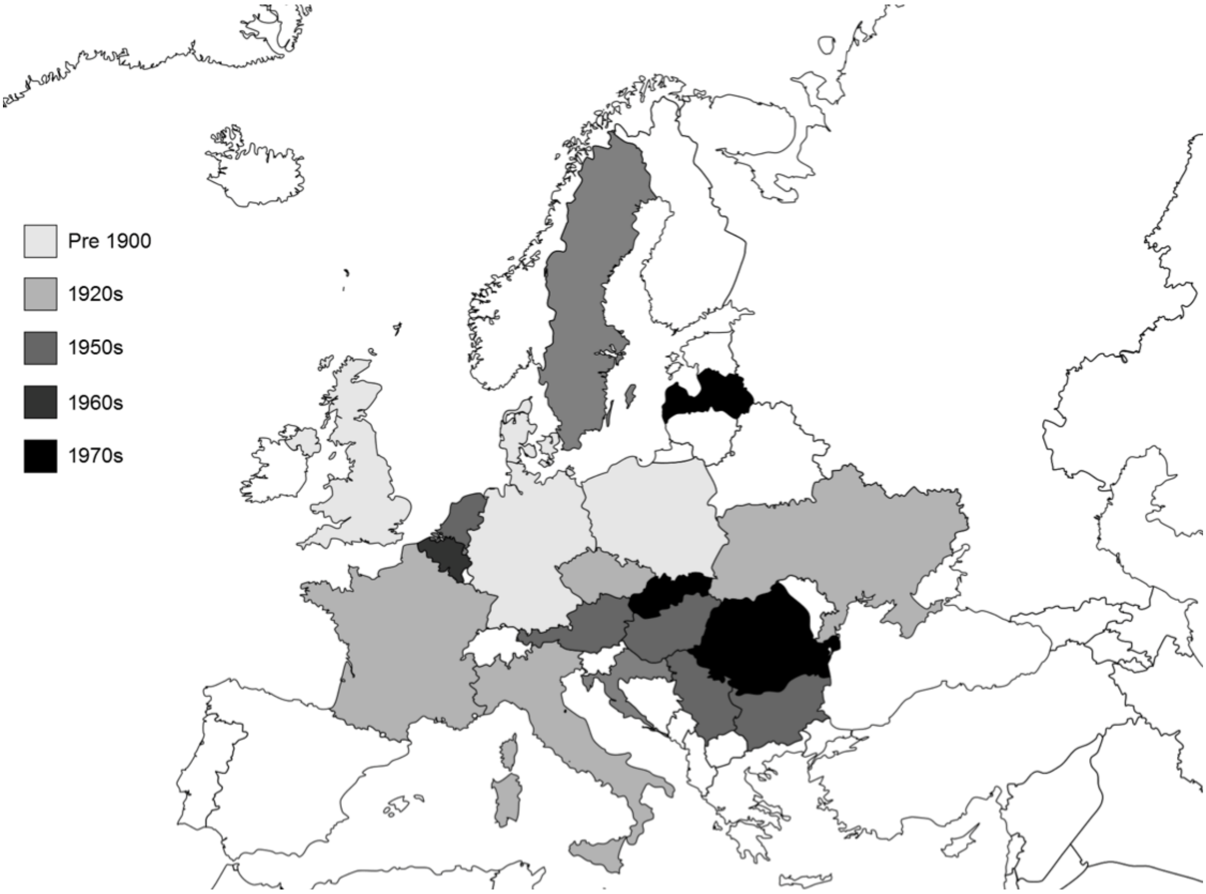


Figure. 5. Distribution of saddle gall midge in Europe. (from Rowley et al., 2016).

6.9.3. Distribution and abundance

The saddle gall midge was first recorded as a pest in 1692 and 1693 in north-east Bavaria, Germany (Weidner, 1985) but not until 1889 in England, in Lincolnshire (Golightly and Woodville, 1974). The saddle gall midge is widely distributed throughout central and northern Europe. Infestations were recorded in Bulgaria, Denmark, north-west Germany, Holland, Serbia, southern Sweden and Switzerland in the 1950s and 60s (reviewed in Woodville, 1968) but many other European countries have had some epidemics in later years: Austria, Belgium, Czechoslovakia (now the Czech Republic and Slovakia), northern France, Hungary, the Netherlands (although it is regarded as rare in the latter country; Daamen and Stol, 1993), Poland, Romania and the former Yugoslavia (reviewed by Skuhravy et al., 1983, Basedow, 1986; Popov et al., 1998; Rowley et al., 2016) (Fig. 5). More recently, outbreaks have been recorded in France and Belgium in 2010 (Anon, 2011; Censier et al., 2015)), Germany in 2004 (Mölck, 2006) and Greece in 2009-10 (Deligeorgidis et al., 2012). These outbreaks were attributed to the increasingly common practice of growing continuous cereals. On the other hand, damage tended to be little or absent during periods of low soil temperature (<15^{o}C) and dry weather, especially if such conditions occurred between mid-April and mid-May, inhibiting the emergence of the adults (Skuhravy et al., 1983; Popov et al., 1998). Interestingly, in the latter study, cultivation of soil to allow planting of maize in spring encouraged emergence of adults by dissipating the crust on the soil surface, even in dry weather.

6.9.4. Damage

The feeding activities of saddle gall midge larvae on the stem result in the formation of galls by the plant that resemble saddle-shaped depressions swollen at either end, hence the descriptive name given to the pest. These galls occur mainly on the top three internodes but may occur on lower internodes in backward crops. However, the galls themselves are not immediately visible as they are usually covered by the leaf sheath and the outwardly visible symptoms are subtle, comprising a slight discolouration and swelling of the sheath. If the galls are numerous, they result in a very much weakened stem that can break easily during heavy rain, especially if accompanied by high winds, causing lodging of the crop. Galls also result in broken stems which facilitate the entry and development of plant pathogens such as fungi and bacteria (De Clerq and D'Herde, 1972; Nijveldt and Hulshoff, 1968).

Host plant preferences

Before man's development of graminaceous crops, *H. marginata* must have evolved in association with wild grasses. Of 48 grass species examined by Schütte (1964), couch grass, *Agropyrens repens*, was the most heavily infested, followed by false barley, *Hordeum murinum* and darnel, *Lolium temulentum.* All other grass species examined, including the Phalaridae, Agrostidae and Aveneae either had no larvae at all, or were only slightly infested. Within the cultivated crops examined, wheat, *Triticum aestivum*, barley, *Hordeum vulgare,* and rye, *Secale cereale,* were all attacked equally but the Einkorn wheat, *Triticum monococcum*, and oats, *Avena sativa*, remained undamaged (Schütte, 1964; Nijveldt and Hulshoff 1968; Golightly, 1979; Skuhravy et al., 1983)

If a choice of host plants is available at the time of egg laying, the egg-laying behaviour of females has been shown to reflect the observations of Schütte (1964) with respect to the plant species attacked; however, in the absence of favoured hosts, females will lay eggs on many different species of grass and on some non-graminaceous species such as potato, *Solanum tuberosum,* directly on the soil (Skuhravy et al., 1983) and on sugar beet leaves (Alan Dewar per comm). This indicates that antixenosis, i.e. deterrence of egg-laying behaviour, is likely to play a role in host plant choice, an effect that can be overcome in the absence of choice. The suitability of oats seems to be variable. In contrast to Schütte's (1964) report that oats were not damaged, in a study by Woodville (1973), 24% of spring sown oats crops surveyed in Bedfordshire between 1967 and 1971 and 33% (one of three fields) of those surveyed in 1972 were infested. Perhaps differences in variety or the state of maturity of plants at the time of egg hatch determined whether oats were a suitable host plant or not. Despite these observations, the author concluded that oats were a less-favoured host plant than wheat or barley.

Yield effects

Damage to the stems causes a restriction in the nutrient flow to the grains in the ear, resulting in small, poorly developed or even blind ears (Golightly and Woodville, 1974), thus reducing yield. Feeding damage can also cause reductions in crop height (Rijsten, 1967; Popov et al., 1993), and allow secondary infections by fungi and bacteria that exacerbate yield losses. Yield can also be reduced by the lodging of damaged stems (Golightly and Woodville, 1974; Gratwick, 1992; Nijveldt and Hulshoff, 1968). Surprisingly, however, if the stems do not break, yield potential can sometimes still be achieved (Alan Dewar pers. comm.). Both kernel number and thousand-grain-weight (TGW) were significantly reduced by saddle gall midge larvae in studies in Romania (Popov et al., 1998), with consequent effects on yield. Losses of 0.6 t/ha were estimated from one study done in England in 1967 in which the damage was extensive (Woodville, 1968). Theoretical yield losses of 12.6% were calculated by Golightly and Woodville (1974), but much higher losses (circa 70%) were recorded in some fields in 2010 (Ellis et al., 2014). In recent studies by Censier et al. (2015) in Belgium, yield losses of up to 6% and 15% were recorded in 2012 and 2013, respectively; these figures are a more accurate reflection of the damage that saddle gall midges can do, and the losses were linearly related to the number of galls on the stem.

6.9.5. Forecasting and monitoring

Due to the sporadic nature of this insect pest, it is difficult to acquire sufficient data to construct meaningful models of its population dynamics. Even where epidemics occur more often, e.g. in Germany, attempts to do so have not been successful (Basedow, 1986). In 10 years of monitoring continuous winter wheat plots in Germany from 1975 to 1985, peaks of abundance were observed in 1976 and 1983 but in the other years numbers remained low despite good emergence conditions in some years. There was a good positive correlation between rainfall in July and the abundance of adults the following year in eight out of ten years (Basedow, 1986). High rainfall in July may have enabled mature larvae to penetrate the soil more easily to find overwintering sites. Some anecdotal reports also link abundance to levels of rainfall in April and May but with insufficient accuracy for modelling (Basedow, 1986).

Monitoring of adult activity during their emergence phase can give some forewarning of impending risk. Of the methods available, water traps were considered to be more efficient at trapping adults than sweep nets or sticky traps (Popov et al., 1998). However, the major influence of weather on the development of life stages makes forecasting difficult (Golightly and Woodville, 1974). Pheromone traps for this species have recently been developed and tested in Belgium (Censier et al., 2014; 2016). They demonstrated that sticky traps baited with 5 mg pheromone-loaded rubber dispensers and renewed every 6 weeks were suitable for accurate monitoring of male *H. marginata* flights, thereby allowing insecticides to be applied at the most effective times.

6.9.6. Thresholds for control

Few trials have established realistic thresholds for control. A study in Romania suggested that if there were 30 larvae/m^2 in the soil, treatments applied at the appropriate time would give economic returns (Popov et al., 1998). However, Golightly and Woodville (1974) and Gratwick (1992) cited populations of 5-12 million larvae /ha (>500 /m^2) were necessary before economic damage would be caused. Woodville (1973) cited a Danish threshold of 5 eggs per tiller as a level at which yield reduction would occur but found no significant relationships between field yields and percent infestation. A similar economic threshold of seven larvae per stem on wheat was suggested by Golightly and Woodville (1974), with lower levels suggested for barley due to its greater vulnerability to stem breaking. Significant damage was reported when 5-10 galls per stem were present in wheat in Germany (Schütte, 1983).

6.9.7. Chemical Control measures

Soil applied

Attempts to control saddle gall midge larvae in fields yet to be sown with spring crops such as maize or soya were not very effective. Applications of chlorpyrifos (as Lorsban at 5 kg/ha; Dow), lindane (as Lindatox 20 at 5 l/ha), dimethoate (as Sinoratox R 35 at 4 l/ha or Sinoratox 5G at 40 kg/ha) and various dusts, gave poor control (<53%) (Popov et al.,1998). This was probably due to the difficulty of getting sufficient penetration of the soil to reach the larvae.

Foliar applied

Foliar sprays have a much better chance of success if the application is timed to coincide with egg hatch and subsequent larval migration down the stem to the leaf sheath. Control of larvae once they are beneath the leaf sheath is very difficult (Gratwick, 1992). However, in the UK and most of Europe, none of the currently available insecticides approved for use in cereals, mention saddle gall midge on their labels. This is probably because of the sporadic nature of this pest, which make it difficult to predict when epidemics will occur and therefore also difficult to establish registration trials to gather evidence of efficacy. Some evidence of the effectiveness of control measures is available in the literature, although many of the chemicals mentioned (mostly organophosphate [OP] products) have long since been withdrawn from use due to their hazardous nature. Some examples are given below.

Fenitrothion (now banned) gave almost complete control of damage in wheat when applied in late June 1972, 11 days after the peak flight measured by trapping, compared with at least 24% damage in untreated plots (Woodville, 1973). DDT plus parathion and fenitrothion applied 8-14 days after peak midge emergence reduced the level of damage in four trials conducted in 1971 in the UK and a list of seven other OPs were tested as alternatives with promising results (Golightly and Woodville, 1974). Insecticides used in Czechoslovakia reduced the number of larvae and damage by more than 85% (Skuhravy, 1982).

The number and timing of applications of insecticides can be critical. In a trial in wheat in Romania in 1986, when conditions for saddle gall midge colonisation were very favourable (with 90% of tillers attacked), one application of alpha-cypermethrin (as Fastac at 0.1 l/ha; Cyanamid) on 5 May gave only 63% control and later single applications were even less effective. The best control was acheived using three applications approximately two weeks apart, but good control was also achieved with two sprays, especially when one was applied in early May (Popov et al., 1998). Experiments by the same authors with insecticides then currently available in Romania showed that deltamethrin, alphacypermethrin, lambda-cyhalothrin and esfenvalerate all gave excellent control, comparable to if not slightly better than that given by the older OPs, dimethoate, fenitrothion or malathion (Popov et al., 1998). No mention was made of the number of applications however. More recently, two or three well timed sprays of lambda-cyhalothrin, timed to target the flight peak and egg hatch, reduced the number of galls per stem from circa nine in untreated plots to less than one when these sprays were timed to protect each new node as it extended (Censier et al., 2012). This study and a later one also confirmed previous benefits of using pyrethroids, giving over 80% control with cypermethrin and tau-fluvalinate (Censier et al., 2015). Two applications of chlorpyrifos was also shown to give good control (95%) in wheat when applied at GS37 and 41 (Roberts et al., 2014), but this insecticide has now been withdrawn for use in cereals in the UK (HSE 2016).

6.9.8. Biological control

Consumption of larvae in the soil by soil-inhabiting predators, such as carabid and staphylinid beetles and spiders, may provide some control (Golightly and Woodville, 1974; Basedow, 1986), although no hard evidence has been reported for this. The larvae when feeding on plants can also be attacked by the parasitoid, *Platygaster equestris* (Spittler, 1969). As many as 26.5% of larvae collected from wheat in a long-term study in Germany were parasitised in 1976, but few parasitoids were found in other years (Basedow, 1986). One specimen of the species, *Chrysocharis seiuncta* was also identified. We are not aware of any studies on the ecology or encouragement of saddle gall midge’s natural enemies.

6.9.9. Cultural control

Given the difficulties of monitoring and forecasting epidemics of this pest, avoidance of the need for control is probably more effective.

Crop rotation

Anecdotal evidence from the UK suggested that crops in fields where continuous wheat or barley had been grown were more at risk than those grown in rotation with other crops. This was confirmed in Czech studies where first-year barley was reported to have 12% of tillers infested, but this rose sharply to 37 and 62% when successive barley crops were grown, and there were more galls per infested tiller (Skuhravy et al., 1983). Similar observations were made on successive crops of wheat. Very heavy infestations of cereals were recorded in Romania when the preceding crop was wheat (66%) or barley (44%) and infestation was much less following maize (11%), sunflower (11%), flax 8%), beans (7%) or peas (3%) (Popov et al., 1998), the lower infestations being due to immigration from neighbouring fields rather than emergence from the soil beneath the crop. The use of rotations that include no more than one or at most two successive cereal crops (at least of wheat and/or barley) may help keep numbers of midge larvae below damaging levels.

Sowing date

Studies in the UK in the 1970s showed that damage was greatest when cereal plants were at the stem extension stage (GS 31-39; Zadoks et al, 1974) at the time of egg laying and least when at or past the boot stage (GS45) (Golightly and Woodville, 1974). Skuhravy et al., (1983) reported that crops sown in September had less damage than those sown in October and attributed this to the growth stage of early sown plants being less favourable at the time when the larvae hatched. Thus, backward winter-sown or spring-sown cereals are usually at greatest risk (Gratwick, 1992). Surveys done in England from 1970-1972 showed that spring barley was the most heavily infested crop in two of those three years (Woodville, 1973). Early sowing of cereals in high risk areas may therefore help crops get past the susceptible stages before the adult midges emerge (Golightly and Woodville, 1974; Gratwick, 1992).

Oats as a break crop or trap crop

It has been suggested that it may be useful to grow winter-sown oats as a break crop and to act as a trap crop on which eggs are laid but damage is slight (Gratwick, 1992; Skuhravy et al, 1983).

Weed and margin management

Control of susceptible grass weeds in and around wheat and barley fields have been suggested as a means of reducing risk (Woodville, 1968). However, grasses in field margins are also likely to be of value in maintaining populations of natural enemies.

Tillage

Saddle gall midge larvae enter the soil in mid-July and overwinter there, and so, by analogy with the orange wheat blossom midge and the brassica pod midge (*q.v.*), they are likely to suffer from the effects of deep tillage. However, any advocacy of inversion ploughing for their management should be tempered by consideration of the environmental and cost benefits associated with the current trend to reduced tillage, the deleterious effects of ploughing on many generalist soil predators (Holland, 2004) and the likely destruction of parasitoids of the saddle gall midge which also overwinter in the soil.

Genetic resources

No evidence of resistance in existing varieties of wheat has been recorded. In a study on the effect of leaf hairiness on gall formation at an infested site in the Netherlands, all cultivars tested, hairy or otherwise, became heavily infested (Lange and Jochemsen, 1987). Likewise, Popov et al. (1998) found no sign of any resistance within wheat varieties in Romania, but barley, rye and triticale had less than a third of the number of larvae per stem than were supported on all the wheat varieties examined, even though the proportion of tillers attacked in each crop was similar. This and other evidence for host plant preferences amongst wild and cultivated graminaceous plants (see above) suggest that there is plenty of scope for the introgression of resistant characters into cereal varieties.

6.9.10. Recommendations for Research

The achievement of many research goals are likely to be made more difficult by the sporadic nature of this pest.

1. Keep a watching brief on the incidence and severity of saddle gall midge. Given the dependence of activity on weather conditions in April and May, its incidence could be influenced by climate change.
2. Weather-based models to forecast damage risk are urgently needed.
3. Reliable evidence-based control thresholds are needed.
4. Advice to farmers is needed on the appropriate insecticides for control, given the lack of on-label approval.
5. There is a need to understand more about natural enemies of the saddle gall midge and how they might be conserved and encouraged.
6. Routine screening of breeders’ lines for pest as well as for disease resistance should be encouraged.

6.10. Yellow cereal fly

The yellow cereal fly, *Opomyza florum*, can be a pest in wheat but it became a concern in UK farming only during the 1980s when winter crops began to be drilled earlier, favouring their proliferation (Holland and Oakley, 2007). They remain an occasional pest in UK but without any major impact on yield (e.g. ADAS Report, 2011). Most current research on yellow cereal fly is in Eastern Europe where their pest status seems to be greater (e.g. Krusteva et al., 2011, 2012).

6.10.1. Life cycle

As its name suggests, the yellow cereal fly is yellow-orange in colour with distinctive black marks on its transparent wings. It is a univoltine species and eggs are laid on the soil at the base of cereal plants in the autumn (October) where they overwinter (unlike most other opomyzids that overwinter as 3rd instar larvae). Eggs hatch in spring (February - March) and the larvae crawl up the tillers and tunnel their way down into the centre of the shoots where they feed. Larvae are yellowish white in colour and pass through three larval instars (reaching a maximum length of about 7 mm) before pupating in May. Sources vary as to whether pupation takes place within the tiller or in the soil. The first new generation adults begin to emerge in June, reaching peak numbers by July when they move away from the crops and into woodland. They are relatively long-lived remaining in woodland until late September or early October when they mate and return to crops to lay their eggs and start the cycle again. This life cycle is summarised from a number of references (Bayer Pest Spotter, 2014; Drake, 1993; AHDB Cereals & Oilseeds, 2003; Vickerman, 1982).

6.10.2. Damage

Like WBF, gout fly and frit fly, yellow cereal fly causes 'dead heart' symptoms because the larvae enter through the top of the shoot thereby damaging it. However, unlike WBF, there is no characteristic entry hole. Young seedlings are most susceptible. Each larva damages only a single shoot and so economic impact is generally low; most plants can withstand a large number of larvae by producing compensating tillers (AHDB Cereals & Oilseeds, 2003). In the 1980s some varieties, such as Maris Freeman, actually overcompensated by producing a second tier of small, late secondary tillers but modern varieties do not do this and recover well (Holland and Oakley, 2007)

6.10.3. Thresholds for control, monitoring and forecasting

Currently there is no scientifically-established threshold for yellow cereal fly in the UK (AHDB Cereals & Oilseeds, 2003). Ellis et al. (2009b) report a threshold of 300 eggs/ m^2 for crops drilled before mid-October but that the origin of this threshold is unknown. Moreover, it is unclear how easy this threshold is to assess; the authors say that it is possible to dissect tillers though this would be time consuming (Ellis et al., 2009b). There has been little pressure to develop a more practical threshold as the fly is univoltine, plants recover well even when heavily infested, and numbers are generally controlled by autumn applications targeted at BYDV vector control. In Bulgaria where damage is more severe, Krusteva et al., (2011) found infestation levels were significantly correlated both with temperatures during the flight period and with adult numbers caught in sweep nets; they proposed to use these parameters to help predict spray requirements.

6.10.4. Control with insecticides

Treatment for BYDV vectors also controls yellow cereal fly and no treatments are recommended once the larvae have entered the shoot (AHDB Cereals & Oilseeds, 2003). These recommendations are the same as those for gout fly, reflecting similarities between the yellow cereal fly life cycle and the autumn generation of gout fly, but also its low pest status. As the current EU restriction on neonicotinoids does not apply to seed dressings of autumn-sown cereals (AHDB Cereals & Oilseeds Handout, 2014; Nicholls, 2013), there should be no effect on control of BYDV vectors and incidental control of yellow cereal fly.

6.10.5. Cultural control

Early sown winter crops are most at risk as they have the greatest overlap with the oviposition period of the fly (Krusteva et al., 2012; Vickerman, 1982). Avoiding early sowing is therefore advisable, especially in sheltered fields near woodland, as these are more vulnerable (AHDB Cereals & Oilseeds, 2003). In a recent study in Bulgaria, crops sown in late September and early October were generally more heavily infested than those sown in late October; November sowing sometimes avoided infestation altogether (Krusteva et al., 2012). In vulnerable situations higher seed rates to establish densities of at least 200 plants/ m^2 are recommended (AHDB Cereals & Oilseeds, 2003).

6.10.6. Biological control

There are reports of the ladybird *Coccinella septempunctata*, the ground beetle *Poecilus cupreus* and the soldier beetle *Cantharis fusca* feeding on pupae (Holland and Oakley, 2007) and of ground beetles feeding on eggs (AHDB Cereals & Oilseeds, 2003). This is unlikely to represent the entire guild of natural enemies and is likely to underestimate their potential to regulate yellow cereal fly populations.

6.10.7. Plant breeding for resistance

There are no reports of plant breeding for resistance to yellow cereal fly.

6.10.8. Recommendations for research

1. Keep a watching brief on the incidence and severity of yellow cereal fly damage for any changing trend.
2. There is a need to understand more about the natural enemies of the yellow cereal fly and how they might be conserved and encouraged. In particular there is a lack of information about parasitoids.
3. New and safe insecticide actives are needed with benign profiles in regard to natural enemies. This need will be accentuated should the restriction on use of neonicotinoids be extended to autumn-sown cereals.

7. Pesticide use in oilseed rape

Oilseed rape, *Brassica napus,* has become the 6th most important crop in Europe, with almost 9 m hectares under cultivation, mostly in France, Germany, Ukraine, Poland and the UK (FAOStat, 2010). It is second only to sunflowers for oilseed production. It has thus become a major crop in the last two decades and, as such, has attracted the attention of many pests, which are still mostly controlled by insecticides. The area grown in the UK reached a peak of over 700,00 ha in 2012 (AHDB, 2014), but has declined since then to 627,000 ha in 2015 (AHDB, 2015), and is predicted to decrease even further as prices fall, and as it becomes more difficult to grow due to the activities of pests such as the pollen beetle and the cabbage stem flea beetle that have developed resistance to insecticides (see section 8.3).

7.1. Insecticide seed treatments

In 2009/10 most oilseed rape in the UK (76%) was treated with one of three neonicotinoid-based seed treatments, thiamethoxam (with the fungicides fludioxinil + metalaxyl-M) (Cruiser OSR), imidacloprid plus beta-cyfluthrin (Chinook) or clothianidin plus beta-cyfluthrin (Modesto) (Table 6). The area treated with imidacloprid declined substantially to less than 1% by 2012 and even less in 2014, having been superceded by the other two products (Table 6).

In 2010, only imidacloprid plus betacyfluthrin (Chinook) was applied to linseed crops, of which 21,693 ha (50%) were treated; the rest were treated only with a fungicide (prochloraz). However, in 2012, 85 % of the census area was treated with imidacloprid + betacyfluthrin (Garthwaite et al., 2013), but this declined to just 224 ha (4%) in 2014 (Garthwaite et al., 2015).

Since December 2013, the use of all three of these neonicotinoid seed treatments in oilseeds, amongst other crops, has been rescinded by the European Commission (European Commission, 2013) due to their perceived potential harm to bees (Desneux et al., 2007; Krupke et al., 2012; Henry et al., 2012; Gill et al., 2012; reviewed by Goulson 2013; Rundlöf et al., 2015). Adverse effects on birds have also been attributed to use of imidacloprid (Hallmann et al, 2014). At present, the use of clothianidin, imidacloprid and thiamethoxam in the EU is prohibited on all oilseed, sunflower and maize crops and any cereal crop sown between January and June (Nicholls, 2013). Concerns about the safety of the neonicotinoids were expressed in reports by the European Food Safety Authority (EFSA, 2012, 2013). At the time of writing there are no seed treatments to replace these for control of oilseed rape pests, although seed treated with methiocarb (Mesurol) has been imported by Frontier Agriculture to provide some protection (Impey, 2014).

Table 6. List of seed treatments applied to oilseed rape in 2009/2010, 2011/2012 and 2013/14. (Garthwaite et al., 2011, 2013 and 2015).

Insecticide a.i.	Brand name	Area treated (ha)			% of treated area		
		2009-10	2011-12	2013-14	2009-10	2011-12	2013-14
Thiamethoxam	Cruiser OSR	243,116	301,168	311,897	37	51	51
Imidacloprid + betacyfluthrin	Chinook	139,986	4921	1680	21	1	<1
Clothianidin + beta-cyfluthrin	Modesto	119,521	193,692	203,960	18	33	33
(Prochloraz + thiram)	(fungicide only)	104343	89551	88,532	16	15	14
(Thiram)	(fungicide only)	52005	3425	6613	8	1	1

Insecticide sprays

In 2009-10, 2011-12 and 2013-14, 82% 87% and 83% of oilseed rape crops respectively were sprayed at least once with an insecticide; of those that were treated, sprays were applied on average 2.1, 2.6 and 2.3 times per crop respectively (Table 7a). The timing of these sprays was at two distinct periods of the year – in the autumn (October/November), and in the spring (March-May). About a third of insecticides were applied in the autumn in 2012, and roughly double that in the spring, the latter probably mostly to control pollen beetles (Garthwaite et al, 2013). The proportion treated in 2014 was more equivalent to 50:50 between autumn and spring based on anecdotal evidence.

Linseed generally received fewer sprays than oilseed rape, probably because it is a spring sown crop, and therefore is not subjected to attack by autumn pests. Nevertheless, increasing proportions of the crop were treated between 2010 and 2014, from 37% to 72% (Table 7b).

Pyrethroids were the dominant class of insecticides used against the pest complex of both oilseed rape and linseed crops. Cypermethrin was the most popular active used in oilseed rape in 2009/10 (32%) followed by lambda-cyhalothrin (27%), but these relative positions were reversed in the 2011/12 and 2013/14 seasons (Tables 7a). Tau-fluvalinate (14-15%), alpha-cypermethrin (12-8%) and zeta cypermethrin (7-9%) made up most of the remainder. The neonicotinoid, thiacloprid made its first appearance on the list (1%) in the 2012 survey, presumably following its approval for use against pollen beetles in the interim, but was not listed separately in the 2014 survey because it’s use was below the threshold hectarage. This also applied to acetamiprid and pymetrozine.

Table 7a. Area of oilseed rape (spray ha) treated with insecticides in 2009/10, 2011/12 and 2013/14 (Garthwaite et al., 2011, 2013 and 2015)

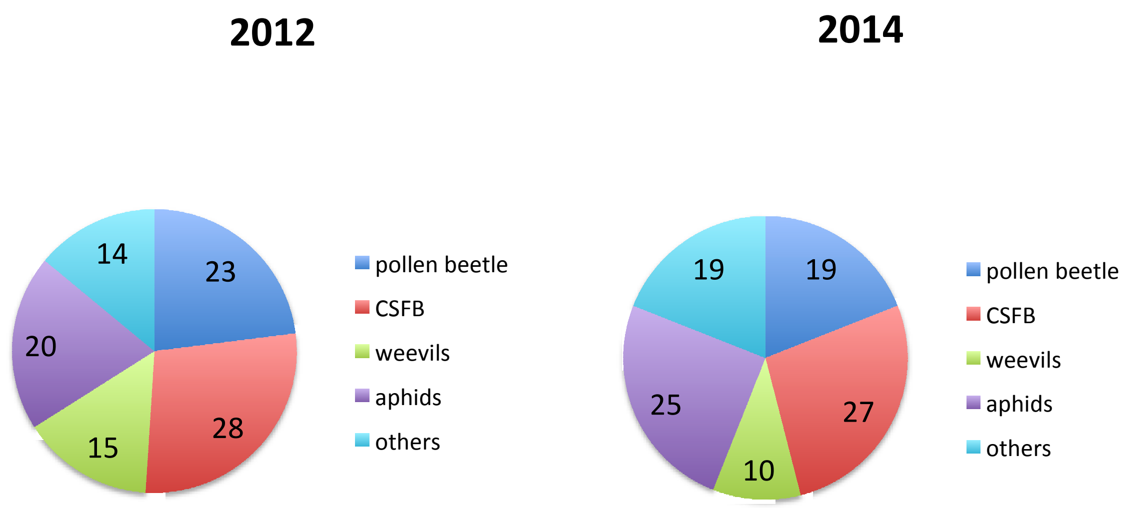
Insecticide	**Oilseed rape**			**% of treated area**		
	2009-10	**2011-12**	**2013-144**	**2009-10**	**2011-12**	**2013-144**
cypermethrin	350,276	488,519	383209	32	28	29
lambda-cyhalothrin	294,314	548,826	429703	27	32	33
tau-fluvalinate	154,232	267,816	262371	14	15	20
alpha-cypermethrin	127,771	139,596	101198	12	8	8
zeta-cypermethrin	74,244	162,809	86578	7	9	7
bifenthrin	55834	0	0	5	0	0
deltamethrin	12864	0	10956	1	0	1
pirimicarb	4533	12406	0	<1	<1	0
esfenvalerate	110	0	0	<1	0	0
thiacloprid	0	21605	-	0	1	<1
chlorpyrifos	0	0	1950	0	0	<1
others	5607	88535	40564	<1	5	3
Total area sprayed	1,079,787	1,730,112	1,316,529	100	100	100
Area grown (ha)	641,562	755,717	674580			
% area treated	81.7	86.9	83.1			
Actual area treated	524,156	656,718	560576			
Sprays/crop	1.7	2.3	2.0			
Sprays/treated crop	2.1	2.6	2.3			

Table 7b. Area of linseed (spray ha) treated with insecticides in 2010, 2012 and 2014 (Garthwaite et al., 2011, 2013 and 2015)

Insecticide	**linseed**			**% of treated area**		
	2010	**2012**	**2014**	**2010**	**2012**	**2014**
cypermethrin	8640	5,847	4258	45	28	23
lambda-cyhalothrin	2917	11,122	8303	15	52	44
tau-fluvalinate	0	3,318		0	16	
alpha-cypermethrin	460	526		2	2	
zeta-cypermethrin	4611	306	5953	24	1	32
bifenthrin	2444	0		13	0	
deltamethrin						
pirimicarb						
esfenvalerate						
thiacloprid						
chlorpyrifos	0	97	350	0	<1	2
others	0	0		<1	0	
Total area sprayed	19,073	21,217	18864	100	100	100
Area grown (ha)	43,838	27,953	15955			
% area treated	37.3	49.9	72.4			
Actual area treated	16,352	13,948	11551			
Sprays/crop	0.4	0.75	1.2			
Sprays/treated crop	1.2	1.5	1.6			

8. Target pests for insecticides in oilseed rape

The main target pests against which insecticides are applied in oilseed rape in the UK are cabbage stem flea beetles and aphids in the autumn at the seedling stage, and pollen beetles and seed weevils in mature crops before or during flowering (Fig 6). Other pests, including unspecified flea beetles, several weevils and brassica pod midge were not considered to be important target pests by UK farmers. Aphids carrying turnip yellows virus (TuYV) were relatively low on the list of priorities in 2010, but increased in importance by 2012 and 2014. In contrast, pollen beetles declined in importance. A good overview of the major pests attacking oilseed rape is available in Williams (2010).



Source: Pesticide Usage Surveys in Arable Crops: Garthwaite et al., 2013 and 2015

Figure 6. Insecticide use in arable crops in the UK in 2012 and 2014 (not including seed treatments): % of total area treated. Source: Defra Pesticide Usage Survey of Arable Crops 2012 and 2014; Garthwaite et al., 2013, 2015.

8.1. Pollen beetles

Pollen beetles, especially *Meligethes aeneus*, are considered to be major pests of oilseed rape at bud stage in spring across Europe (Williams, 2010). Other species of *Meligethes*, such as *M. viridescens* and *M. nigriscens* can be confused with *M. aeneus*, but tend to occur later in the year, *M. aeneus* being by far the most abundant species in early spring (Büchi and Roos-Humbel, 1991; Thieme et al, 2008; Toth et al., 2013).

8.1.1. Life cycle

Pollen beetles are univoltine. Adults overwinter in the soil, leaf litter and herbaceous vegetation around fields and woods (Büchi, 2002). The relative abundance of adults in any particular locality has been attributed to the relative altitude, litter thickness, soil moisture and the proximity to the previous year's oilseed rape fields (Rusch et al., 2012). After emerging from their overwintering sites, they feed on a wide range of spring-flowering plants from different families, until they attain sexual maturity (Ruther and Thiemann, 1997), whereupon they migrate to cruciferous plants, including Brassicaceae, to mate and lay their eggs (Williams and Free, 1978; Ekbom and Borg, 1996; Williams, 2010). Eggs are laid inside buds, preferably those that are 2-3 mm long (Nilsson, 1988; Borg, 1996), usually up to 2-3 eggs per bud (Scherney, 1953), although larger numbers up to ten per bud have been reported (Ekbom and Borg, 1996). After hatching, the larvae feed on developing anthers within the buds, moving into flowers, when they are open, to eat pollen. They moult through two instars (Osborne, 1964) before achieving maturity after about two weeks (Bromand, 1983), when they fall from the plants to pupate in the soil. New generation adults emerge in late July to early August and feed on a wide range of autumn flowering plants to build up their fat reserves before hibernation in woods, field margins, hedges etc. (Hiiesaar et al., 2011). Very few hibernate in open fields (Hokkanen, 1993). Mortality of beetles during hibernation can be high, especially in the colder northern European countries such as Sweden (85-98% (Hokkanen, 1993).

8.1.2. Monitoring and forecasting

Various trapping methods can be used to monitor migration of beetles into vulnerable crops. Pollen beetles are attracted to yellow water traps in preference to all other colours, and this attraction is enhanced when the yellow is fluorescent with high UV reflectance (Döring et al., 2012). Yellow sticky traps also attract beetles in large numbers, especially when accompanied by an attractant bait such as phenylacetaldehyde and indole (Cook et al., 2007b, 2013). These traps were available commercially in 2013 for the first time. Traps should be located upwind in a field to attract beetles migrating into the field against the prevailing wind (Williams et al., 2007). Numbers in traps do not necessarily correlate with numbers on plants (Nicholls and Cook, 2012; Cook et al., 2013) but they do give an indication that adults are on the move prior to examination of the plants themselves.

Assessment of numbers on plants within the crop should be done every couple of metres along a transect at least 30 m into the crop, beyond the headland, (AHDB Cereals & Oilseeds, 2013b; Cook et al., 2004) as beetles colonise from the edge inwards (Williams and Ferguson, 2010). The nationwide progress of pollen beetle migration into crops is forecasted using the ProPlant model

(Johnen et al., 2010), which predicts migrations based on local temperatures and other weather data (Cook et al., 2013). Following field testing over several years, this system was shown to model pollen beetle phenology reliably in the UK, helping to reduce monitoring time, and it is now available through the AHDB web site (http://cereals.ahdb.org.uk/crop-management/pest-management.aspx) on the Bayer Crop Science Pest Spotter web site (http://www.bayercropscience.co.uk/tools-and-services/agronomy-online-tools-and-services/pollen-beetle-predictor/), and is free to access. Growers in Germany who use ProPlant apply less insecticide than non-users (Johnen, and von Richthofen; Johnen et al, 2010), indicating the value of local monitoring to decision makers.

8.1.3. Damage

Adult pollen beetles cause the most important damage to oilseed rape at bud stage before flowers open. They bite into flower buds, damaging the reproductive parts and feeding on developing anthers, and they lay eggs into the buds. Damage is especially severe if the infestation begins at early bud stage (reviewed by Williams, 2010). Larvae that hatch before the flowers open contribute to the damage by consuming the developing anthers and pollen. Adult beetles can cause damage to up to nine buds each when there is no competition for feeding sites (Ellis and Berry, 2012). The consequence of beetle damage to a bud is a podless stalk after flowering has finished. If present in large enough numbers at the vulnerable pre-flowering stage, pollen beetles can cause serious damage to crops. In 2006, 30,000 hectares of oilseed rape crops were totally devastated with a further 200,000 ha seriously damaged in Northern Germany, estimated to be worth 22-25 m euros (EPPO, 2007, cited in Cook et al., 2013a). Up to 70% losses have been reported in spring-sown crops (Nilsson, 1987; Dewar et al., 2015). Where damage is lighter, plants can compensate by producing more flowers if conditions for growth are favourable (Tatchell, 1983). For example, in a semi-field scale study in the UK, removal of up to 60% of flowers by hand caused no significant yield loss (Williams and Free, 1979).

8.1.4. Thresholds for control

Until recently, UK thresholds for control of pollen beetles with insecticides varied considerably, ranging from 15 per plant for autumn-sown rape to three per plant for spring sown crops, and there were intermediate thresholds for backward crops or for those suffering from pigeon damage (Nicholls and Cook, 2012; Ellis and Berry, 2012). However, none of these thresholds were based on any published scientific studies and so they have recently been revised following extensive re-evaluation (Ellis and Berry, 2012; AHDB Cereals & Oilseeds, 2013b).

The new thresholds make no distinction between sowing date, variety, type (e.g. hybrid or conventional) or vigour of growth. They combine consideration of the number of pods that an adult beetle can damage (up to nine, as cited above) and the propensity of the crop to produce far more flowers than it needs to produce an optimum number of viable pods containing viable seeds (6-8000 per m²). Thus a crop with a high population of plants (e.g. >80 per m²) will produce far fewer excess flowers per plant than one that is growing at a sparse density (<20 plants/m²). In such a case, the smaller plants producing fewer flowering racemes can tolerate fewer beetles per plant than the larger plants producing multiple racemes, and thresholds can therefore vary from <5 to >30 per plant accordingly (Fig. 7). The thresholds for spring rape also vary according to plant population, but the relationship is steeper.

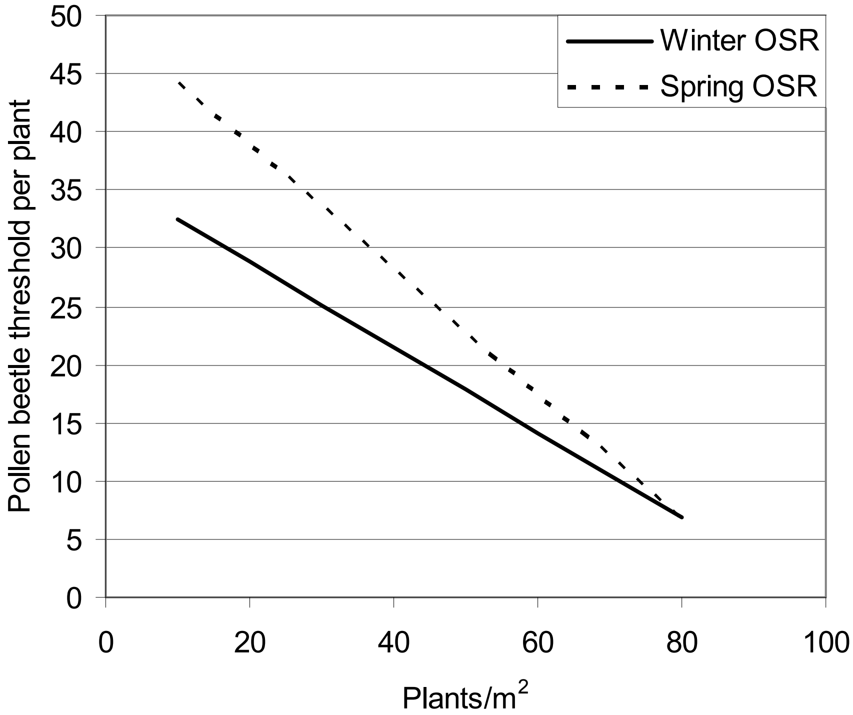


Figure 7. Suggested pollen beetle thresholds (Ellis and Berry, 2012).

8.1.5. Control measures

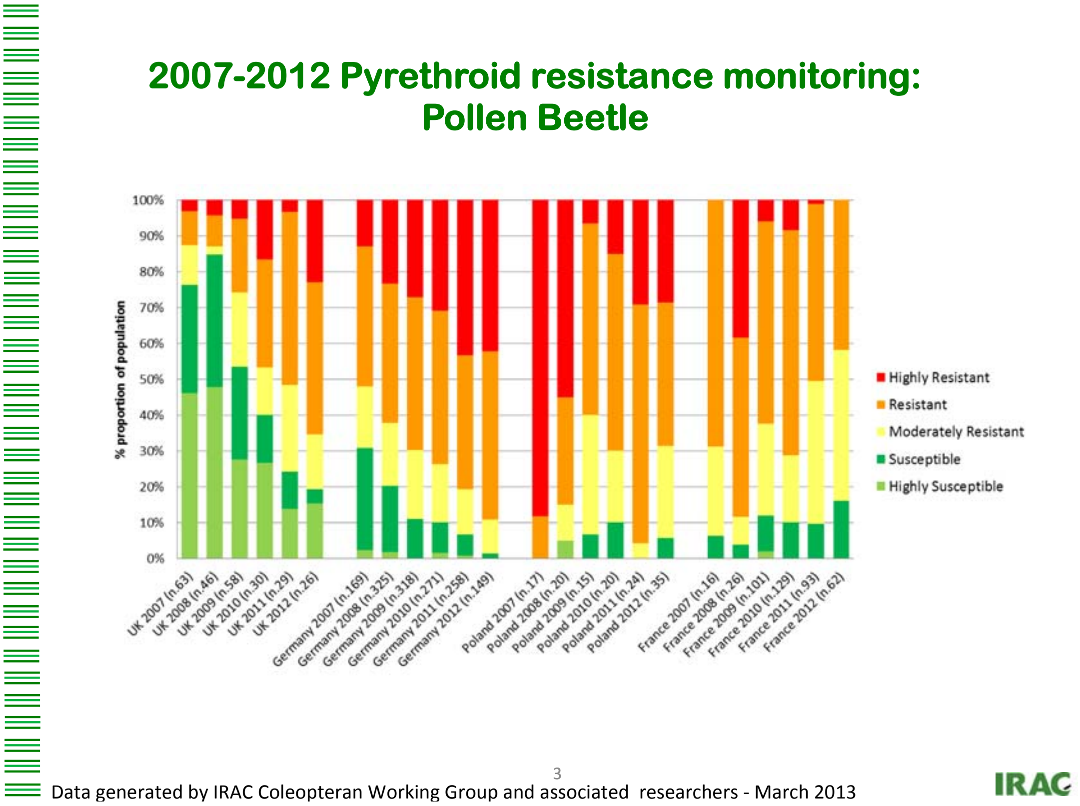
Pyrethroids have given good control of pollen beetles since they were first introduced in the 1980s, but are less effective now due to the evolution of resistance (Thieme et al., 2010). More recently, in many of the 52 trials conducted in 13 countries across Europe from 2007-2010, pymetrozine gave excellent control of pollen beetles for up to 7-9 days after application. Control by pymetrozine was at least equivalent to (occasionally better and seldom poorer than) the pyrethroid lambda-cyhalothin and the foliar neonicotinoid thiacloprid, especially when pyrethroid-resistant beetles were present. In some of those trials (six winter rape and three spring rape) the use of pymetrozine and thiacloprid also resulted in significantly increased grain yields compared to untreated plots (Tait et al., 2011). With the ever-increasing proportion of beetles becoming resistant to pyrethroids (see below), alternative insecticides are likely to replace them, although they will be more expensive. Best control in recent comparative experiments was given by pymetrozine, followed by indoxacarb, and latterly by the neonicotinoids, thiacloprid and acetamiprid (Dewar 2014b). There is some evidence that the efficacy of pyrethroids can be enhanced by the addition of a synergist at the time of application, which can overcome the resistance within the beetles, and allow the insectidies to exert their killing effect (Dewar et al., 2015).

8.1.6. Evolution of resistance to insecticides

Pyrethroids have been the mainstay of pollen beetle control for many years (Thieme et al., 2010), but their cheapness probably encouraged many growers to apply insecticides even when numbers were well below threshold levels. Evidence for this in the UK has been seen in surveys of pollen beetle numbers conducted by Fera each spring/summer and published in their Crop Monitor web site. Numbers rarely reached threshold levels even for spring rape, yet the proportion of crops sprayed was much higher than thresholds would have indicated (Ellis and Berry, 2012; Ellis et al., 2009; Garthwaite et al., 2009, 2011, 2013, 2015; Table 7).

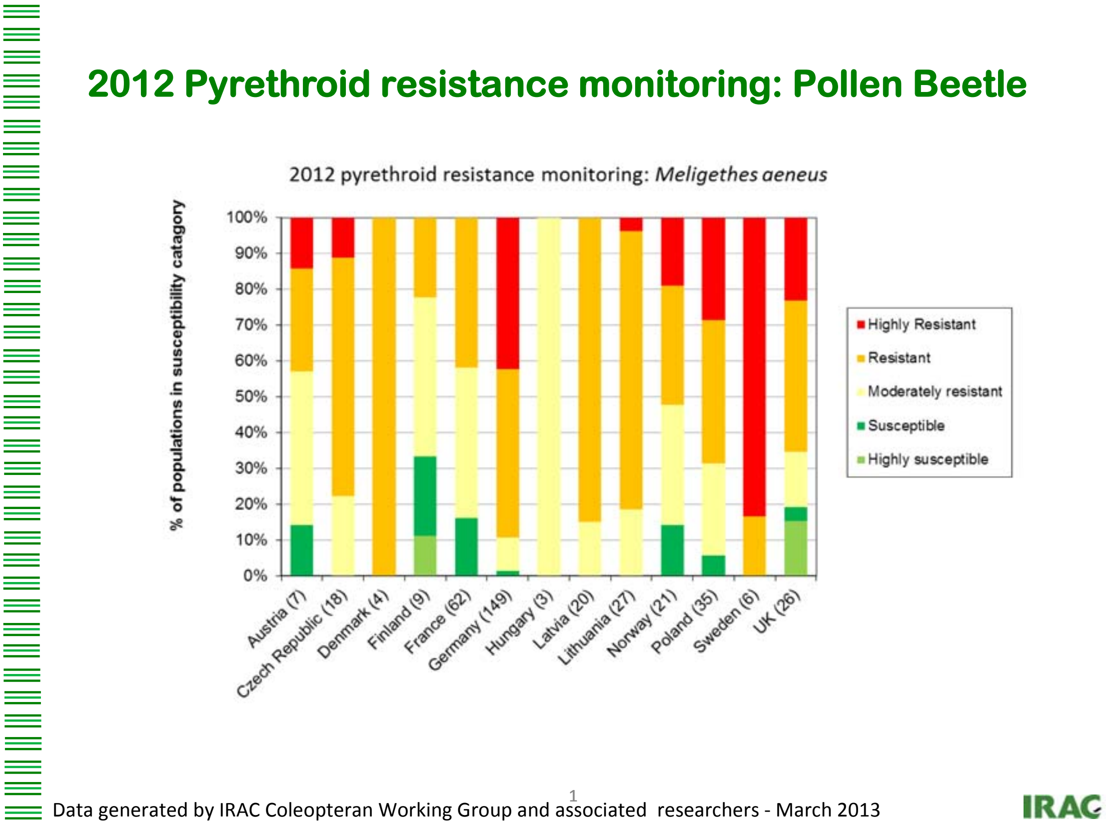
The consequence of the over-use of this class of chemicals has been the evolution of resistance to pyrethroids within pollen beetle populations, which was first recorded in Sweden in 2001 (Hansen, 2003) and is now widespread across Europe (Thieme et al., 2010; Philipou et al., 2011; Zimmer and Nauen, 2011; Heimbach and Muller, 2012; Tait et al., 2012; Slater et al., 2011; Zimmer at al 2014; IRAC, 2016; Figs. 8 and 9). The resistance factors that have been measured in bioassays range from 3.6 in Switzerland to 34 in Poland (Philippou et al., 2011).

In the UK, resistance was first recorded in Kent in 2006, but has since spread to the whole country (Thieme et al., 2010). The latest results from the Insecticide Resistance Action Committee (IRAC) suggest that more than 80% of beetles in the UK now have at least moderate resistance to pyrethroids (IRAC, 2016; Figs. 8 and 9).


2007-2012 Pyrethroid resistance monitoring: Pollen Beetle

Data generated by IRAC Coleopteran Working Group and associated researchers - March 2013

Figure. 8. Evolution of resistance to pyrethroids in pollen beetles in Europe 2007-2012 (from IRAC website, 2013).


2012 Pyrethroid resistance monitoring: Pollen Beetle

2012 pyrethroid resistance monitoring: *Meligethes aeneus*

Data generated by IRAC Coleopteran Working Group and associated researchers - March 2013

Figure. 9 Incidence of resistance in pollen beetles in Europe in 2012 (from IRAC website 2013)

In the majority of pollen beetles that are resistant to pyrethroids, the resistance is metabolic, mediated by an elevation of the levels of P450 monoxygenase enzymes (Wegorek et al., 2011; Zimmer and Nauen, 2011), although esterases were implicated in one case of resistance (Phiippou et al., 2011). The resistance mechanism(s) is/are especially effective against class II pyrethroids such as cypermethrin, lambda-cyhalothrin and deltamethrin, but are thought to be less effective against bifenthrin, ethofenprox, and tau-fluvalinate (Glattowski et al., 2008; reviewed in Heimbach and Muller, 2012). However, another resistance mechanism, target-site resistance found in beetles containing the L1014F mutation (termed kdr), was discovered in 2007 in samples collected from Denmark and Sweden following control failures with tau-fluvalinate (Nauen et al., 2012). This suggests that these latter pyrethroids have also been compromised, or will be in due course, despite the absence of cross-resistance (Zimmer and Nauen, 2011).

The resistance can be overcome (suppressed) by use of synergists such as piperonyl butoxide (PBO) or EN 16/5-1 when used in combination with pyrethroids such as alpha-cypermethrin (Philippou et al., 2011), lambda-cyhalothrin (Dewar et al., 2015) or tau-fluvalinate (Moores et al., 2012), but these can have adverse effects on bees when high doses are used (Johnson et al., 2006). Cross-resistance to other insecticides (e.g. thiacloprid), which have replaced pyrethroids where they were least effective (e.g. in Germany and Poland), has not yet been detected (Zimmer and Nauen, 2011), although a separate resistance mechanism to thiacloprid has been detected in Germany, and is being monitored in other European countries (IRAC, 2013)

Better risk assessment and the targeting of insecticide applications strictly according to need are essential tools in the effort to limit resistance problems. In 2013, AHDB commissioned a three-year project to validate an integrated pest management strategy for pollen beetle to minimise the development of insecticide resistance (AHDB, 2013). Another current project, funded jointly by Levy Boards and Defra CRD, uses a modelling approach to examine the effectiveness of different insecticide resistance management strategies for different insects and to develop resistance risk assessment criteria (Paveley, 2013).

8.1.7. Biological control

Given the parlous nature of long-term insecticidal control of these pests, it is important that all methods of control should be employed. Precious little attention is given to natural control measures by growers or their agronomists when recommending treatments, yet there is evidence that predators and parasitoids can provide useful control. In a study in Switzerland from 1997-1999 the level of larval parasitism ranged from 6-54% and the mortality of pollen beetle larvae caused by predators was 16-27%, much of this after the beetles had fallen from the plants to pupate in the soil (Büchi, 2002); while this may seem too late to interest growers it reduces the overwintering population and contributes to long-term control over years.

Parasitism of pollen beetles is most significant at the larval stage. In Europe, the larvae of *M. aeneus* are parasitised by at least nine species of endoparasitoids. Amongst these, *Phradis interstitialis*, *Phradis morionellus, Tersilochus heterocerus* and *Diospilus capito* (Hymenoptera, Ichneumonoidea) are the most abundant and widespread (Nilsson, 2003; Ulber et al., 2010b). In the UK, rates of larval parasitism rarely fall below 20%, often reach 50% and at one site reached 97% (Ulber et al., 2010b). The within-field distribution of pollen beetle parasitoids is more or less closely associated with that of host larvae, depending on species (Williams and Ferguson, 2010). Pollen beetle parasitoids are active during flowering and so their significant biological control potential is at risk from insecticides targeted at pod pests during flowering. They are also subject to mortality factors associated with overwintering in the soil, chief of which appears to be soil tillage.

The susceptibility of pollen beetle larvae to natural enemies other than parasitoids is much greater once they have left the flowers and fallen to the soil. As mentioned above, predation rates can rise to significant levels, although not all studies have shown this. For example, Büchs and Nuss (2000) found that emergence of new generation pollen beetle adults was reduced by 13% by natural populations of soil predators and by up to 56% by enhanced predator populations. In contrast, Zaller et al. (2009) found emergence to be only marginally reduced by the addition to exclusion arenas that prevented the activity of *Anchomenus dorsalis* and *Poecilus cupreus*, two carabid beetle species that are spatio-temporally associated with, and feed on, pollen beetle larvae in Europe. Interestingly, in the latter study, parasitised larvae were less susceptible to attack. In the UK, the carabids, *Amara similata*, *Nebria brevicollis* and *Asaphidion* spp. are most closely associated with pollen beetle larvae as they fall to the soil and *N. brevicollis*, *A. similata*, *Pterostichus madidus* and *P. cupreus* feed on pollen beetle larvae (Williams et al., 2010).

Exposure of pollen beetle larvae to entomopathogens may also be substantial in the soil environment. The entomopathogenic soil inhabiting nematodes *Steinernema bicornutum, S. feltiae* and *Heterorhabditis bacteriophora* reduce the successful pupation of pollen beetle larvae in the laboratory, although parasitised larvae were less affected (Neilsen and Philipsen, 2005). Augmentative release of entomopathogenic nematodes for pollen beetle control has met with mixed success. At best 92% control was achieved but the technique used was considered prohibitively expensive (Hokkanen et al., 2003). Three species of soil-dwelling entomopathogenic fungi, *Beauveria bassiana*, *Metarhizium anisopliae* and *Isaria fumosoroseus*, are also known to infect pollen beetles (Hokkanen et al., 2003),

Adult pollen beetles are also susceptible to infection with entomopathogenic fungi. Infection by *M. anisopliae* can be augmented in oilseed rape fields by introducing honey bees, *Apis mellifera*, carrying fungal spores from flower to flower (Carreck et al., 2007); larvae too were infected using this procedure. In cage experiments, adult mortality was increased 8-9 fold when spore-contaminated bees were introduced, whereas larval mortality was only increased by 20-30%.

8.1.8. Cultural and conservation biological control

Tillage

Parasitoids of pollen beetles overwinter in the soil beneath the crop and can be conserved by the adoption of reduced tillage. Experiments have shown that survival of pollen beetle parasitoids in direct-drilled plots is commonly two to five times higher than in ploughed plots (Nilsson 2010). Ploughing also reduces the survival of many carabid beetle species, whereas soil predators are enhanced in minimum tillage or conservation tillage regimes, where a richer habitat is provided by crop residues and greater weed diversity (Holland, 2004; Kromp, 1999).

Trap cropping

Models (Mosaic-Pest) developed to predict the influence of tritrophic interactions showed that crop rotation and the use of trap crops could greatly affect pollen beetle densities and parasitism rates, while ploughing only had a small effect (Vinatier et al., 2012). Use of trap crops, such as turnip rape, *Brassica rapa*, which flowers up to three weeks earlier than the main oilseed rape crop, can reduce the number of beetles to below threshold levels within spring oilseed rape until it is past the vulnerable pre-flowering stage. However, the success of the strategy was variable with winter oilseed rape, probably because the growth stage differential between the main crop and the trap crop was not always sufficient (Cook et al., 2004, 2006, 2007b, 2013a). A recent study demonstrated potential to increase the differential attractiveness of the main crop and trap crop if red flowered cultivars of oilseed rape were to be developed (Cook et al., 2013b). This could make trap cropping a more viable proposition. Growers might have problems keeping trap crop and main crop seed separate at harvest, but this could be overcome if oilseed rape varieties with flowering properties similar to that of turnip rape were used for the trap crop, obviating the need for segregation at harvest. Trap crops could be sprayed separately from the main crop to limit the area that needs to be treated.

Temporal targeting of insecticides

Parasitoids are at risk from insecticides applied to oilseed rape (Ulber et al., 2010a). Studies of the migration phenology of the pollen beetle and its parasitoids on the crop show there is a time-lag between the arrival of the pest and the arrival of the parasitoid, offering a time-window of some weeks for insecticide to be applied (Ulber et al., 2010a; Williams and Ferguson, 2010). However, parasitoids of the pollen beetle are present in the crop during flowering when treatment for seed weevil is recommended (Oakley, 2003; Williams and Ferguson, 2010). Phenological models for the immigration of several key parasitoids of oilseed rape pests have been developed and could be integrated into a Decision Support System such as proPlant (Johnen et al., 2010) to enable the timing of insecticide applications to be optimised for parasitoid conservation.

Spatial targeting of insecticides

Given the patchy distribution of pollen beetles within the crop, often edge-distributed and/or related to wind direction, there is potential to spatially target insecticides, conserving natural enemies in untreated areas and reducing resistance risk (Ulber et al., 2010a; Williams and Cook, 2010; Williams and Ferguson, 2010). However, the ability to predict pest distributions in crops is not an imminent prospect and further studies on the effects of landscape factors are needed (Rusch et al., 2010).

Landscape management

In spring, pollen beetle parasitoids migrate to new crops from their overwintering sites in the soil beneath the previous year's crops. Their distribution is influenced by the presence of adjacent meadows or wildflower rich field margins. In particular, *T. heterocerus,* one of the most abundant parasitoids of pollen beetles, which can cause high levels of mortality (Ulber et al., 2010b), is affected by levels of nectar nutrition available in the vicinity of their emergence sites (Rusch et al., 2012). In a Swedish study, emission of six volatiles from oilseed rape that was infested with pollen beetles attracted the parasitoid, *P. morionellus*. This behaviour was affected by the feeding status of the parasitoids – starved females were less responsive that non-starved (Johnsson and Anderson, 2007; reviewed by Williams and Cook, 2010 and Ahuja et al., 2011). The key to higher rates of parasitism is a more diverse local landscape, especially one containing flowering plants (Scheid et al., 2011).

On a wider landscape scale, in a French study the number of pollen beetles and the damage they caused was significantly correlated with the proportion of woodland and grassland within 1750 m of the crop landscape (Rusch et al., 2011). A German study suggested that pollen beetle abundance was due to multi-annual population build-ups resulting from long-term oilseed rape planting in rotations in the local landscape (Gladbach et al., 2011). In contrast to these studies however, Cook et al. (2013) found that trap catches were only weakly affected by landscape features. Possibilities for improved habitat management to reduce the risk of pollen beetle infestation are currently being examined under a Defra project PS2141 (DEFRA, 2013).

Margin management

The potential to manage field margins to enhance the abundance and diversity of generalist predators and to maintain local populations of parasitoids by including brassica species as 'banker plants' in margins has been investigated under Defra Project IF0139 (DEFRA, 2009). Field margin mixtures containing Brassicaceae were found to have more parasitoids, including those of pollen beetle, than those without Brassicaceae (Cook, 2014). This approach is being further investigated under Defra Project IF01122 (DEFRA, 2012; Cook et al., 2016).

Crop nutrition

Other cultural factors, such as levels of nitrogen fertiliser applied to the crop, can influence the crop's ability to compensate for bud abortion caused by mining beetles (Rusch et al., 2011) but can also influence the attractiveness of the crop to beetles in the first place (Valantin-Morison et al., 2007; Veromann et al., 2013). In the latter study, more pollen beetles were found on plots with some of the higher levels of nitrogen applied than where none was applied, although the relationship was not consistent across all rates tested. More parasitoids were attracted to these higher beetle populations. The authors suggested that plant chemical cues, such as acetic acid or methyl salicylate, played a minor role in selection of oviposition sites by adult pollen beetle females; other chemicals seemed to act as repellents.

8.1.9. Factors potentially influencing future risk

The presence of metabolic resistance to pyrethroids in pollen beetles in the UK constitutes a serious risk to the management of this pest that would be further exacerbated should target-site resistance spread from continental Europe. The small number of available insecticide actives puts pressure on alternatives to pyrethroids. AHDB guidance on the use of insecticides in spring and early summer should be carefully followed (AHDB Cereals & Oilseeds, 2013b).

Modelling suggests that climate change could increase the abundance of *M. viridescens* on oilseed rape in Canada (Olfert and Weiss, 2006). However, the outcomes of different climate change scenarios are difficult to predict due to the complexity of interactions amongst pests with host plants, natural enemies and alterations in agronomic practices as farmers adapt to change (Parsche et al., 2011; Thomson et al., 2010).

8.1.10. Recommendations for research and other actions

Much research attention has been focused on pollen beetle management in recent years due to the spread of pyrethroid resistance and many research needs are addressed by the current or recent AHDB and Defra-sponsored projects discussed above (Cook et al., 2013a; Cook, 2014; Defra, 2013; Ellis and Berry 2012; AHDB, 2013; Paveley, 2013). Other recommendations:

1. Monitor resistance status of pollen beetle.
2. Routine screening of breeders' lines for pest as well as for disease resistance should be encouraged.
3. If trap cropping is to be developed into a practical IPM strategy, further work is needed to build on AHDB Cereals & Oilseeds LINK project LK09108. This research should focus on

the selection of suitable cultivars for the main crop and for the trap crop with contrasting flowering phenologies and attractiveness to pests but with similar agronomic requirements and good yield.

4. New and safe insecticide actives are urgently needed for oilseed rape pests.

8.2. Flea beetles

As a group, flea beetles in recent years, have been perceived to be more important than pollen beetles, albeit at the other end of the season. Flea beetles cause most damage to young newly-emerged oilseed rape seedlings, but the flea beetle species that are important vary with the time of sowing (late summer or spring) and location. The most important and largest species causing damage to autumn-sown rape in the UK is the cabbage stem flea beetle (CSFB) (*Psylliodes chrysocephala*) (Winfield, 1992). Other flea beetles that occur in the autumn include the turnip flea beetles *Phyllotreta cruciferae* and *P. nigripes,* and the Wessex flea beetle, *Psylliodes luteola,* the latter especially in the south of England. With the exception of *Psylliodes* spp.*,* in spring these and other flea beetles, including the large striped flea beetle *P. nemorum*, can also attack spring-sown crops of oilseed rape (Oakley 2003; Ekbom, 2010) and linseed. For the purposes of this review, only the cabbage stem flea beetle will be considered in detail.

8.3. Cabbage stem flea beetles

8.3.1. Description

Adult cabbage stem flea beetles are about 5 mm long and shiny black with a hint of green-blue metallic sheen (Alford, 1979; AHDB, 2016c), although some variants with brown thoraxes can occur (Williams, 2010). All flea beetles have characteristic large hind femurs, which enable them to jump. The larvae are predominantly creamy white in colour, with numerous small dark dots on the back and three pairs of dark thoracic legs. Fully-grown larvae are around 6 mm long and have a black head and a large black plate on the upper surface at the hind end (AHDB, 2016c).

8.3.2. Distribution

Cabbage stem flea beetles are widespread in the UK and northern Europe. In the UK, the beetle originally infested brassica seed and mustard growing areas of southern and eastern England but has since spread northwards and into Scotland as the area under rape has increased (Green, 2007; 2008; Holland and Oakley, 2007). In Germany they are more common in the north around the Baltic Sea than in southern areas (Heimbach and Müller, 2013). They have also been recorded in the Middle East, Asia, North Africa and the USA (reviewed by Williams, 2010)

8.3.3. Life cycle

Cabbage stem flea beetles have one generation per year (i.e. they are univoltine). Following a period of aestivation during the summer, cabbage stem flea beetles migrate into emerging oilseed rape crops in late August or early September. Having reached the crop, their flight muscles atrophy but short range movement can occur throughout the winter if the temperatures are mild enough. After a period of about 12-14 days of feeding on the cotyledons and new leaves, during which time their developing ovaries mature, the females mate and begin to lay eggs (0.9 x 0.4 mm in size) in cracks in the soil around young seedlings. Up to 1000 eggs per female may be laid (Saringer, 1984). Most eggs are probably laid from mid-September to mid-October (Warner, et al., 2003) but a few may be laid during winter and early spring when temperatures permit adult activity.

The time to egg-hatch is variable, dependent on the temperature prevailing, so eggs laid on early emerging crops are likely to hatch faster than those laid in later emerging crops, assuming that temperatures drop in the interim. Studies done in Cambridgeshire in the 1970s showed clear variability between years in the time to egg hatch, ranging from 35 days when mean temperatures were relatively high (10^{o}C) to 70 or more days when relatively low (<6^{o}C). The first larval invasion of plants usually occurs when 240 day-degrees above the 3.2^{o}C threshold temperature for egg development has been achieved (Alford, 1979). In practical terms, if mid-August crops are invaded in early September, when the plants are at cotyledon stage, it will be another two weeks before the eggs are mature enough to be laid, and another 35-70 days before they hatch and the larvae invade the plants. In Alford’s study, larvae were first found in mid-November in 1975, but as early as mid-October in 1976 and 1977. In more recent years, larvae have been found as early as late September in early sown crops (Sam Cook pers. comm.). Egg hatch, however, can take place over a long period, with new larvae appearing as late as the following spring from late-laid, or late-hatching eggs (Alford, 1979).

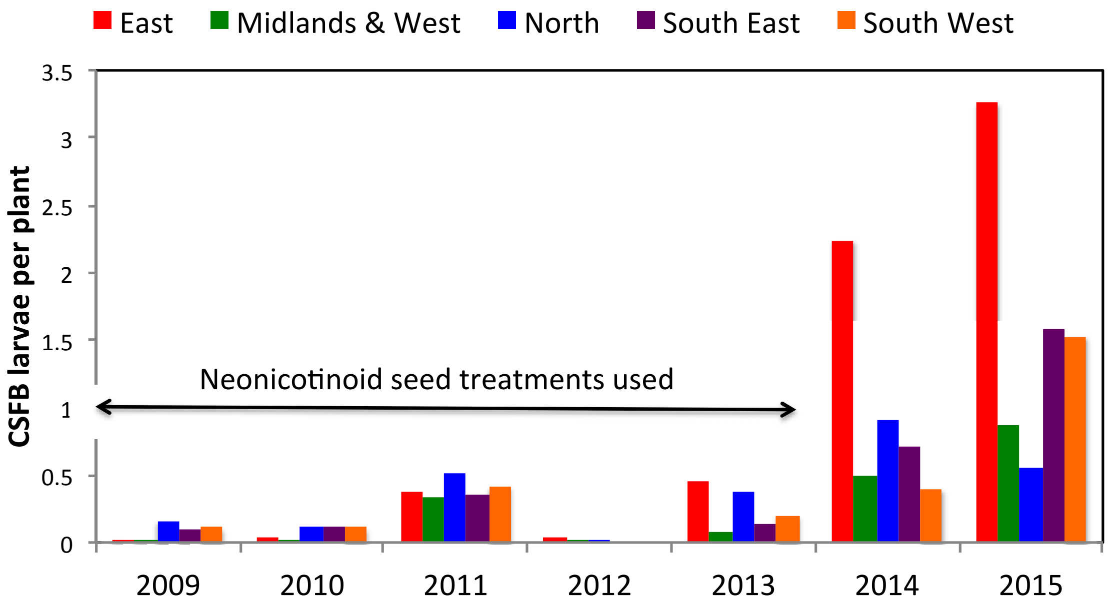
Newly hatched larvae burrow into the upper surfaces of leaf petioles. They feed in plants from October to early April, undergoing three larval instars in that time (reviewed in Williams, 2010; AHDB, 2016c). The larvae feed whenever it is warm enough in winter, successively mining the older and then younger leaf petioles and finally entering the stems and growing points where they can be found in the later part of their development in early spring (Saringer, 1984; Williams, 2010; AHDB, 2016c). From late winter onwards, larvae leave plants to pupate in the soil. Adults emerge from late May to early July and feed on foliage. In mid-summer they seek moist sheltered places where they rest (aestivate) for 1-2 months before migrating into emerging oilseed rape crops again (Oakley, 2003; Williams, 2010). However, some must be present in ripening oilseed rape crops in quite large numbers, as they can be found in their thousands in grain stores or harvest trailers shortly after the harvesters have been through a field (Dewar pers. comm).

8.3.4. Damage

Damage to autumn sown crops is initially by adults to the foliage. Adult beetles migrate into oilseed rape crops during crop emergence. This is the stage at which the crop is most vulnerable, as the beetles can feed on and destroy the growing point. If damage is severe, beetle feeding can kill seedlings even before they emerge (AHDB, 2016c). ‘Shot-holing’ damage to cotyledons and early leaves results in stunting, poor plant vigour and can result in reduced plant density and occasionally total crop failure. In 2014, the first year following the neonicotinoid seed treatment ban, serious crop losses due to adult flea beetles (2.7% of the national crop) were recorded in an AHDB-funded national snapshot survey carried out at the end of September 2014 by ADAS. Most serious losses occurred in several counties in eastern and southern England, including Hampshire/Surrey (14%), Bedfordshire/Hertfordshire (10%), Cambridgeshire (8%) and Suffolk (5%) (Wynn et al., 2014). The AHDB Planting Survey 2014 also surveyed losses to cabbage stem flea beetles and by December 2014 national losses in England were estimated at 5% (Nicholls, 2015).

In the autumn of 2015, another similar, but more extensive survey, funded by AHDB and carried out by ADAS, found that over 65% of crops had some damage, and that the damage was more widely distributed around the country than in 2014, although nationally only 1% of crops were lost. However, most losses again occurred in the eastern and sourthern regions, including Buckinghamshire (9%), Cambrdigeshire (4%), Essex (3%), Hampshire (1%), Lincolnshire (1%), Bedfordshire (1%) and east, south and west Yorkshire (1%) (Alves et al., 2016). Even when crops were not lost, more severe damage occurred in these southern and eastern counties, and is likely to result in yield reductions at harvest in 2016. The distribution of CFSB damage identified in these two snapshot surveys was confirmed by other, longer-term Defra-funded surveys of larval numbers in oilseed rape in autumn and spring conducted by Fera, and published in their Crop Monitor web site (e.g. Fig. 10). These showed that average numbers of larvae per plant had risen substantially in all regions since the neonicotinoid ban was implemented, especially in the east and south east regions, where adult damage was greatest (DEFRA 2015; 2016).

Fig. 10 The number of cabbage stem flea beetle (CSFB) larvae found per plant in the national Defra-funded autumn survey done by Fera each year before and after the ban on neonicotinoid seed treatments in oilseed rape



Larvae affect plant vigour by boring into the leaf petioles and, later, into the stems. At high densities of larvae plant development and even survival may be severely affected (Williams, 2010). Early-hatching larvae cause more damage than late-hatching larvae. In trials using systemic products applied in autumn or spring, Purvis (1986) found that spring applications of granular systemic insecticide gave as good control of cabbage stem flea beetle as autumn applications but did not increase yield if an autumn application had already been made. This suggests that the smaller late-hatching larvae that were present in spring, and which must have hatched after the autumn insecticide application had worn off, were perhaps too small to cause serious damage to leaves. By contrast, the damage that autumn hatching larvae cause can result in stunted plants in the spring with impaired stem elongation (AHDB 2016e; Oakley, 2003). Early-sown crops tend to be more susceptible to cabbage stem flea beetle attack and suffer greater damage as a result (Leach et al., 1994). A warm autumn favours egg laying and early hatching of larvae that coincides with smaller, more vulnerable plants (AHDB, 2016c). Significant yield losses have been recorded by Purvis (1986), and Nilsson (1990). Larval damage can also make the plants more vulnerable to frost damage resulting in leaf drop, and infection by stem canker, *Leptosphaeria maculans* (Schulz and Daebler, 1984).

It is difficult to separate out the relative impact of adult and larval damage, as the occurrence of one usually leads to the other, although it might be expected that effective control of the adults should prevent the eggs being laid, and thus result in fewer larvae later. However recent experiences have shown that this does not necessarily happen if the adult migration is prolonged, leading also to prolonged egg hatching (Alan Dewar pers comm.).

8.3.5. Monitoring and forecasting

Migrations of adult flea beetles can be monitored using sweep nets, D-vac suction samplers, sticky traps (Alford, 1979), yellow water traps, and of course by observing the appearance of shot-holes and other grazing on the leaves, although the latter can sometimes be confused with slug damage.

Monitoring adult numbers gives some indication of the likely severity of larval attack, but not always, as egg hatch is affected by temperature (reviewed in Johnen et al., 2010). A study carried out in Canada using yellow sticky traps showed little correlation between trap catches and the level of damage to the crop (Carcamo et al., 2007). The traps gave an indication of beetle activity but had limited application for making management decisions. However, the authors found that visual assessments of flea beetle damage to cotyledons were a better indication of beetle population size. This suggests a need for additional work to test for correlations between adult cabbage stem flea beetle catches in sticky traps or other traps and damage both by adults to seedlings and, later, by larvae to established plants.

Weather conditions after egg laying can have substantial effects on subsequent damage, and this can be modelled using the weather-based proPlant model to identify years when risk from larval attack is high (Johnen et al., 2010). Such a model can also suggest the best time to apply foliar control measures if necessary.

Numbers of larvae have been monitored through longer-term Defra-funded surveys in oilseed rape in autumn and spring conducted by Fera, and published in their Crop Monitor web site. Twenty five plants from each of 50 sites are destructively sampled at the Food and Environment Research Agency. The plants are checked for cabbage stem flea beetle larvae and rape winter stem weevil larvae. A summary of the results of this sampling and a graphical comparison with the results from previous years are published on the CropMonitor Website (www.cropmonitor.co.uk).

8.3.6. Thresholds for control

Unfortunately there are no firm thresholds for decision-making on the control of adult cabbage stem flea beetle. However, the size of the plants and their ability to grow away from initial damage is considered important. Control is usually recommended if the rate of adult feeding damage exceeds the rate of new leaf production (Green, 2008). An assessment of the percent loss of leaf area due to shot-holing can be used to determine the need for control. The current advice is to consider treatment if adults have eaten over 25% of leaf area at the cotelydon-2 leaf growth stage, or if adults have eaten over 50% of the leaf area at the 3-4 true leaf stage, or if the crop is growing more slowly than it is being destroyed (AHDB, 2016c). According to an AHDB Cereals & Oilseeds-funded review of pest thresholds published in 2009, the origin of the treatment threshold associated with over 25% of leaf area eaten is unknown. The review identified that it should be possible to develop a quantified threshold scheme for flea beetle damage, using knowledge of the minimum plant number for potential yield and the potential number of plants that a single cabbage stem flea beetle may destroy. This is an area that requires further research to quantify these two parameters and develop this threshold scheme. New research must also assess the practicality of being able to assess plant/seedling numbers in time to make a decision about control (Ellis et al., 2009b).

For control of larvae, early work by ADAS suggested that significant economic damage would occur when there were more than five larvae per plant (Purvis, 1986), and this was confirmed in later studies by Lane and Walters (1994). A more recent project looking at a quicker and less intensive method of threshold assessment concluded that about 70% of leaves scarred was equivalent to five larvae/plant, however, due to variability in results a lower threshold of 50% leaves scarred was proposed, equivalend to two larvae/plant (Walters et al., 2001). This project assumed that shot-holing was unlikely to be a reliable indication of treatment needs for larval infestations, contrary to published grower guides giving spray thresholds based on the area eaten by adult beetles. In 2008, AHDB Cereals & Oilseeds-funded research came up with an alternative method to plant damage assessment, linking the number of beetles caught in water traps to larval thresholds (Green, 2008). Current advice reflects the results from this project, recommending that four yellow water traps should be set on the soil surface in early September, two on the headland and two in the field along a wheeling. The traps should be filled with water and a drop of detergent added to ensure that insects caught sink and drown. The traps should be visited regularly, weekly if possible, and the number of cabbage stem flea beetles recorded, before emptying and resetting the traps. If cheap pyrethroids are to be used, that have not yet been compromised by resistance (see later section), a spray is justified if an average of more than 96 beetles per trap have been caught in total over the monitoring period (AHDB, 2016c). This is equivalent to the threshold of five larvae per plant (Green, 2008). The threshold was altererd from two larvae/plant to five larvae/plant in 2015 following the confirmation of resistance to pyrethroids. Therefore, in areas where pyrethroid resistance is high (see section 8.3.8), the higher cost of alternative insecticides suggests that the economic threshold for their use should be five larvae per plant (Oakley and Green, 2006). However there are doubts about the effectiveness of many of the alternatives.

8.3.7. Control measures

Damage by adults, was until recent years, not considered as serious as that caused by larvae. Adults can be controlled by sprays, usually of pyrethroids, but more reliance has been placed on seed treatments since gamma-HCH was replaced by imidacloprid + betacyfluthrin (Chinook) in 2001 (Birch and Nicholson, 2001). More recently, and before the recent ban on neonicitoid seed treatments in oilseed rape, growers had choices of second generation neonicotinoid seed treatments, clothianidin + betacylfuthrin (Modesto or Elado in continental Europe) (Adam and Hopkinson, 2008; Adam, 2009), or thiamethoxam (Cruiser), which have had significant effects of the level of shot-holing, and survival of plants, sufficient in serious cases to protect crops from being totally devastated (Sacha White, pers comm; Alan Dewar pers. comm.). However, these seed treatments only provide protection for about 4-6 weeks after sowing, and so may have little effect on larvae hatching and colonising plants after this protection window has ended. So, in years when adults colonise later or eggs hatch later, perhaps due to late occurring Indian summers, larvae may have to be controlled by supplementary sprays. Larvae move between leaves frequently under these conditions, especially if the leaves are about to fall off when they senesce, and it is during these external movements that opportunities arise to control them with non-systemic insecticides such as pyrethroids. As the data in Table 7a suggests, many growers this, even when it may not be necessary. It is likely that it is perceived as too time-consuming to set up and check water traps, or to assess leaf scarring, or (the ultimate measure) to dissect leaf petioles. Time-poor farmers and/or agronomists need something much simpler and so, to save time in risk assessment and to save money on application costs, they often revert to the inclusion of insecticide sprays as tank mixes with fungicides or herbicides, whether the crops need insecticide treatments or not. Recent experience of trials to assess the efficacy of currently-approved alternatives to pyrethroids, such as thiacloprid or acetamiprid, show that systemic insecticides, designed to control sucking pests, provide little or no control of cabbage stem flea beetle larvae within plants (Alan Dewar pers. comm.).

8.3.8. Development of resistance to pyrethroids

It is not surprising that some cabbage stem flea beetle have developed resistance to pyrethoids as a consequence of exposure to the large quantities of this group of chemicals that have been applied to oilseed rape to control flea beetles and other pests (Table 7a). First records of cabbage stem flea beetle resistance were reported in a major oilseed rape-growing region in northern Germany from 2008 onwards, resistance factors up to 81 being detected (Heimbach and Müller, 2013). More recent studies have shown that this resistance is associated with a target site mutation (L1014F) commonly known as knock-down resistance or *kdr*, that is known to confer resistance to pyrethroids in at least 20 other pest insects, including the pollen beetle *Meligethes aeneus* (Zimmer et al., 2014). Bioassays of live flea beetles have shown cross-resistance to the class I and class II pyrethroids, lambda-cyhalothrin, ethofenprox, tau-fluvalinate and bifenthrin, suggesting that the whole group of pyrethroids could be compromised. If this situation spreads across Europe in a similar way to that seen with pollen beetles, then growers will have serious problems trying to control cabbage stem flea beetle in the future. The risk is accentuated by the above-mentioned withdrawal of neonicotinoid seed treatments, which will increase the risk of damage by adults early in the season and, more than likely, will stimulate the application of additional pyrethroid sprays to control them. After reports of poor control of cabbage stem flea beetle in 2013 in the UK, resistance was later confirmed (Højland et al., 2015). Highest levels of resistance occurred where most damage was seen in central and eastern England (AHDB 2015b; Rothamsted Research 2015, cited by Nicholls, 2016; Fig. 11). Unfortunately, potential alternatives to pyrethroids for control of adults or larvae this pest, such as thiacloprid, pymetrozine, acetamiprid, and flonicamid, have not shown good efficacy in trials (Dewar Pers, comm,). Future control of this pest may have to rely on non-chemical methods.

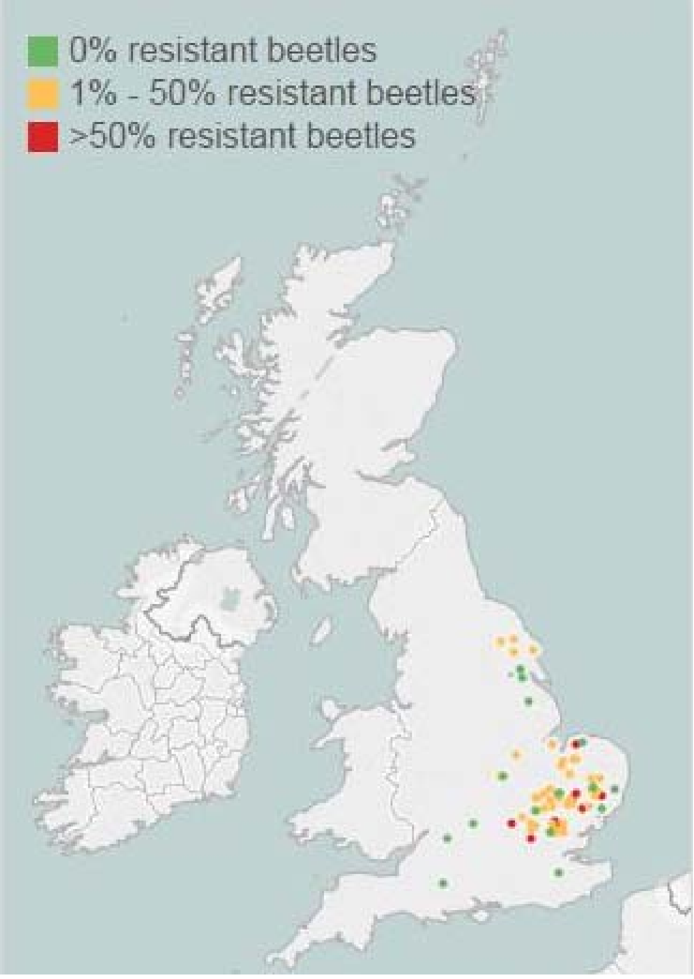


Figure 11. Incidence and distribution of resistance to lambda-cyhalothrin in adult cabbage stem flea beetle, Psylliodes chrysocephala, in summer 2015 (Rothamsted Research 2015)

8.3.9. Biological control

Parasitoids and predators of cabbage stem flea beetle have been identified in recent European studies on biological control (e.g. MASTER; Williams, 2006a, b). These include the larval endoparasitoid *Tersilochus microgaster,* which was the only significant parasitoid recorded in the UK, Sweden, Poland and Germany during the study (Ulber et al., 2010a). Rates of larval parasitism in these countries were found to be variable, ranging from 0-57%. The within-field distribution of *T. microgaster* is strongly associated with that of cabbage stem flea beetle larvae, demonstrating its efficient host-finding ability. The importance of parasitoids' contribution to control of cabbage stem flea beetle has not been quantified. However, they are likely to be present in the crop at bud stage and early flowering which will render them vulnerable to overuse of pyrethroids against pollen beetles (Ulber et al., 2010b; Williams and Ferguson, 2010).

Cabbage stem flea beetle are vulnerable to generalist soil predators both at the egg stage (eggs are laid on the soil) and when mature larvae fall to the ground to pupate. In a study at Rothamsted Research, the distributions of two ground beetles, *Trechus quadristriatus* and *Pterostichus madidus* were shown to be spatio-temporally correlated with the distribution of cabbage stem flea beetle egg-laying, suggesting that these beetles may be predators of cabbage stem flea beetle (Warner et al., 2003; Williams et al., 2010).

Two entomopathogenic fungi, *Metarhizium anisopliae* and *Beauverai bassiana*, are known to infect cabbage stem flea beetle but their impact on the field populations is not known (Hokkanen et al., 2003).

8.3.10. Cultural and conservation biological control

Tillage

The adoption of reduced tillage, e.g. minimum tillage, or direct drilling, markedly enhances the survival of parasitoids like *T. microgaster* that overwinter in the soil and also tends to improve the survival of many ground beetle species (Nilsson, 2010; Holland, 2004; Kromp, 1999). Reduced tillage is therefore likely to contribute towards integrated control of cabbage stem flea beetle. Anecdotal observations by agronomists who contributed to the survey of cabbage stem flea beetle damage in 2014 and 2015 (section 8.3.4), also reported that less cloddy seed beds provided fewer opportunities for adult flea beetles to hide, and therefore made them more vulnerable to sprays applied during the day. Cabbage stem flea beetle are more active at night, and may avoid sprays applied at other times by hiding in crevices or under clods.

Sowing rate

Cultural control methods for management of *Phyllotreta* flea beetles in spring oilseed rape include higher seed rates, which would dilute the level of damage amongst seedlings within crops at a given level of immigration (Ekbom, 2010). Similar approaches may also be useful for autumn-sown rape. The current tendency towards low seed rates (circa 2.5 kg/a), especially with hybrid varieties, has concentrated the attention of pests on to fewer plants, increasing the pest density per plant, which has particular implications for plant survival at the seedling stage. Although higher seed rates cost more, if insecticide treatments don't work due to resistance, this could be a cost worth paying to guarantee a healthy crop.

Trap cropping

A border trap crop of turnip rape, such as proposed for the management of pollen beetle (see above) has also been shown to reduce the abundance of cabbage stem flea beetle in the main crop (Barari et al., 2005).

Temporal targeting of insecticides

The larval parasitoids of cabbage stem flea beetle are active in early spring (Williams and Ferguson, 2010; Ulber et al., 2010). Therefore the use of overall sprays in the autumn to control cabbage stem flea beetle adults will avoid the parsasitoids, and thus conserve them. However cabbage stem flea beetle parasitoids are likely to be more vulnerable to insecticides applied for pollen beetle control in the spring.

Carabid beetles and other potential predators of larvae in the autumn may be affected by the increased number of insecticide sprays applied to control flea beetles since the withdrawal of neonicotinoid seed treatments.

Landscape management

More research is needed to link the evidence that provision of semi-natural habitats increases the activity of natural enemies to evidence for improved biological control of pests (ENDURE, 2009; Ferguson and Alomar, 2010; Rusch et al., 2010).

8.3.11. Factors potentially influencing future risk

The presence of pyrethroid resistant cabbage stem flea beetle in the UK poses a significant risk to management of this pest given current restrictions on the use of neonicotinoids adopted by the European Commission. These have led to a dependence upon foliar sprays of pyrethroids. Care is needed to ensure that pyrethroid treatments are applied only if absolutely necessary and according to thresholds (AHDB 2016e).

Climate change could lead to more severe cabbage stem flea beetle problems as warmer autumns favour egg laying and earlier larval hatch (Oakley 2003). It is unclear what effect milder winters may have but if temperatures are suitable for increased larval activity but not for significant plant growth, plant losses may increase.

8.3.12. Recommendations for further research

1. Test alternative insecticide sprays for control of cabbage stem flea beetle
2. Test alternative seed treatments
3. Monitor the development of resistance in the UK
4. Routine screening of breeders' lines for pest as well as for disease resistance
5. There may be scope to make greater use of existing datasets to model the effect of landscape and field margin management on cabbage stem flea beetle and its natural enemies.

8.4. Brassica pod midge

8.4.1. Description and geographic distribution

The brassica pod midge, *Dasineura brassicae,* (hereafter referred to as pod midge) is a small midge (a true fly of the family Cecidomyiidae) 0.7 – 2.2 mm long. The female is slightly larger than the male and has a reddish abdomen when seen close-up. The male has conspicuous backward-curved antennae (Williams, 2010). The larvae are white- to cream-coloured, legless and up to 2 mm long. This midge is considered an important pest of both winter and spring oilseed rape across most of Europe (Gratwick, 1992; Alford et al., 2003b; Williams, 2010).

8.4.2. Life cycle

The pod midge has two or three generations each year and is a brassica specialist. Midges emerge in mid-May from diapause in the soil beneath the previous season's crops, where they can survive for several years (Axelsen, 1995; Nilsson et al., 2004; Williams et al., 1987b) and mating of the first generation takes place at the overwintering site. The female midges then migrate to winter oilseed rape crops, where they usually have two generations, or to spring rape crops where they usually have one (Williams, 2010; Williams et al., 1987a, b). Eggs are laid into pods in clutches of 20-30. The ovipositor of the pod midge is fragile and is not thought strong enough to penetrate the pod wall unless there is some injury or weakness. Punctures made by the cabbage seed weevil for feeding, oviposition or larval emergence are most often used as egg-laying sites (Williams, 2010) although it has been shown that feeding damage by other insects can also be used (Hughes and Evans, 2003). Three or four days after eggs are laid they hatch and legless translucent pink larvae emerge, which soon become white. They feed on the pod wall for up to a month and moult twice, the third instar being up to 2 mm long and cream-coloured. In common with others of this family of gall midges, the larvae influence the development of plant tissues, the pod wall swelling, and ultimately splitting ('pod shatter'). This releases the larvae, which fall to the ground and burrow about 5cm into the soil. After spinning cocoons, some larvae pupate immediately, emerging a few weeks later as adults to infest the crop again, and other larvae enter diapause (Williams, 2010).

Later in the year the proportion of larvae entering diapause increases, probably in response to cumulative solar radiation during the larval stage (Axelsen et al., 1997).

8.4.3. Damage and pest status

Infested pods that have split to release pod midge larvae usually lose most or all of their seed, resulting in significant yield loss from infested plants. The damage is usually most severe in headlands, where this pest invades the crop, and so swollen, yellowed infested pods and shattered pods are clearly seen from outside the crop (Ferguson et al., 2004; Free and Williams, 1979a, b; Williams and Ferguson, 2010). Damage is most severe in crops where there is a large infestation of first generation pod midges in May (Ellis et al., 2009), leading to an abundant second generation, which is always considerably more numerous. Damage by the second generation on winter oilseed rape occurs too late for the plant to be able to compensate (Ellis et al., 2009). Damage in spring oilseed rape crops can be more severe than in winter rape if winter and spring rape crops are close enough for the more numerous second generation to migrate between the two (Ekbom, 2010; Oakley, 2003).

In 2007, Holland and Oakley summarised the pest status of pod midge as “static [i.e. status unchanged], highly visible damage on headlands, but of no consequence” (Holland and Oakley, 2007). Currently there appears to be no reason to revise this opinion, probably in part because insecticide applications targeted at cabbage seed weevil give incidental control of pod midge by denying them many oviposition sites. In the 2010 harvest year, 2% of insecticide applications to oilseed rape in the UK were specified as targeted against pod midge and 10% against seed weevils (Garthwaite et al., 2011a). In 2012 and 2014 respectively, 15 and 10% of insecticide applications were specified as targeted at ‘weevils’ and any targeted against pod midge were included in the ‘others‘ category (Garthwaite et al., 2013, 2015; Fig. 6). ADAS Pest, Disease and Weed Incidence Reports reported few if any insecticide applications against pod midge in 2008 and none in 2009 or 2010, and that pod midge incidence was less than normal in 2012 (ADAS, 2013; Lole, 2009, 2010, 2011).

8.4.4. Thresholds for control

There is currently no specific threshold for control of the pod midge (Ellis et al., 2009; Oakley, 2003) but it has been recommended that the threshold for control of the cabbage seed weevil may be halved if significant pod midge damage is likely (AHDB Cereals & Oilseeds, 2002; Lane and Gladders, 2000; Williams, 2010). Ellis et al. (2009) reported that there was potential to develop improved thresholds for pod midge / seed weevil because of the quantitative relationship between pest numbers and yield loss, but that the priority for such work was relatively low as there was no legislative threat to the availability of the insecticide actives usually used.

8.4.5. Monitoring and forecasting

Growers are advised that pod midge adults are present in crops from May onwards and larvae from June (Ellis et al., 2009; Oakley, 2003). However, consistent with the lack of an economic threshold for the pod midge, there are no recommendations to farmers as to how to monitor for adults or larvae. Adults can be monitored using water traps or sticky traps (Williams et al., 2003) but distinguishing the pod midge from other midges requires basic taxonomic skill and low power magnification. Identification of pods infested with third instar pod midge is simple but alerts the grower too late to prevent egg-laying by the first generation on the crop. In practice, control decisions are normally made on the basis of local experience with the pest in recent seasons. As with all pests, monitoring should not be confined to the crop edge but should be done across the crop to more accurately reflect the risk to the whole crop (AHDB, 2016c). This is particularly important for pod midge, which is usually edge-distributed (Williams, 2010), but is more difficult to implement as the crop can be quite tall by this stage, and become entangled, even along spray wheelings.

The pod midge is a weak flier but, in areas sheltered from strong wind, it flies upwind towards odour cues emanating from the oilseed rape crop (Williams and Cook, 2010). Whether it is distributed in crops upwind or downwind of its emergence site (e.g. last year’s crop) appears to depend on the strength of the wind at migration (Williams and Cook, 2010). It is not therefore possible to advise that monitoring should be focused on either the upwind or the downwind side of any crop.

Spring emergence has been shown to be accurately predicted in mainland Europe by the DSS proPlant, which incorporates a weather-based phenological model (Johnen et al., 2010, 2013; Johnen and von Richthofen, 2013). This DSS is not currently in use in the UK for brassica pod midge.

8.4.6. Control measures

Current advice is that sprays for seed weevil provide incidental control of pod midge by reducing the number of egg laying sites available (Oakley, 2003). Control is therefore usually by the application of pyrethroid sprays during flowering (May/June in winter oilseed rape; see the section on cabbage seed weevil below for further information) (ADAS, 2013). However the choice of pyrethroid should be made according to their toxicity to bees, which are more likely to be present after flowering begins, when pod midges invade the crop. Some growers confine treatment to the headlands as this pest is usually edge-distributed. The effectiveness of a Neem–based botanical insecticide against pod midge has been tested with promising results (Pavela et al., 2009).

8.4.7. Evolution of resistance to insecticides

There is no evidence of the development of insecticide resistance in European populations of the the pod midge and it is believed that the risk is currently low (Heimbach et al., 2006; Müller et al., 2006; Nauen, 2011). This is in part due to the fact that the pod midge is among the last pests to migrate into the crop and is therefore less likely to be exposed to multiple applications of insecticides targeted at other pests. Nevertheless, there is evidence of resistance in some German populations of another late spring pest, the seed weevil (Heimbach and Müller, 2013). The availability of few modes of action of insecticides, together with any increase in the frequency of oilseed rape in the rotation may be likely to increase any small risk.

8.4.8. Biological control

Thirty or more species of parasitoids have been reported to parasitise the pod midge in Europe but, of these, two, the egg-larval parasitoid *Platygaster subuliformis* and the larval parasitoid *Omphale clypealis*, are much the most important and widespread (Ulber et al., 2010b). Rates of parasitism in winter oilseed rape in the UK are variable but can be high. Murchie (1996) found 0-74% of larvae were parasitised by *P. subuliformis* and Ferguson et al. (2004) reported that in 1999 and 2000, 42% and 49%, respectively, of the insects emerging from overwintered pod midge cocoons were parasitoids (the proportion that were *O. clypealis* and *P. subuliformis* varying between years). There is strong spatial coincidence between the pod midge and it's parasitoids, both being edge-distributed in the crop (Ferguson et al., 2004). The biocontrol potential of these parasitoids is clearly great. However, both the pest and its parasitoids are vulnerable to insecticides and to mortality factors associated with overwintering in the soil, chief of which appears to be soil tillage.

Generalist predators such as carabid beetles and spiders have an opportunity to prey upon pod midge larvae as they fall to the ground and as they overwinter and/or pupate in the soil. In Germany, adult emergence may be reduced by as much as 58% by ground predators (Buchs, 2003b; Buchs and Nuss, 2000), although this was estimated to account for only 10% of total pod midge mortality. Ferguson et al. (2004) estimated that an average of 7342 pod midge larvae per m^2 fell to the ground in the course of one season at an oilseed rape field at Rothamsted Research. Estimates at different sites in Europe have ranged from 1,800 to 35,000 larvae per m^2 (Buchs, 2003b). This represents a significant resource. About 42 species of carabid beetle occur commonly in oilseed rape fields in Europe (Williams et al., 2010). At Rothamsted Research, *Amara similata*, *Anchomenus dorsalis*, *Nebria brevicollis*, *Loricera pilicornis*, *Bembidion lampros, Asaphidion flavipes, Harpalus rufipes, Pterostichus madidus* and *P. melanarius* were all active during the time when pod midge larvae fall from pods to the ground. Of these, the activity-density of *A. dorsalis* and *H. rufipes* were spatially associated with the larvae, though some caution is needed in the interpretation of activity-density data (Warner et al., 2000; Williams et al., 2010). Eleven species of carabid are known to feed on pod midge larvae in the laboratory, although only one, *A. similata,* has been shown to feed on them in the field (Williams et al., 2010). Evidence of feeding in the field is difficult to obtain because the soft-bodied pod larvae leave little evidence in the crops of carabids and suitable quantitative molecular methods for detection have yet to be developed. Haschek et al. (2012) found that the nutritional condition of male *Poecilus cupreus* was positively associated with the density of pod midge larvae in a field of winter oilseed rape in Austria.

Staphylinid beetles and several groups of spiders also have the potential to be significant predators of larvae of oilseed rape pests when they fall to the soil (Buchs, 2003b; Frank et al., 2010).

It is likely that the pod midge is subject to attack by entomopathogens during the often prolonged period spent in the soil in diapause or pupation. However, as far as we can ascertain, no pathogens have yet been identified from pod midge larvae and the entomopathogenic nematodes tested appear to be ineffective against this pest (Hokkanen et al., 2003; Nielsen and Philipsen, 2005).

8.4.9. Cultural control and conservation biological control

Tillage

Pod midge overwinter in cocoons in the soil beneath the oilseed rape crop from which they emerge and they are therefore vulnerable to injury during tillage and to deep burial caused by inversion ploughing (Axelsen, 1995; Valantin-Morison, 2012). Ferguson et al. (2004) found that only 0.2% of pod midge larvae emerged from the soil as adult midges or parasitoids the following year. However, any potential benefit of ploughing for the management of pod midge (which is the only major oilseed rape pest in the UK that overwinters in the soil beneath the crop) is likely to be off-set by the harm caused to the key parasitoids of more significant pests, such as the pollen beetle, in which the parasitoid but not the host overwinters in the soil beneath the crop. Pollen beetle parasitoids experience 50% losses or more due to ploughing (Nilsson, 2010). Populations of many invertebrates, including some epigaeic predators, are enhanced in minimum tillage or conservation tillage regimes where soil disturbance is reduced and a richer habitat is provided by crop residues and greater weed diversity; by contrast, ploughing reduces the survival of many carabid species (Holland, 2004; Kromp, 1999).

Trap cropping

In common with other pests of oilseed rape, the pod midge is able to locate the crop guided by host plant volatiles and visual cues (Hall et al., 2012; Williams and Cook, 2010). This implies potential for their management by trap cropping using a border of a more attractive cultivar or brassica species (Cook et al., 2007b). However, as this pest is usually markedly edge-distributed in any case, the value of this strategy for protecting the main crop within the trap crop border is questionable.

Landscape management

There is good evidence that increased landscape complexity, including more semi-natural habitats, increases the activity of natural enemies but despite many recent studies there is conflicting evidence for effects on biocontrol of pests. This has recently been reviewed by Rusch et al. (2010) who concluded that “the variability of responses of insect pests to landscape complexity reported in the previous studies appears to be multifactorial and not completely understood, implying further studies [are needed] on pest populations to understand general patterns.” In a meta-review for the European project ENDURE, landscape scale studies comprised only 19% of reports of conservation biological control and nearly half of the 90 reviews that were surveyed from 1989-2009 considered that more research was needed on landscape-scale interactions. In particular, more work was needed on resource management, on the appropriate scale for landscape management and on the movement of natural enemies (ENDURE, 2009; Ferguson and Alomar, 2010).

The midge is a weak flier and much of the dispersal is short-range or passively wind-born (Evans and Allen-Williams, 1989a, b). Consistent with this, Zaller et al. (2008b) found that the pod midge tended to respond to landscape variables at a small scale and there seems to be little influence of the distribution of other oilseed rape crops in the current year on the distribution of the pest in the crop (Moser et al., 2009). It seems likely that pod midge infestation may be minimised by avoiding the placement of an oilseed rape crop adjacent to the site of a rape crop the previous year and by block-cropping, which presents less crop edge compared to the crop area (Oakley, 2003)*. Zaller et al. (2008a) found that pod midge damage was negatively related to the area of the crop in the local landscape, presumably indicating a dilution effect (probably temporary).

* There is recent evidence for a positive influence of oilseed rape crops on biocontrol in neighbouring wheat crops, probably through provision of floral resources to flying predators and parasitoids (Cook, 2014). The benefit of this influence is likely to be enhanced by the wide distribution of oilseed rape crops amongst the fields in the landscape rather than by block-cropping.

Margin management

Many studies provide evidence that field margin habitats can be managed to enhance populations of epigaeic and other generalist predators, and there is good evidence for movement of predators from the margins into the field (Buchs, 2003a). However, few studies demonstrate a link with pest control and crop yield and this deserves further research (Griffiths et al., 2008).

The potential to manage margins not only to enhance the abundance and diversity of generalist predators, but also to maintain local populations of parasitoids by including brassica species as ‘banker plants’, has been investigated under Defra Project IF0139 (DEFRA, 2009). Field margin mixtures containing Brassicaceae were found to have more oilseed rape pest parasitoids, including those of pod midge, than those without Brassicaceae (Cook, 2014). This approach is being further investigated under Defra Project IF01122 (DEFRA, 2012; Cook et al., 2016).

Crop nutrition

Experiments in Germany suggest that excessive fertilisation with nitrogen leads to increased infestation by pod midge and that it is therefore important to control nitrogen use carefully (Aljmli, 2007). It was further found that sulphur fertilisation increased pod midge infestation but, as it conferred vigour to plants and increased resistance to generalist pests and to fungi, it was recommended that sulphur should be applied at the optimum rate for plant growth.

Genetic resources

We are not aware of any genetic material in *Brassica napus* that is currently resistant to the pod midge. However, there is no shortage of characters that could be selected to this end, ranging from host recognition cues (Cook et al., 2013b) to characters conferring constitutive resistance such as changes to pod size, pod wall chemistry and resistance to pod shattering (Cook, 2009).

8.4.10. Factors potentially influencing future risk

The area of OSR production has increased since 1984 but has fallen in recent years due to lower returns and higher risks. If OSR production picks up again and its frequency in the rotation is high, it could lead to increased populations of pod midge as these weak fliers will have less far to travel to infest a new crop. However, any further reductions in crop area grown, in reponse to difficulties of controlling CFSB for example, would have the opposite effect.

Loss of insecticide actives puts greater pressure on the existing range of chemistry, especially those classes of compound that are cheaper, notably pyrethroids. Without the assiduous use of pest thresholds and rotation in the use of different actives, there is a risk that more pests will become resistant to insecticides. Pod midge is probably less susceptible to the development of resistance than many oilseed rape pests as it is late to migrate to the crop and therefore less likely to receive sprays targeted at other pests.

Climate change could cause pod midge to begin migration from overwintering sites earlier in the year and over a longer period of migration (Eickermann et al., 2013). It is suggested that such changes can make accurate timing of control measures more difficult (Harrington et al., 2001).

8.4.11. Recommendations for research and other actions

1 Keep a watching brief on the incidence and severity of pod midge damage for any changing trend.

2 Assess the risk of resistance using the outputs of AHDB project RD-2012-3780 ‘Combating insecticide resistance in major UK pests’ when available.

3 Monitor resistance status of pod midge.

4 As part of an effort to reduce insecticide pressure on all pests in oilseed rape, consideration should be given to the most appropriate advice to offer on pod midge management and how to deliver it. In particular this should include whether it is appropriate to offer advice on pod midge immigration through a DSS such as proPlant in the absence of any quantitative threshold for this pest.

5 Plant breeding for resistance of oilseed rape to its pests has been neglected. Routine screening of breeders’ lines for pest as well as for disease resistance should be encouraged.

6 As with other rape pests, there may be scope to make greater use of existing datasets to model the effect of landscape and field margin management on pod midge and its natural enemies.

7 New and safe insecticide actives are urgently needed for oilseed rape pests.

8.5. Cabbage seed weevil

8.5.1. Description and geographic distribution

The cabbage seed weevil, *Ceutorhynchus obstrictus*, synonym *C. assimilis*, (hereafter referred to as the seed weevil) is a 2-3 mm long grey beetle with a pronounced down-curved rostrum or 'snout' typical of many weevils. The larvae are legless, creamy-white in colour with a brown head capsule and up to 5 mm long. This pest is widely distributed throughout the rape growing areas of the UK, Europe and North America (Gratwick, 1992; Alford et al., 2003b; Williams, 2010).

8.5.2. Life cycle

The seed weevil is a brassica specialist that has a single generation each year. Adults emerge from overwintering sites amongst perennial vegetation and leaf litter in woodland and field margins from April onwards (Bonnemaison, 1957; Dmoch, 1965; Williams and Ferguson, 2010) and initially feed on flowering Brassicaceae in field margins or in flowering rape for about two weeks while females' ovaries mature. Both sexes usually migrate to oilseed rape during flowering when temperatures exceed 13-15 °C (Williams, 2010). Eggs are laid singly in pods through holes bored with the rostrum, young pods 20-40 mm long being preferred. Caged females lay 24-240 eggs each (Bonnemaison, 1957; Dmoch, 1965; Lerin, 1991). The larvae have three instars and each consumes about five seeds in the course of development before boring a hole through the pod wall to emerge and fall to the ground, where they burrow up to 130 mm into the soil to pupate. From late July, new generation adults emerge and, after feeding on brassicaceous plants for a week or more, they seek overwintering sites (Williams, 2010).

8.5.3. Damage and pest status

The consumption of five seeds by a larva in a pod represents a loss of about 8-15% of seed in the pod, reducing yield of the pod by about 18%, and it has been estimated that an average of one weevil per plant would reduce crop yield by about 4% (Williams, 2010). More severe damage can occur indirectly, through the provision of egg-laying sites in pods for the pod midge, which makes use of seed weevil feeding and oviposition holes. Seed weevil damage may be more important on spring oilseed rape (Oakley, 2003).

In 2007, Holland and Oakley (2007) described the status of the seed weevil as "incidence low and remaining so". In the intervening years ADAS Pest, Weed and Disease Incidence Reports suggest that this has remained true for England but that Scotland experienced a notable peak in seed weevil abundance in 2008 and 2009 (ADAS, 2013; Lole, 2009, 2010, 2011). Despite the low incidence of seed weevils, this pest was cited as the reason for 9%, 4%, 10%, 15% and 10%* of insecticide applications to oilseed rape in 2006, 2008, 2010, 2012 and 2014*, respectively (* in

2012 and 2014 identified as ‘weevils’ only (Fig. 6) (Garthwaite et al., 2009, 2011a, b, 2013, 2015). This suggests that many applications are made as ‘insurance sprays’, probably as tank mixes with fungicides (Ellis et al., 2009).

8.5.4. Thresholds for control

The threshold widely published by AHDB for seed weevil control is >0.5 weevils/plant during flowering in northern Britain and 1 weevil/plant elsewhere (AHDB, 2014c; Berry et al., 2012; Ellis et al., 2009). There has been a certain amount of confusion over this, however (see incorrect citations in Lole, 2010; Williams, 2010), and this may be related to the continued availability on the web of an earlier document published by AHDB Cereals & Oilseeds (AHDB Cereals & Oilseeds, 2002). However, the latter guide did suggest that the threshold could be lower in the north if a fungicide is also needed, a practice that is widely adopted across the UK when tank-mixing with a fungicide (Ellis et al., 2009). It has been recommended that the threshold for control of the cabbage seed weevil may be halved if significant pod midge damage is likely (AHDB Cereals & Oilseeds, 2002; Lane and Gladders, 2000; Williams, 2010). No difference in threshold for winter and spring oilseed rape crops is specified. There is potential to develop improved thresholds for pod midge / seed weevil (Ellis et al., 2009).

8.5.5. Monitoring and forecasting

Monitoring for assessment of adult weevil populations in relation to spray thresholds is done by counting weevils on plants during flowering (Berry et al., 2012; Oakley, 2003). We have been unable to find any clear advice to growers about how this should be done but Ellis et al. (2009) suggested that they should be monitored by beating 25 randomly chosen plants over a white tray, similar to monitoring advice then current for pollen beetles. Adult seed weevils can also be caught by a range of trapping methods (Williams et al., 2003) and trap catches can be enhanced by the use of colour and odour cues (Williams and Cook, 2010).

Seed weevils are strong fliers at temperatures above 15 °C and may migrate considerable distances from their overwintering sites to oilseed rape crops in spring, attracted by the odour and colour of flowering oilseed rape (Williams and Cook, 2010; Williams and Ferguson, 2010). Although they fly upwind in response to host plant odour, the tendency to colonise crops more abundantly at the downwind side does not appear to be marked. Monitoring should not be restricted to a small area of the crop as this pest shows a patchy and dynamic distribution within crops and is particularly edge-distributed in the immigration phase (Williams and Ferguson, 2010). Unlike the pod midge, edge distribution diminishes and is often lost as weevils move into the crop.

Spring emergence of the seed weevil has been shown to be accurately predicted in mainland Europe by the DSS proPlant, which incorporates a weather-based phenological model (Johnen et al., 2010, 2013; Johnen and von Richthofen, 2013). This DSS is not currently in use in the UK for seed weevil.

8.5.6. Control measures

Growers are advised to “apply a pyrethroid spray approved for use during flowering if the threshold is exceeded. This should be applied [before] petal fall and before too many eggs are laid” (Oakley, 2003). Practice has reflected this advice, the top five insecticide formulations applied to oilseed rape in 2006, 2008, 2010, 2012 and 2014 all being pyrethroids and comprising >90% of the insecticide treated area (Garthwaite et al., 2009, 2011a,b, 2013, 2015). Latterly, in the light of the development of widespread pyrethroid resistance in pollen beetles, strong advice has been issued by AHDB to consider using neonicotinoids, indoxacarb or pymetrozine as alternatives to pyrethroids for all spring and early summer insecticide applications and that no more than one application of any one class of actives should be made (AHDB, 2016c). There are restrictions on some of these for use in flowering crops (e.g. pymetrozine) due to their potential toxic effects on bees, so the label should be checked before use.

8.5.7. Evolution of resistance to insecticides

Recent tests provided evidence that insecticide resistance in the seed weevil is a real risk. Samples from the German region with the longest tradition of high intensity oilseed rape production have shown pyrethroid resistance factors of up to 140 (Heimbach and Müller, 2013). In contrast, Zimmer et al. (2014) surveyed samples from several European countries and concluded that there was no evidence of resistance in the seed weevil. This suggests that the incidence of resistance is as yet very localised but it could become more of an issue in future and the situation should be carefully monitored.

The use of insecticides during flowering for control of seed weevil is likely to harm the parasitoids of pollen beetles as they are active during flowering (Ferguson et al., 2013). Any agronomic practices that may harm populations of pollen beetle parasitoids potentially put more pressure on the management of resistance in the pollen beetle because parasitoids exert significant control on pollen beetles (Ulber et al., 2010b).

8.5.8. Biological control

More than 30 species of parasitoids have been reported to parasitise the seed weevil in Europe. Most are larval ectoparasitoids. The three most common and widespread of these are the pteromalids *Trichomalus perfectus*, *Mesoplobus morys* and *Stenomalina gracilis* (Ulber et al., 2010b). Rates of parasitism in winter oilseed rape in the UK are variable but can exceed 50% (Ulber et al., 2010b). In Switzerland larval ectoparasitism has been found to account for 7-15% of generational mortality (Haye et al., 2010). The spatial distribution of *T. perfectus* in a winter oilseed rape field was found to be closely associated with that of the seed weevil (Ferguson et al., 2000). It is likely that parasitism exerts significant degree of control over this pest.

As with pod midge, seed weevil larvae are vulnerable to generalist epigaeic predators such as carabid beetles, staphylinid beetles and spiders when they fall to the ground to pupate. Up to 820 larvae per m^2 have been found to fall from plants in Germany and adult emergence from these may be reduced by as much as 39% through the activity of ground predators (Buchs and Nuss, 2000). In the UK, the carabids *Amara similata*, *Anchomenus dorsalis, Pterostichus madidus* and *P. melanarius* are active in rape crops during the fall of *Ceutorhynchus* spp. larvae (cabbage seed weevil and cabbage stem weevil) from plants and, of these, *A. dorsalis* was spatially associated with the larvae (Warner et al., 2008). Five carabid species, including all of those listed above except *P. melanarius*, feed on the larvae of weevil pests of oilseed rape in the laboratory or in the field (Williams et al., 2010). Haye et al. (2010) believed that carabid predators were probably mainly responsible for the 60–80% mortality of seed weevil larvae from the time larvae fell to the soil until adult emergence.

The seed weevil is known to be susceptible to the entomopathogenic fungi *Metarhizium anisopliae* and *Beauveria bassiana* and to the entomopathogenic nematode *Steinernema feltiae* in experimental field applications but entomopathogens are not expected to become available as commercial products in the short term (Hokkanen et al., 2003). None of the significant coleopteran pests of oilseed rape are susceptible to commercially available strains of the entomopathogenic bacterium *Bacillus thuringiensis* and it is unclear whether any promising strains have been isolated (Hokkanen et al., 2003). The potential for conservation of naturally-occurring entomopathogens to improve the management of oilseed rape pests is also unclear.

8.5.9. Cultural control and conservation biological control

Tillage

Unlike all other key parasitoids of oilseed rape pests, the pteromalid parasitoids of the seed weevil overwinter outside the crop in perennial seminatural habitats (Ulber et al., 2010b) and therefore, like their host, they are not affected by tillage. There would therefore be no advantage in modifying tillage to conserve seed weevil parasitoids. By contrast, populations of some epigaeic predators are enhanced in minimum tillage or conservation tillage regimes, where soil disturbance is reduced and a richer habitat is provided by crop residues and greater weed diversity, whereas ploughing reduces the survival of many carabids (Holland, 2004; Kromp, 1999).

Trap cropping

Like the pollen beetle, the seed weevil shows greater attraction to the odour of turnip rape (*Brassica rapa*) than to that of oilseed rape (Cook et al., 2006). In Canada and the UK, perimeter trap crops of turnip rape have shown potential for reducing populations of seed weevils in the main crop of oilseed rape that they surround, potentially reducing the need for insecticide, although the strategy appeared rather less successful than for pollen beetle (Cárcamo et al., 2007; Cook et al., 2004, 2006). In order to develop trap cropping into a practical IPM strategy, further work is needed to build on the findings in AHDB Project Report 504. This research should focus on the selection of suitable cultivars for the main crop and for the trap crop. These should have contrasting flowering phenologies and attractiveness to pests but should have similar agronomic requirements and good yield (Cook et al., 2013a).

Temporal targeting of insecticides

Parasitoids are at risk from insecticides applied to oilseed rape (Ulber et al., 2010a). Studies of the migration phenology of the seed weevil and its parasitoids on the crop show there is a time-lag between the arrival of the pest and the arrival of the parasitoid, offering a time-window of some weeks for insecticide to be applied for seed weevil control before large numbers of its parasitoids arrive (Alford et al., 1996; Murchie et al., 1997; Oakley, 2003 ; Williams and Ferguson, 2010). Current UK recommendations for the seed weevil are in accord with this timing (Oakley, 2003). The same immigration time-lags exist for other oilseed rape pests and their parasitoids (Ulber et al., 2010a; Williams and Ferguson, 2010).

The migration of a succession of pests into the crop brings the risk that insecticides targeted at one pest may injure the parasitoids of another. For example, parasitoids of the pollen beetle are present in the crop during flowering when treatment for seed weevil is recommended (Oakley, 2003 ; Williams and Ferguson, 2010). Phenological models for the immigration of several key parasitoids of oilseed rape pests have been developed (Johnen et al., 2010). Once validated, these could be integrated into a DSS such as proPlant to enable the timing of insecticide applications to be optimised for parasitoid conservation. The diel periodicity of parasitoid activity in the crop suggests there may also be an opportunity to conserve parasitoids by targeting treatments early in the day before parasitoids begin to fly (Ferguson et al., 2013). The effectiveness of this approach remains to be tested (Johnen et al., 2010).

Spatial targeting of insecticides

If it is necessary to apply insecticide to a trap-cropping system, it may be sufficient to spatially target the application to the trap crop only, where the pest is concentrated, reducing pesticide use. Given the patchy distributions of pests within the crop, often edge-distributed and/or related to wind direction, there is also potential to spatially target insecticides in normal cropping systems, conserving natural enemies in untreated areas (Ulber et al., 2010a; Williams and Ferguson, 2010). However, the ability to predict pest distributions in crops is not an imminent prospect, except for markedly edge-distributed species such as the pod midge.

Landscape management

As discussed in the section on pod midge, there is good evidence that increased landscape complexity, including more semi-natural habitats, increases the activity of natural enemies. However, despite many recent studies, there is conflicting evidence for effects on biocontrol of pests. To date there have been no studies that directly address effects on the seed weevil.

Margin management

The potential to manage margins not only to enhance the abundance and diversity of generalist predators but also to maintain local populations of parasitoids by including brassica species as ‘banker plants’ has been investigated under Defra Project IF0139 (DEFRA, 2009). Field margin mixtures containing Brassicaceae were found to have more oilseed rape pest parasitoids, including those of the seed weevil, than those without Brassicaceae. Of the Brassicaceae compared in small plot experiments as candidates for inclusion in margin mixtures, forage rape cultivars appear to have the most potential for promoting parasitoids of several rape pests without promoting the pests themselves (Cook, 2014). In a small plot experiment, Kovács et al. (2013) found that seed weevil infestation was highest on oilseed rape but rates of seed weevil parasitism were highest on *Brassica juncea and B. rapa* and they suggested that such plant species could be used to enhance the natural enemy complex. This approach is being further investigated under Defra Project IF01122 (DEFRA, 2012; Cook et al., 2016).

Crop nutrition

There is evidence that the level of nitrogen and sulphur fertilisation influence seed weevil host plant preference and infestation levels. The relationships do not appear to be linear and there may be an interaction between the effects of nitrogen and sulphur. Nevertheless, there is a consensus that for each nutrient separately high levels tend to increase infestation (Aljmli, 2007; Blake et al., 2010, 2011; Veromann et al., 2013). This effect may be mediated by changes in host-plant volatiles (Veromann et al., 2013). However, Blake et al. (2011) concluded that under Canadian conditions “fertiliser management regimes currently recommended were considered to be optimal for management of [the seed weevil] as the yield benefits from higher rates of nitrogen fertilisation would more than compensate for increased level of infestation.”

Genetic resources

In the last ten years there has been a major effort in Canada, where the seed weevil is an exotic pest with few natural enemies, to breed seed weevil resistant cultivars of rape. Introgression of resistance from white mustard, *Sinapis alba*, to oilseed rape produced genetic lines resistant to the weevil in replicated field trials (Dosdall and Kott, 2006; Ross et al., 2008; Shaw et al., 2009; Tansey et al., 2010; Ulmer and Dosdall, 2006). The resistance is thought to be both antixenosis- and antibiosis-based and to be mediated by glucosinolates and flavonoids (Lee et al., 2014; Tansey et al., 2010).

There has been much interest over the last 20 years in the potential to develop transgenic cultivars of brassicas that express pest-resistance-conferring toxins, particularly proteinase inhibitors (PIs), plant lectins and Bt toxins derived from *Bacillus thuringiensis* (Alford, 2003; Melander et al., 2003). Much of this work has focussed on lepidopteran and sucking pests and on the risk of gene flow into wild relatives of oilseed rape (e.g. Lei et al., 2011). Studies on resistance to coleopteran pests do not appear to have met with conspicuous success. In the case of the seed weevil, the effect of oilseed rape expressing the PI oryzacystatin I on the development of larvae was not promising (Girard et al., 1998). It is likely that future research on transgenic oilseed rape expressing Bt-toxin may focus on introgression of the Cry3 gene as this codes for the protein most toxic to Coleoptera (Scholte and Dicke, 2005).

8.5.10. Factors potentially influencing future risk

The potential for development of insecticide resistance in the seed weevil is a risk that should be taken seriously. Loss of insecticide actives increases this risk. AHDB guidance on the use of insecticides in spring and early summer should be carefully followed (AHDB, 2016c).

Modelling suggests that climate change could increase both the geographic range and the abundance of seed weevils in Canada (Olfert and Weiss, 2006). Given that the seed weevil can already be found abundantly across the UK, any impact of climate change on the pest status of the seed weevil in the UK may depend upon effects on the weevil’s overwintering success and on the synchrony of its emergence with the flowering stage of oilseed rape crops (Bale and Hayward, 2010; Junk et al., 2012).

8.5.11. Recommendations for research and other actions

1. Keep a watching brief on the incidence and severity of cabbage seed weevil damage for any changing trend.
2. Assess the risk of insecticide resistance using the outputs of AHDB project RD-2012-3780 ‘Combating insecticide resistance in major UK pests’ when available.
3. Monitor resistance status of the seed weevil.
4. Consideration should be given as to whether it is appropriate to offer advice on seed weevil immigration through a DSS such as proPlant, as part of an effort to reduce insecticide pressure on all pests in oilseed rape.

5. Consider clarification of advice on monitoring methods for the seed weevil.
6. Should the threat of resistance in the seed weevil increase, consideration should be given to up-dating control thresholds for seed weevil with and without pod midge.
7. Developments in plant breeding for oilseed rape resistance to the seed weevil should be monitored. Promising lines should be tested in UK conditions for resistance not only to the seed weevil but also to other pests. Routine screening of breeders' lines for pest as well as for disease resistance should be encouraged.
8. In order to develop trap cropping into a practical IPM strategy, further work is needed to build on the research reported in AHDB Project Report 504. This research should focus on the selection of suitable cultivars for the main crop and for the trap crop with contrasting flowering phenologies and attractiveness to pests but with similar agronomic requirements and good yield.
9. As with other rape pests, there may be scope to make greater use of existing datasets to model the effect of landscape and field margin management on seed weevil and its natural enemies.
10. New and safe insecticide actives are urgently needed for oilseed rape pests.

8.6. Rape winter stem weevil

8.6.1. Description and geographic distribution

The rape winter stem weevil, *Ceutorhynchus picitarsis*, (hereafter referred to as RWSW) is a typical ceutorhynchid weevil with a pronounced down-curved rostrum or 'snout'. The size range of the adult is slightly larger than the seed weevil, at 2.4 – 3.7 mm long, and it is metallic black with distinctive reddish tarsi (Evans, 2007; Winfield, 1986). The larvae are white in colour and legless with a yellow-brown head capsule and grow to 4-5 mm long in the third and final instar. The distribution of this weevil is widespread in Europe (Balachowsky, 1963).

8.6.2. Life cycle

RWSW is a brassica specialist that has one generation a year. Unlike other weevil pests of oilseed rape, it lays eggs in the autumn and early winter; its life cycle similar to that of the cabbage stem flea beetle. Adults migrate from aestivation sites to oilseed rape crops in late September and October and eggs are laid mainly from September to mid-November (Alford et al., 2003b; Winfield, 1986). Eggs are laid in batches in punctures or crevices at the base of leaf petioles. The larvae bore into the petioles to feed and later invade the main stem and developing crown. Feeding continues through the winter and, in spring, mature larvae fall from the plant and pupate in the soil at depth of 3-4 cm (Balachowsky, 1963). New generation adults emerge in May-June and aestivate in leaf litter in woodland margins (Büchi, 1986).

8.6.3. Damage and pest status

Heavy infestations can cause distortion of plants, stunting and death of the terminal bud, leading to the production of many lateral stems. Plants attacked early in autumn may be killed (Alford et al., 2003b; Ellis et al., 2009; Winfield, 1986). Damage symptoms may not be visible until spring. RWSW is likely to have more effect on yield than the cabbage stem weevil as the latter does not migrate to the crop until the spring (Ellis et al., 2009), but plants that survive attack are capable of good compensation through the growth of lateral racemes (Burghause, 2008).

In the 1980s RWSW was reported to be a widespread pest of oilseed rape in the east of England (Lane and Cooper, 1989; Winfield, 1986). Alford et al. (2003b) stated that it was locally and sporadically important, most frequently found to be a pest in England, France, Germany and Switzerland. In the mid 2000s, significant problems were reported in south-east Scotland and as far north as Aberdeenshire (Evans, 2007; Oxley and Evans, 2009). In their review of arthropod pests for AHDB Cereals & Oilseeds, Holland and Oakley (2007) stated that numbers of the pest were currently increasing in the infested areas of the Midlands and East Anglia and they assessed the pest status of RWSW as “incidence increasing”. In 2008, ADAS reported infestations of RWSW in Cumbria but not elsewhere (Lole, 2009). Ellis et al. (2009) stated that RWSW was a potentially serious pest of winter oilseed rape and that recent reports had indicated severe damage to crops in Cambridgeshire and Northumberland, although they cautioned that confirmation was needed that the weevil species responsible was indeed RWSW.

In recent years national Defra-funded surveys of autumn and spring pest incidence in oilseed rape in England, conducted by Fera and published on the CropMonitor website, indicate that there was a decline in the incidence of RWSW in England during the years in which noenicotinoid seed treatments were used (2006-2014). However, there are indications that numbers have been rising again since the ban was implemented in the 2014 season (Fig. 12). The incidence of RWSW was generally highest in the East, and Midlands and West regions, lowest in the South-East and the South-West regions.

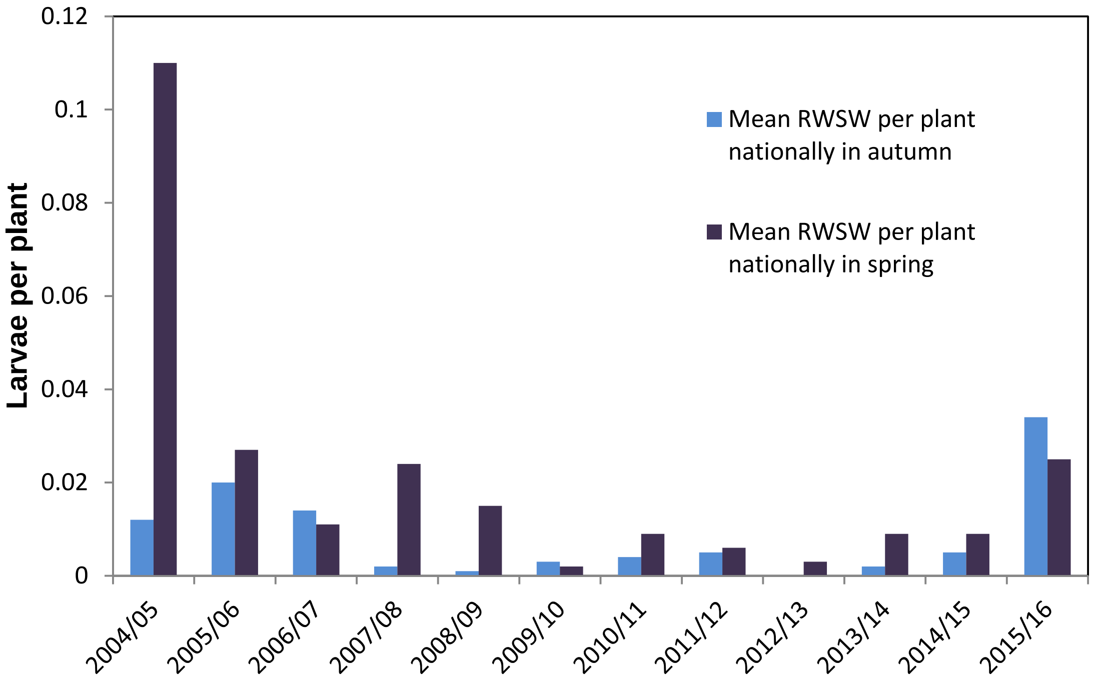


Figure 12. Mean number of RWSW larvae per plant in autumn and spring samples of oilseed rape from sites across England over nine years. 25 plants per site dissected, 100 sites in autumn, 50 sites in spring. Source: Fera CropMonitor http://www.cropmonitor.co.uk/wosr/surveys/wosr.cfm

By contrast, there remains concern about the incidence of RWSW in Scotland and in the north-east of England. ADAS Pest, Disease and Weed Incidence Reports stated that there were continued RWSW problems in Northumberland in 2009 and 2010 and that in Scotland in 2010 the pest had spread north to Aberdeenshire, where “about 100% of the oilseed rape planted …… was infected by rape winter stem weevil” causing yield losses estimated at 0.5-0.6 t/ha (Lole, 2010, 2011). They suggested that an autumn insecticide spray for RWSW might become standard practice in affected areas. In the report for 2012, no further trend in RWSW incidence was reported (ADAS, 2013). RWSW were reported in some crops in the ADAS Arable Crop Report for March 2014 (AHDB, 2014b) but have not been mentioned in those reports since.

These reports bear out the statement that the RWSW “is a locally and sporadically important pest of winter rape” (Alford et al., 2003b). Its potential to seriously damage crops warrants vigilance and more information is needed on its geographic distribution (Ellis et al., 2009).

8.6.4. Thresholds for control

No spray threshold exists for RWSW in the UK. In France, current advice from the French organisation, CETIOM, is that crops should be sprayed after the first weevils are caught in traps in autumn, however few are caught (CETIOM, 2014a). Ellis et al. (2009) recommended that establishment of a UK threshold for this pest should be given priority.

8.6.5. Monitoring and forecasting

Growers in Scotland are advised to monitor crops for RWSW from September although there is no advice on the method to be used in the UK. In France, CETIOM advises that RWSW should be monitored using a trap (presumably a water trap) placed amongst the vegetation in autumn at 3-4 leaf stage (CETIOM, 2014a). RWSW colonises crops in France over a period of time in several peaks of flight activity and numbers caught in water traps are not found to reflect infestation levels well (Robert, 2013). As RWSW aestivates outside crops in leaf litter in woodland edges (Büchi, 1986), it may be edge-distributed at the beginning of immigration to the crop. Monitoring for RWSW at the crop edge is likely to provide an early indication of immigration but, if it is to reflect the risk to the whole crop, monitoring should not be confined to the edge.

Ellis et al. (2009) reported that more information was needed about the timing of immigration of RWSW to allow better temporal targeting of control. A phenological model for RWSW that would enable the proPlant DSS to forecast RWSW migration is under development (von Richthofen et al., 2010; Andreas Johnen pers. com.).

8.6.6. Control measures

The pyrethroid sprays that are recommended for cabbage stem flea beetle also give control of RWSW (Büchi, 1986; Oakley, 2003 ; Oxley and Evans, 2009). The advice is to spray before adults begin to lay eggs on the crop. Oxley and Evans (2009) advised that there is a 3-4 week window from September for RWSW control before they have begun to lay eggs and that a pyrethroid can be applied as a tank mix with a light leaf spot fungicide treatment if the timing is appropriate.

CETIOM (2014a) recommends that sprays should be applied 8-10 days after the first weevils are caught in traps but if RWSW arrives early in the autumn, this delay can be longer, allowing later immigrating RWSW to be targeted at the same time (Robert, 2013). Neonicotinoid insecticide seed treatments that were formerly available are not thought to be effective against RWSW (Oxley and Evans, 2009).

8.6.7. Evolution of resistance to insecticides

There are no reports of insecticide resistance in this pest and we have been unable to find evidence that it has been tested for. Robert (2013) expressed concern that infestations by RWSW and cabbage stem flea beetle had become very important in some areas of France since 2009/2010 and that despite repeated treatments, farmers had been unable to control them. She suggested that, amongst other hypotheses, this could be explained by re-infestation after treatment or by the presence of populations resistant to pyrethroids.

8.6.8. Biological control

The parasitoids of RWSW appear to be relatively little studied. It has been reported in France that larvae are frequently parasitized by ichneumonids of the genus *Tersilochus* (Balachowsky, 1963). Jourdheuil (1960) suggested that this was *Tersilochus stenocari* but it is possible that *T. obscurator*, a parasitoid of the cabbage stem weevil that is present on the crop from mid-April (Williams and Ferguson, 2010), also parasitizes mature RWSW larvae before they emerge from plants to pupate. The larvae are also parasitised by the braconids *Diospilus oleraceus* and *Sigalphus obscurellus* (Holland and Oakley, 2007; Jourdheuil, 1960). The braconid *Microctonus melanopus* attacks adult RWSW as well as adult cabbage stem flea beetle, cabbage seed weevil and cabbage stem weevil (Ulber et al., 2010b).

In common with other pests of rape, RWSW larvae are likely to be vulnerable to predation by epigaeic predators when they fall to the ground to pupate (Buchs, 2003b). Prepupae and pupae in the soil can be attacked by nematodes of the family Steinernematidae and by the entomopathogenic fungi *Beauveria bassiana* and *B. globulifera* (Balachowsky, 1963). The potential for managing entomopathogens to improve control of oilseed rape pests is unclear (Hokkanen et al., 2003).

8.6.9. Cultural control and conservation biological control

Tillage

RWSW is not vulnerable to tillage as the new generation weevils that emerge from the soil beneath the crop in May-June seek aestivation sites outside the crop, and do not migrate to new crops until after they are established in autumn (Alford et al., 2003b; Büchi, 1986; Winfield, 1986). However, it is likely that the *Tersilochine* parasitoids of RWSW are present in cocoons in the soil at the time of pre-drilling cultivations and that they, together with many epigaeic predators, would benefit from reduced or no tillage (Holland, 2004; Nilsson, 2010).

Trap cropping

RWSW has been found to prefer turnip rape to oilseed rape (Burghause, 2008), suggesting that trap crop strategies for their management may be worth investigating. However, results of trap-cropping experiments with other stem-mining pests have been mixed and have not been promising for the cabbage stem weevil and the rape stem weevil (Barari et al., 2005; Nerad et al., 2004).

Mixed cropping

Experiments have been conducted in France on mixed plantings of oilseed rape with legume mixtures that are designed to be killed by frost during the course of the winter. RWSW damage was reduced in mixed plantings and there was no yield penalty associated with the legume companion planting (Landé et al., 2013).

Landscape management

As discussed in the section on pod midge, there is good evidence that greater landscape complexity and greater abundance of semi-natural habitats increase the activity of natural enemies. However, despite many recent studies, there is conflicting evidence for effects on biocontrol of pests. To date there have been no studies that directly address effects on RWSW.

Genetic resources

We are not aware of any research on plant resistance specifically against RWSW in oilseed rape. However, oilseed rape lines and cultivars have recently been tested for resistance to the cabbage stem weevil and the rape stem weevil, *Ceutorhynchus napi*, with some success (Eickermann and Ulber, 2010; Eickermann et al., 2011; Schaefer-Koesterke and Ulber, 2013) and those lines showing promise may be worth testing for resistance to RWSW also.

8.6.10. Factors potentially influencing future risk

Too little is known about the population dynamics and ecology of this very sporadic pest to speculate with any confidence about the factors that may increase or decrease the risk it poses. In his investigation of the potential threat of invasive species to crops under climate change, Evans (2012) cited RWSW as an example of a pest problem recently arising in Scottish crops but did not test it under future climate change scenarios using the CLIMEX model, presumably through lack of appropriate ecological data.

8.6.11. Recommendations for research and other actions

1. Keep a watching brief on the incidence and severity of RWSW damage for any changing trend.
2. Should RWSW become a more established (rather than sporadic) pest in any region, assess the risk of resistance using the outputs of AHDB project RD-2012-3780 'Combating insecticide resistance in major UK pests' when available. Like the cabbage stem flea beetle, this stem borer is present though most of the crop's development and risks being exposed to insecticides targeted at other pests and hence receiving multiple exposure.
3. Monitor insecticide resistance status should a significant risk be identified.
4. Given the potential severity of this pest, RWSW should continue to be assessed in Fera's regionally-referenced national surveys of autumn and spring pest incidence, as published on CropMonitor. A similar systematic survey in Scotland would be valuable. In spring samples, these surveys must be careful to distinguish RWSW larvae from those of other stem weevils (Ellis et al., 2009).
5. Better information on the factors governing the timing of RWSW immigration to crops is needed to allow appropriate temporal targeting of control. Consideration should be given as to whether it is appropriate to offer advice on RWSW immigration through a DSS such as proPlant (when the model for RWSW has been incorporated into this DSS).
6. Advice on appropriate monitoring methods for RWSW is needed.
7. A control threshold for RWSW is needed, based on studies of the impact of the pest on growth and yield (Ellis et al., 2009).

8.7. Peach–potato aphid

Three species of aphid can occur in oilseed rape in either winter or spring sown crops. These include the peach–potato aphid, *Myzus persicae,* the cabbage aphid, *Brevicoryne brassicae,* and the turnip aphid, *Lipaphis erysimi* (Alford et al., 2003; Ekbom, 2010; AHDB, 2015a). The latter two species are associated almost exclusively with cruciferous crops, but *M. persicae* has a very wide host range, of which oilseed rape is but one. Of the three species, *M. persicae* is by far the most abundant and almost exclusively the species against which control measures are targeted in winter oilseed rape. *Brevicoryne brassicae* can overwinter in autumn sown crops and lays its eggs there, and, where spring oilseed rape is grown in proximity to winter oilseed rape, the spring crop can be more vulnerable to infestation (Ekbom, 2010). *Lipaphis erysimi is* quite rarely found in UK crops (Lane and Gladders, 2000). All three can transmit turnip yellows virus (TuYV, formerly known as beet western yellows virus), but *B. brassicae* is also a major vector of cauliflower mosaic virus (CaMV) and turnip mosaic virus (TuMV) (Lane and Gladders, 2000; Ekbom, 2010). For the purposes of this review, only *M. persicae* and *B.brassicae* merit full consideration.

8.7.1. Description

Adult alate *M. persicae* are medium-sized dark-looking aphids with pale green undersides. The upper abdomen has characteristic black pigmentation in a patch and the cornicles are slightly swollen (Gratwick, 1992; Blackman and Eastop, 2007). Apterous aphids vary in colour from pale green to dark red, almost black, with many intermediate colours.

8.7.2. Distribution

Myzus persicae is one of the most widely distributed aphid species in the world, having adapted to many crops in addition to brassicas, including potatoes, many vegetable crops, lettuce, ornamentals, tomatoes and sugar beet (Blackman and Eastop, 2007; many chapters in van Emden and Harrington, 2007). In the UK it is largely anholocyclic (asexual), due to the dearth of peach trees, and its distribution is related to overwintering temperatures. Thus it is more common in the south-west of the UK than in the north–east. *Myzus persicae* is the most common aphid to be found on oilseed rape, colonising the crop in the autumn when it migrates from summer host plants, often from volunteer oilseed rape growing in neighbouring fields after harvest. When a winter has been too mild to cause *M. persicae* significant mortality, winter oilseed rape is often the source of spring and early summer migrations of this species to other crops.

8.7.3. Life cycle

Myzus persicae originally evolved as a host-alternating (holocyclic) species, migrating between its primary woody host, peach trees (*Prunus persicae*) in Europe, and its many secondary hosts on which it survives the summer months (Williams and Dixon, 2007; Blackman and Eastop, 2007). In the holocyclic form, eggs hatch on the primary host in spring, undergo two or three generations on the tree, and then winged individuals develop that migrate to secondary hosts in early summer. On these secondary hosts they undergo many generations during the summer months, the number of generations depending on temperature and the host plants they colonise, some plants being better hosts than others. In the autumn, in response to shorter days and lower temperatures, they produce specialised winged individuals (gynoparae and males) that return to the primary host. Once there, the gynoparae give birth to egg-laying oviparae, which then mate with later-arriving males and lay their eggs around the buds of the peach, where they overwinter, thus completing the life cycle.

However, *M. persicae* has also evolved an anholocyclic, asexual life cycle which does not involve the formation of sexual morphs during the autumn, thus bypassing the egg-laying stages. The anholocyclic form overwinters as active stages on secondary hosts, provided that winter temperatures remain above their lethal limit (LD50 = -7°C; Bale et al., 1988). It is as anholocyclic aphids that this species represents the greatest risk to crops, not so much by direct feeding damage, but as a vector of many important plant pathogenic viruses, including TuYV which infects oilseed rape (AHDB, 2015b; Blackman and Eastop, 2007; Katis et al., 2007; Stevens et al., 2008; Stevens and Clark, 2009). The massive increase in the area of oilseed rape grown in the UK since the 1980s (Nicholls, 2016) has probably enhanced the national abundance of *M. persicae* by providing up to 700,000 hectares of suitable overwintering host plants annually, most of which are sown early enough for autumn migrants to colonise. Prior to that, these aphids would have colonised suitable overwintering weeds (Stevens et al., 2008), which would have been much scarcer, and would have been associated with the higher biodiversity of an uncultivated environment where aphids are more vulnerable to predation and parasitism than in cultivated fields.

8.7.4. Monitoring and forecasting

Several forecasting schemes are available for *M. persicae* (summarised in Harrington et al., 2007) but none in Europe are specifically designed for use in oilseed rape in the autumn. One model exists for forecasting aphid infection with TuYV in Australia (Maling et al., 2010). However, monitoring schemes are available to measure the migration of aphids into autumn-sown crops, involving the use of suction traps (Rothamsted Insect Survey, RIS; Harrington et al., 2007; Bell et al., 2015) and water traps (Stevens et al., 2008). Both are now funded and incorporated into AHDB's Aphid News. The water traps were set up in a network across the UK specifically to monitor the abundance of aphids at a local level, together with the incidence of TuYV that they were carrying. Aphids carrying virus were detected using an ELISA test specific for TuYV. The proportion carrying virus ranged from 5-20% in 2004, when autumn weather was not conducive to aphid migrations, to as high as 50-72% in 2007, when there was an Indian summer throughout

October and into November (Stevens et al., 2008). Similar fluctuations were recorded in water trap catches between 1994 and 2002. Very high incidences of TuYV were measured in aphids in 2007, and this correlated well with large numbers of aphids recorded within oilseed rape crops during the 2007/2008 winter (Stevens et al., 2008).

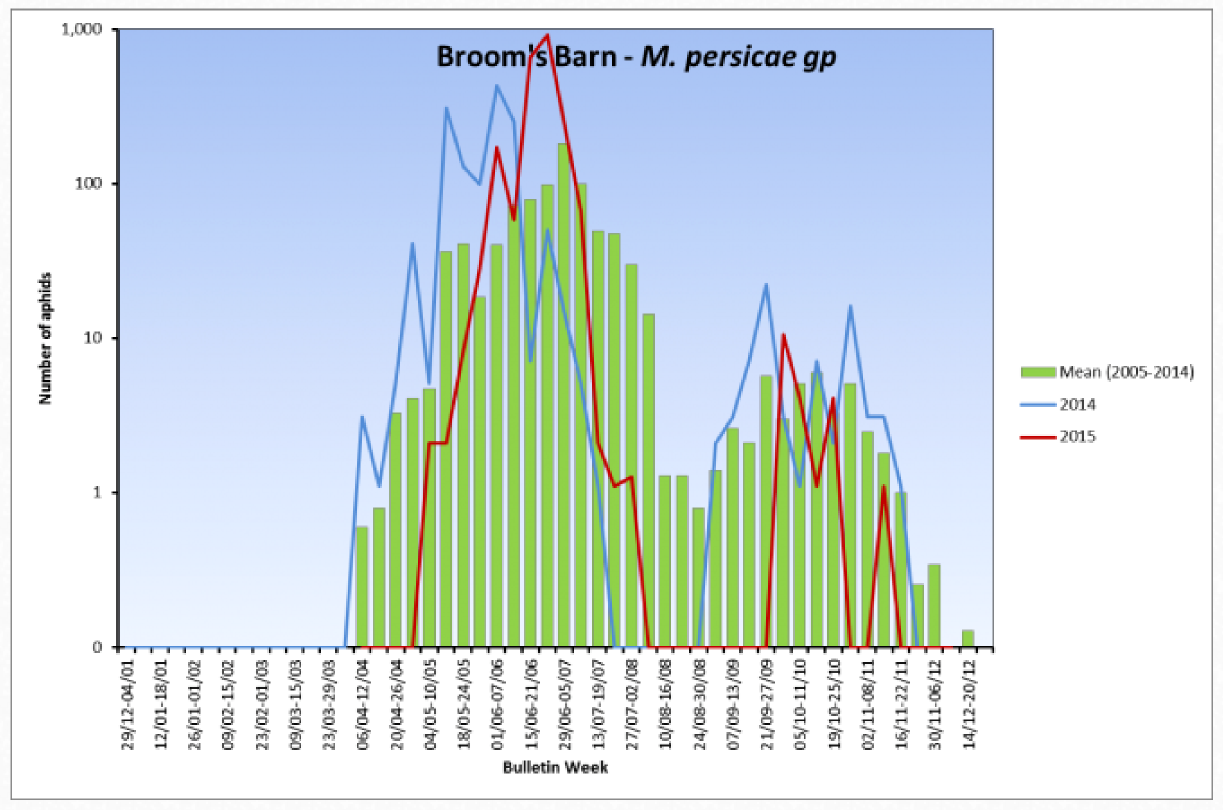


Figure 13. Example of data produced by the Rothamsted Insect Survey suction trap network: *Myzus persicae* caught in the Broom's Barn suction trap in 2015 (red line), compared to the previous year (blue line). The green columns are means for the previous 10 years.

As with cereal aphids, catches from the suction trap survey also give useful information about the timing of migrations of *M. persicae* in different parts of the country and allow comparisons of current migrations with the previous year and with the long-term (10 year) mean; this allows recipients of weekly AHDB Aphid News or the RIS Bulletins to judge whether the current year is earlier or later than usual. Such background knowledge helps decision-making regarding control measures. For example, *M. persicae* was not caught until early May at Broom's Barn in 2015, two weeks later than in the previous year, and the 10 year mean for this site (Fig. 13). Peak numbers in late June were very high in 2015. In the autumn of that year, numbers were lower than normal, falling almost to zero after early October (apart from a small peak at the end of the month), signifying relatively low immigration into oilseed rape crops that autumn, compared to the previous year (2014), when migration was high and continuous until mid-November, which was confirmed by field observations (Alan Dewar pers. comm.).

8.7.5. Damage

As mentioned earlier, aphids rarely build up to high numbers in oilseed rape in the autumn, so most of the damage caused by their presence is through infection of plants with TuYV (Jay et al., 1999).

In oilseed rape, symptoms of TuYV infection include reddening of leaf margins, interveinal yellowing and reddening, and purple tinges to leaf margins. Plants may also be stunted. However, these symptoms can also be caused by stress and by nutrient deficiencies, and have probably been attributed to such causes in previous years by growers, who have underestimated the effect of this disease on yields (Stevens et al., 2008; Stevens and Clark, 2009).

In years when up to 75% of aphids are carrying TuYV, primary aphid colonisation is the main cause of virus infection within the crop, e.g. 2007 or 2010 (Stevens et al., 2008; Dewar et al., 2011). Insecticides can do little to prevent such infection as they usually have an effect on the aphid only once it has probed and fed on the leaves, transmitting the persistent virus in the process. In years when the proportion of infective aphids is lower (>25<50%), e.g. 2008 (Dewar et al., 2011), secondary spread of virus and aphids within the crop is dependent on the prevailing weather. This spread can be considerable in some years if the winter weather is relatively mild (Stevens et al., 2008), with temperatures higher than the LD50 for *M. persicae* (-7^{o}C). In these situations, use of insecticides can reduce secondary spread. In cold autumns and winters, when aphid migration is curtailed early and the infective proportion of the few aphids that do manage to migrate is low (<25%), e.g. 2009 (Dewar et al., 2011), primary infection remains very low, and insecticide spray treatments are usually not necessary.

The consequences of infection by TuYV are manifested in reduced yields at harvest, reductions ranging from 10% (Smith and Hinckes, 1987) to as much as 46% in one study in Australia (Jones et al., 2007; reviewed by Stevens at al., 2008). The time of infection is important, as early infection has a greater effect on yield than later infection. In one study, plants infected in late September by artificial inoculation with infective aphids lost 10% of their yield, compared to 9% when infected in late October and only 1.5% with a late November inoculation (Dewar et al., 2011). In practice, control of the early migrants is often all that is required in some years, as aphid flight ceases below 15^{o}C (reviewed by Irwin et al, 2007) and so no further colonisation will take place if temperatures remain below that level in late autumn.

8.7.6. Thresholds for control

Currently there are no known thresholds for control of aphid vectors of TuYV.

8.7.7. Control measures

In the UK and across Europe good control of early aphid colonisers was achieved using neonicotinoid seed treatments, as mentioned in earlier sections of this review (Dewar et al., 2011). There was not much to choose between products containing thiamethoxam (Cruiser, Syngenta) and clothianidin + betacyfluthrin (Modesto, Bayer), both of which reduced aphid numbers by at least 85%, but the product containing imidacloprid (Chinook, Bayer) achieved much less control, largely due to the lower rate of neonicotinoid applied to the seed. Incidence of virus was also significantly reduced as a consequence of aphid control, but despite yield benefits up to 18%, these were not significant.

However, in the absence of neonicotinoid seed treatments for oilseed rape following EU restrictions (see section 6.4.5), aphid control currently relies on insecticide sprays, yet the advent of almost 100% resistance to pyrethroids (super-kdr), and also to pirimicarb (MACE) has rendered many of the approved alternatives impotent (Foster et al., 2013). The currently approved products that will give reasonable control of pyrethroid- and pirimicarb-resistant *M. persicae* are pymetrozine (Plenum) especially when applied with specific adjuvant oils (e.g. Toil) (Dewar and Evans, 2014) and thiacloprid (Biscaya, Bayer).

8.7.8. Resistance to insecticides

Resistance of *M. persicae* to insecticides has been monitored for many years, originally to measure resistance to organophosphate compounds, but latterly to pyrethroids and pirimicarb. (Foster et al., 2013; Fenton et al., 2010). Resistance to neonicotoinoids has also been recorded in southern France, Spain and Italy, mostly in fruit orchards, but not yet in the UK. In the UK now, most (>95%) *M. persicae* are resistant to both pyrethroids and pirimicarb. As mentioned above, one insecticide that is approved for aphid control in oilseed rape, is pymetrozine (Plenum), most effective when mixed with adjuvant oil (Dewar and Evans, 2014). There is an urgent need to find other modes of action before resistance to pymetrozine develops, as exposure to this insecticide is likely to increase selection pressure dramatically in future years if it is the only option left.

8.7.9. Biological control

As with other pests mentioned earlier, aphids are subject to predation and parasitism by a large array of natural enemies including predators, parasitoids and pathogens (Ekbom, 2010), so practices that enhance their abundance will contribute to biological control (Snyder et al., 2008). Conservation biological control using habitat manipulation has potential, particularly as advances to achieve this have been made for other aphid species in brassica systems (Chaplin-Kramer and Kremen, 2012; Chaplin-Kramer et al., 2013; van Rijn et al., 2013). For a discussion of conservation biological control of aphids, see section 6.4.8.

8.7.10. Host plant resistance

Breeding for resistance to *M. persicae* has been attempted on many occasions but with no lasting success, largely because of the need for polygenic resistance. However, breeding for resistance to TuYV may have greater promise. One resistant variety R54 was discovered in screening trials in 1994 (Graichen, 1994; Stevens et al., 2008) but the resistance gene has yet to be incorporated into a commercial variety. However, the variety Amalie (http://www.limagrain.co.uk/products/details/297.html), from Limagrain, has shown great potential recently, providing 30% increases in yield in the presence of TuYV compared to non-resistant varieties (Limagrain pers. com.). Its yield potential is average in comparison to standard recommended varieties when TuYV is absent or controlled (for example by seed treatments) in variety trials. However, with the withdrawal of seed treatments after December 2013, the usefulness of this variety may become more evident in future trials if virus infection is high enough.

8.7.11. Cultural control

Late sowing of oilseed rape is not an option for controlling aphids in this crop, as it is for cereals, because late sowing confers large yield penalties on oilseed rape. Also the crop is then more vulnerable to other pests such as slugs, flea beetles and pigeons. It is quite common now for oilseed rape to be sown after minimum tillage cultivations, which may have the effect of encouraging predation of aphids in the autumn and winter by soil-inhabiting predators, which are less disturbed than by conventional tillage (Holland 2004; Kromp, 1999; Kendall, 2002; Williams et al, 2010).

8.7.12. Research recommendations

Given the current over-reliance on a single active, pymetrozine, for *M. persicae* control, there are a number of important research recommendations:

1. Continue the suction and water trapping monitoring scheme (AHDB Aphid News) and consider using modern diagnostics to include information about the level of TuYV infection in *M. persicae* populations in the autumn.
2. Develop an economic threshold for control of *M. persicae* as a vector of TuYV.
3. Further research into the identification of genes conferring resistance to TuYV and their incorporation into commercial varieties of oilseed rape is needed.
4. Continue research on how to best conserve natural enemies for aphid management within the arable crop rotation and how this could be achieved through non-crop habitat manipulation options within agri-environment schemes.
5. Alternative and safe insecticide actives with different modes of action are urgently needed for *M. persicae* control before resistance to pymetrozine develops.

6. Maintain vigilance for the eventuality that resistance to pymetrozine may arise.

8.8. Mealy cabbage aphid

8.8.1. Description and life cycle

As the name suggest cabbage aphids, *Brevicoryne brassicae*, are covered in a waxy secretion that makes them look ‘mealy’, but underneath the wax they are blueish-grey to dull green in colour as apterae; adult alates are also blue-grey with a stripey upper abdomen and short stubby cornicles (Gratwick, 1992; Finch and Thompson 1992).

Brevicoryne brassicae, unlike *M. persicae*, is a monoescious species, inhabiting only one host plant group, herbicaeous Cruciferae, throughout its life. Sexual morphs lay small black eggs in the autumn on the stems of overwintering brassicas such as cabbage, kale, Brussels sprouts, broccoli and also oilseed rape (Gratwick 1992; Collier and Finch, 2007; Ekbom 2010). Eggs hatch in the spring between February and April, depending on the prevailing temperatures. In milder areas, e.g. the south west of England, aphids can overwinter anholocyclically in sheltered crops (Gratwick 1992; Harrington et al., 1990; Collier and Finch 2007). Overwintering crops act as a reservoir of the aphids, which multiply in spring and, in the absence of control (natural or otherwise), produce colonies with very many aphids. This overcrowding stimulates the production of alates, which then disperse to found new colonies on uninfested plants, including spring-sown brassica crops such as spring oilseed rape. Thus cabbage aphids are more of a threat to spring crops than winter ones (Ekbom, 2010). Parthenogenetic reproduction takes place throughout the summer alternating between apterous and alate individuals as colonies grow and disperse. Where sexual reproduction takes place in the autumn (i.e. in places where the winter is too severe to allow overwintering survival of active stages), sexual morphs (males and oviparae) are formed which mate, and the oviparae lay eggs betwen September and December (Finch and Thompson, 1992).

8.8.2. Monitoring and forecasting

The number of cabbage aphids in the wider landscape fluctuates from year to year, as can be seen in AHDB Aphid News or the RIS bulletins. It is one of the species monitored regularly in the Rothamsted Insect Survey suction trap network (Harrington et al., 2007). Data on cabbage aphids is issued by AHDB to support their warning schemes (AHDB Aphid News), which also include the use of water traps in strategic locations.

8.8.3. Damage

Cabbage aphids cause serious damage to vegetable brassicas when numbers build up to epidemic levels (Gratwick 1992), made worse by the growth of saprophytic fungal infections on the copious honeydew excreted by large colonies (Finch and Thompson 1992), but this rarely happens in autumn-sown oilseed rape. Direct feeding damage is more likely with spring rape when it is colonised at a young stage from neighbouring winter rape or vegetable brassica crops (Ekbom 2010). However, *B. brassicae* can transmit virus diseases to winter and spring rape, including turnip yellows virus (TuYV), turnip mosaic virus and cauliflower mosaic virus (Finch and Thompson, 1992). The former is usually brought into crops by *M. persicae*, but *B. brassicae* can acquire TuYV from infected plants, and further the secondary spread of the virus (Ekbom, 2010; Collier and Finch, 2007).

8.8.4. Thresholds for control

Ellis et al., (1999; 2009) suggested that control of *B. brassicae* would be economic if sprays were applied when more than 13% of oilseed rape plants were infested with colonies before petal fall, but this was reduced to 4% infestation in spring rape. However, a survey of agronomists and growers during winter meetings organised by AHDB Cereals & Oilseeds suggested that there was little confidence in these thresholds, and that they were regarded as arbitrary (Ellis et al 2009). No thresholds were suggested for autumn colonisation.

8.8.5. Control measures

Many trials have focused on control of *B. brassicae* in vegetable brassicas, but very few have been associated with oilseed rape (e.g. Finch and Thompson, 1992; Collier and Finch, 2007). It is likely that the neonicotiod seed treatments that were used in rape until autumn 2013 gave control of *B. brassicae* as well as *M. persicae*, but no data are available on this specific species, largely because numbers in autumn are relatively low in most years, and thus haven’t provided an opportunity for assessing efficacy.

8.8.6. Resistance to insecticides

There have been no reports to date of resistance to insecticides in *B. brassicae* (Collier and Finch 2007).

8.8.7. Biological control

The aphid parasitoids, *Diaeretiella rapae* and *Aphidius matricariae* attack *B. brassicae* in winter oilseed rape in France (Desneux et al., 2006), but it is likely that this species will be subject to the same attacks from these and other natural enemies as *M. persicae* inhabiting the same niche in the cropping system (reviewed by Ekbom 2010). Conservation biological control using habitat manipulation has potential, particularly as advances to achieve this have been made for other aphid species in brassica systems (Chaplin-Kramer and Kremen, 2012; Chaplin-Kramer et al., 2013; van Rijn et al., 2013). For a discussion of conservation biological control of aphids, see section 6.4.8.

8.8.8. Recommendations for research

Many of the recommendations suggested for *M. persicae* in section 9.7 are equally applicable to *B. brassicae.* However, some attention should be given to investigating the efficacy of currrent and novel insecticides against this species specifically in relation to oilseed rape, as opposed to vegetable brassicas.

8.9. Cabbage stem weevil

8.9.1. Description and geographic distribution

The cabbage stem weevil, *Ceutorhynchus pallidactylus*, formerly *C. quadridens*, is hereafter referred to as CSW. The adult CSW is a typical ceutorhynchid weevil with a pronounced down-curved rostrum or ‘snout’. The size range of the adult is slightly larger than the seed weevil, at 2.5 – 3.5 mm long. The body of the adult is grey-brown with scattered white scales and with fine hairs that form a central white spot at the base of the elytra. The legs are red-brown (Williams, 2010). The larvae are white and legless with a cream-coloured head capsule and can grow up to 6 mm long in the third and final instar. CSW is widely distributed in Europe and North Africa and is also found in North America (Balachowsky, 1963).

8.9.2. Life cycle

CSW is a brassica specialist and has one generation a year. It migrates to oilseed rape crops from its overwintering sites when temperatures reach or exceed 14°C from March onwards, and adults feed on leaf margins, veins, petioles and young stems (Balachowsky, 1963; Williams, 2010). Egg-laying begins in April and takes place in small chambers excavated in the under-side of leaf petioles or occasionally in young stems (Alford et al., 2003b; Balachowsky, 1963). Eggs are laid in clutches of two to eight and larvae hatch 6-11 days later. First feeding in leaf petioles, the larvae continue mining in the main and lateral stems. After three to six weeks feeding, mature larvae emerge from plants and fall to the ground where they pupate at depths up to 8 cm. Adults emerge from July onwards after a pupation period of about three weeks, and feed on brassicas and wild crucifers before seeking overwintering sites amongst plant debris or well-drained soil on forest edges or amongst bushes (Balachowsky, 1963; Williams, 2010).

8.9.3. Damage and pest status

The tunnelling of CSW larvae in the pith of petioles and stems causes loss of vigour and can cause loss of yield through early leaf abscission, reductions in leaf area and in pod set, delayed flowering and lodging of plants (Kelm and Klukowski, 2000; Williams, 2010). Feeding damage can also facilitate fungal infection by *Botrytis cinerea* and *Phoma* stem canker (Alford et al., 2003b; Williams, 2010).

In the UK, CSW is generally considered to be a minor pest of oilseed rape although it is recognised to be a more serious pest of spring rape than winter rape crops both in the UK and in Europe (Alford et al., 2003b; Williams, 2010; Winfield, 1986). There appears to be no reason to revise this assessment.

Holland and Oakley (2007) considered the pest status of CSW to be “static” and didn’t allocate a section to it in the text of their report. Evans (2007) stated that control of CSW in Scotland was “currently not worthwhile as the levels of infestation [were] not a cause for concern”. ADAS Pest, Disease and Weed Incidence Reports cited no confirmed cases of serious CSW damage to crops in 2008, 2009 or 2012 (ADAS, 2013; Lole, 2009, 2010). However, the report for 2009 suggested that damage attributed to rape winter stem weevil (RWSW) may have been caused by CSW (Lole, 2010) and the report for 2010 cited cases of CSW damage found by a number agronomists in the east of the country (Lole, 2011). Nothing definite can be gleaned about CSW incidence from UK Pesticide Usage Survey Reports as these do not report the proportion of usage specifically targeted against CSW. In the 2010 report, 6% of reasons for insecticide applications to oilseed rape crops were given as ‘weevils’ compared to 10% given as ‘seed weevils’ (Garthwaite et al., 2011a) but it is not clear that these two weevil categories were considered by survey respondents to be mutually exclusive so the proportion of ‘weevils’ that were CSW (if any) is unknown.

8.9.4. Thresholds for control

No threshold has been properly established for this pest in the UK (Williams, 2010). In advice from AHDB that remains current, Oakley (2003) advised that the crop should be treated for CSW if a threshold of 2 weevils of any species per plant is exceeded, on the grounds that CSW adults are difficult to distinguish from the cabbage seed weevil. The basis of this advice is unclear (Ellis et al., 2009). In Europe, economic thresholds for CSW have been set only in Estonia, Germany and Poland and they range from one CSW per six plants to six CSW per 25 plants and from 20 to 30 CSW per water trap (Williams, 2010). Research on the impact of CSW on plant growth and yield is needed in order that a well-founded economic threshold can be established for CSW in the UK (Ellis et al., 2009).

8.9.5. Monitoring and forecasting

Growers in the UK are advised to base CSW control decisions on counts of weevils per plant, presumably assessed by beating plants onto a tray although this is not specified (Oakley, 2003). CSW can also be monitored using a range of flight traps; water traps are most commonly used in Europe (Williams et al., 2003; Williams, 2010). We were unable to find any clear advice to growers on how or when (date, weather conditions or plant growth stage) CSW monitoring should be done in the UK.

CSW can fly short distances at temperatures of 12 °C and has been recorded to fly at temperatures as low as 9.6 °C but the accepted threshold for mass immigration flight in spring is above 14 °C (Balachowsky, 1963; Láska and Kocourek, 1991; Nolte, 1956). There is evidence from experiments with traps baited with isothiocyanates that CSW uses host plant odour to locate the oilseed rape crop (Walczak et al., 1998). Consistent with upwind host-location flights along an odour plume, edge-distribution within fields has been found but, like the cabbage seed weevil, the distribution of CSW within fields is patchy (Ferguson et al., 2006; Ferguson et al., 2003). Monitoring should therefore not be restricted to a small area of the crop and should extend well into it.

The timing of insecticide sprays is important, applications being most effective when a substantial population has immigrated but before their ovaries are mature (Seidenglanz et al., 2009). Spring emergence and egg-laying have been accurately predicted in mainland Europe by the DSS proPlant which incorporates a weather-based phenological model (Johnen et al., 2010, 2013; Johnen and von Richthofen, 2013). This DSS is not currently in use in the UK for CSW.

8.9.6. Control measures

Pyrethroids have been the insecticides of choice for control of insect pests of oilseed rape for many years (Thieme et al., 2010) and, no doubt, have been used to target CSW.

8.9.7. Evolution of resistance to insecticides

Tests of populations of CSW from different regions of Germany every year from 2005 to 2011 detected no obvious decline in sensitivity to the pyrethroid lambda-cyhalothrin (Heimbach and Müller, 2013). Nevertheless, vigilance is required as this pest inhabits the crop over a similar period to the pollen beetle. Due to their cryptic habit, the exposure of CSW larvae to contact insecticides may be more limited than for pollen beetle larvae. However, at maturity they may ingest insecticide from the surface of the stem as they bore their way out to pupate.

8.9.8. Biological control

The most important parasitoid of CSW in the UK and throughout Europe is the ichneumonid larval endoparasitoid *Tersilochus obscurator* (Ulber et al., 2010b). The pteromalid larval ectoparasitoid *Trichomalus lucidus* has been reared from CSW larvae in Germany and Poland (Ulber et al., 2006b) and is also found in the UK (Andrew Ferguson pers.comm.). The average rate of larval parasitism by *T. obscurator* in the UK is about 20% (Ulber et al., 2010b) but rates of 10-81% have been recorded in Europe (Kraus and Kromp, 2002; Ulber et al., 2010b). CSW larvae are more likely to escape the reach of ovipositing parasitoids and show lower rates of parasitism if they inhabit plants that are grown at low density and have wider diameter stems (Ulber and Fischer, 2006). Ferguson et al. (2006) found that the spatial distributions of new generation CSW and *T. obscurator* adults emerging from the soil were not closely spatially associated, probably as a result of the impact of the parasitoid on CSW mortality. There is evidence that sub-lethal effects of insecticides reduce the efficiency of host-location by *T. obscurator* and may therefore negatively influence rates of parasitism (Neumann et al., 2013).

CSW larvae fall from plants to the ground to pupate and, like many other pests of oilseed rape, are then vulnerable to generalist epigaeic predators. In Germany, adult emergence may be reduced by as much as 57% by the activity of ground predators (Buchs and Nuss, 2000). In the UK, the carabids *Amara similata*, *Anchomenus dorsalis, Pterostichus madidus* and *melanarius* were found to be active in a rape crop when larvae of *Ceutorhynchus* spp. (cabbage seed weevil and cabbage stem weevil) were falling from plants to pupate; of these, *A. dorsalis* was spatially associated with the larvae (Warner et al., 2008). Five carabid species, including all of those listed above except *P. melanarius*, feed on larvae of weevil pests of oilseed rape in the laboratory or in the field (Williams et al., 2010).

CSW larvae are likely to be vulnerable to the same spectrum of entomopathogens in the soil as are the cabbage seed weevil and RWSW but the potential for managing entomopathogens to improve control of oilseed rape pests is unclear (Hokkanen et al., 2003).

8.9.9. Cultural control and conservation biological control

Tillage

Some CSW larvae and pupae are likely to be vulnerable tillage in preparation for establishment of the following crop as mature larvae continue to fall from plants in July and August (Williams, 2010). However, any benefit of tillage for control of CSW may be more than counterbalanced by injury to its parasitoid *T. obscurator*, the whole population of which overwinters in the soil beneath the crop (Nilsson, 2010).

Sowing rate

Higher sowing rates may encourage biological control of CSW by parasitoids as CSW larvae inhabiting the narrower diameter stems of plants grown at higher density suffer higher rates of parasitism (Ulber and Fischer, 2006).

Trap cropping

Two studies have failed to find evidence that trap cropping (with a border of turnip rape, *Brassica rapa*, or of oilseed rape with a phenology different to the main crop) could be a useful strategy for management of CSW (Barari et al., 2005; Nerad et al., 2004).

Mixed cropping

There is some evidence that mixed cropping of winter oilseed rape with winter barley, winter wheat or winter peas may reduce infestation by CSW in organic systems (Paulsen et al., 2006).

Landscape management

As discussed in the section on pod midge, there is good evidence that increased landscape complexity, including more semi-natural habitats, increases the activity of natural enemies. However, despite many recent studies, there is conflicting evidence for effects on biological control of pests. More research is needed (ENDURE, 2009; Ferguson and Alomar, 2010; Rusch et al., 2010).

As with pollen beetles and pod midge, in crops in Austria the abundance of stem weevils (80% of which were CSW) was found to be positively related to the proportion of wooded areas in the landscape. The response was over a shorter scale than for pollen beetles, suggesting that CSW disperse over shorter distances from overwintering sites (<1250 m) (Zaller et al., 2008b).

Margin management

Forage rape cultivars appear to have most potential for incorporation into field margin mixtures to promote populations of the parasitoids of several rape pests, including CSW, without promoting populations of the pests themselves (Cook, 2014; DEFRA, 2009). This approach is being further investigated under Defra Project IF01122 (DEFRA, 2012; Cook et al., 2016).

Crop nutrition

High levels of nitrogen and/or sulphur fertilisation increased infestation by CSW (Aljmli, 2007) and so care should be taken to balance fertilisation with the crop's needs. The preference of adults for fertilised plants may be related to levels of glutathione, cysteine and glucosinolates and to the associated plant volatiles, which are used by Brassicaceae specialists for host-location and selection (Aljmli, 2007).

Genetic resources

CSW-resistant oilseed rape cultivars are not yet commercially available. However, more than 100 brassicaceous genotypes from *Brassica napus*, *B. rapa*, *B. oleracea,* breeding lines, resynthesised rapeseed lines (*B. oleracea* x *B. rapa*), and wild Brassicaceae have recently been screened in

Germany for resistance to CSW using feeding tests, oviposition choice tests and field tests. Significant reductions in adult feeding and egg-laying were found on 18 genotypes, including nine cultivars of oilseed rape and four resynthesised lines (Eickermann and Ulber, 2010). Two resynthesised lines and one oilseed rape cultivar, ‘Devon Champion’, had significantly fewer stem weevil larvae than the moderately susceptible cultivar ‘Express’ in semi-field tests (Eickermann et al., 2011). The amount of feeding by CSW larvae was related to glucosinolate composition and concentration and it was suggested that this could be a key to breeding pest resistance in oilseed rape, though glucosinolate expression in the seed would have to be maintained at low levels. There is also evidence from evaluation of 15 *B. napus* cultivars and one *B. rapa* cultivar that plant genotypes with fewer lateral racemes and with fewer leaves on the main stem are less heavily infested by CSW (Eickermann and Ulber, 2011). No influence of cultivar on the rate of parasitism of CSW larvae by *T. obscurator* has yet been found (Ulber et al., 2006a).

8.9.10. Factors potentially influencing future risk

There is no evidence for the development of insecticide resistance in CSW. However, in the event that resistance did arise in CSW, it may reveal how much this pest has been controlled incidentally by sprays targeted at the pollen beetle or seed weevil / pod midge and CSW could then become a more significant problem.

The phenology of CSW infestation is likely to alter with climate change. Threshold-based models for spring emergence and migration of CSW have been tested under climate change projections for Luxembourg derived by the EU ENSEMBLES project. The results suggest that the main CSW migration period may begin two days earlier per decade and may be prolonged to 30 days (Junk et al., 2012). However, the authors did not expect any significant change in synchrony between host and herbivore as stem elongation in oilseed rape was also predicted to begin earlier. Moreover, CSW is not critically dependent upon host plant growth stage. Climate change was therefore not thought likely to affect the pest status of CSW through any changing temporal relationship with its host (Junk et al., 2012).

8.9.11. Recommendations for research and other actions

1. Keep a watching brief on the incidence and severity of damage for any changing trend. Given the lack of good information on the incidence of CSW in the UK, a base-line survey could be considered.
2. Assess the risk of resistance using the outputs of AHDB project RD-2012-3780 ‘Combating insecticide resistance in major UK pests’ when available. Vigilance is required as this pest risks exposure to the same insecticide applications as the pollen beetle.
3. Monitor resistance status of CSW.
4. Consider clarification of advice on methods and timing of monitoring for CSW.

5. Research on the impact of CSW on plant growth and yield is needed in order that a well-founded economic threshold can be established for CSW in the UK.
6. Developments in plant breeding for oilseed rape resistance to the CSW should be monitored. Promising lines should be tested for resistance under UK conditions. Routine screening of breeders' lines for pest as well as for disease resistance should be encouraged.
7. As with other rape pests, there may be scope to make greater use of existing datasets to model the effect of landscape and field margin management on CSW and its natural enemies.
8. New and safe insecticide actives are urgently needed for oilseed rape pests.

8.10. Turnip sawfly

Turnip sawflies are commonly found in the vicicnity of brassica fields, including oilseed rape, most noticeably when attracted to water traps, but they are relatively rare pests of the latter crop, the last recorded outbreak occurring in 2006 (Green and Oakley, 2006; Holland and Oakley, 2007; Lole, 2009).

8.10.1. Description and geographic distribution

The adult turnip sawfly, *Athalia rosae*, is a robust sawfly, 6-8 mm long, and is yellow to reddish-yellow and black in colour (Alford et al., 2003b; Green and Oakley, 2006). The larvae are caterpillars with three pairs of thoracic legs and eight pairs of abdominal pro-legs, and with a green-grey body that becomes velvet black as the larvae grows through four instars to a full-size of up to 18 mm long (Alford et al., 2003b; Jones and Jones, 1984). These were called ‘the black’ a couple of centuries ago when, presumably, they were more common pests.

Turnip sawfly is widely distributed in Europe but declined in north-western Europe from the late nineteenth century. Since the 1940s it has become more abundant, especially in central Europe (Alford et al., 2003b).

8.10.2. Life cycle

Turnip sawfly adults emerge in May from pupae that have overwintered in the soil. Eggs are laid singly on the margins of leaves of brassicaceous host plants, each female laying several hundred. Eggs hatch after 5-12 days and the larvae feed gregariously on leaves for up to two weeks, moulting three times before pupating in the soil. Adults emerge 2-3 weeks later in the summer. There are up to three generations per year, adults remaining active until October. The offspring of the last generation overwinter as pupae in the soil (Alford et al., 2003b; Jones and Jones, 1984).

8.10.3. Damage and pest status

In outbreaks, turnip sawfly damage to oilseed rape plants can be very severe, the larvae reducing leaves to skeletons of major veins (Alford et al., 2003b; Green and Oakley, 2006; Jones and Jones, 1984). Turnip sawfly is also a pest of vegetable and salad brassicas and of mustard and stubble turnips, therefore proximity to such crops may increase the risk (Green and Oakley, 2006; Lole, 2011). Oilseed rape is vulnerable in a warm autumn following a warm summer when the sawfly has a third generation. The population is then at its maximum when the leaf area of the crop is still small. Backward crops emerging slowly from dry seedbeds are at greatest risk (Green and Oakley, 2006).

The turnip sawfly is a sporadic pest in the UK that occurs in outbreaks of varying frequency (Benson, 1952). Historically a dramatic defoliator of turnip crops, it died out from the UK in the early 20th century until an outbreak that began in 1947 when the warm summer favoured immigration from the continent. Severe winters kill overwintering pupae (Holland and Oakley, 2007) and the pest apparently again died out from the UK in the second half of the 20th century (Jones and Jones, 1984).

Turnip sawfly incidence increased in vegetable brassicas in 2005 and 2006 (Lole, 2009) and in 2006 the population was supplemented by large-scale migration from the continent (Holland and Oakley, 2007). In September 2006, AHDB Cereals & Oilseeds issued a warning about the risk to winter oilseed rape crops, particularly in southern and eastern counties of England (Green and Oakley, 2006). Holland and Oakley (2007) anticipated that the outbreaks would continue until after a severe winter. ADAS Pest, Weed and Disease Incidence Reports recorded damage to some newly-emerged oilseed rape crops in southern England in September 2007 but thereafter significant infestations were almost confined to vegetable brassicas and stubble turnips (ADAS, 2013; Lole, 2009, 2010, 2011).

The characterisation of the turnip sawfly as a sporadic pest of winter oilseed rape in the UK, boosted by outbreak years resulting from warm summers in the UK and on the continent, seems still to be justified (Alford et al., 2003b; Jones and Jones, 1984). The future status of this pest may depend on the effects of climate change in the region (see the section on factors potentially influencing risk, below).

8.10.4. Thresholds for control

No spray threshold has been established for turnip sawfly in the UK. Green and Oakley (2006) offered to UK growers a threshold based on work in Germany of 1-2 larvae per plant. The current advice to oilseed rape growers in France is to treat with a pyrethroid if more than a quarter of the leaf surface is damaged at any growth stage from emergence to six leaves (CETIOM, 2014b).

8.10.5. Monitoring and forecasting

No guidance has been issued in the UK as to how to monitor turnip sawfly in oilseed rape in the autumn. Advice in France is to examine plants for leaf damage from emergence to the six leaf stage (CETIOM, 2014b). Adult turnip sawflies can be sampled using yellow water traps or sticky traps (Green and Oakley, 2006; Lole, 2009; Williams et al., 2003). As this insect is a strong flier, any edge-distribution in a crop at the start of immigration may be transient.

No phenological models for turnip sawfly forecasting appear to have been developed. However, the flight temperature threshold has been determined as 17.6 °C (Láska and Kocourek, 1991).

Therefore a higher risk for winter oilseed rape crops can be predicted in an autumn that remains warm enough for turnip sawfly flight, especially following a warm summer and in dry conditions when plant development is slowed by lack of moisture (CETIOM, 2014b; Green and Oakley, 2006).

8.10.6. Control measures

Until December 2013, beta-cyfluthrin + clothianidin as ‘Modesto’ (Bayer) was available in the UK as a seed treatment for control of turnip sawfly in winter oilseed rape (Berry et al., 2012); two other neonicotinoid seed treatments available at the time would likely have had similar effects at early growth stages. These are no longer available to all growers due to the EU-wide restriction on use of neonicotinoid seed treatments (Nicholls, 2013). Pyrethroid sprays approved for control of cabbage stem flea beetle on oilseed rape are suggested for control of turnip sawfly where leaf damage is severe (CETIOM, 2014b; Green and Oakley, 2006).

8.10.7. Evolution of resistance to insecticides

There appear to be no reports of insecticide resistance in turnip sawfly. So long as it remains a sporadic pest, it seems unlikely that resistant populations will arise on oilseed rape crops. However, there is some risk of development of locally resistant populations on vegetable crops if they are repeatedly sprayed for cosmetic reasons. Resistance genes could move long distances in this mobile pest.

8.10.8. Biological control

A large number of species have been reported as larval parasitoids of turnip sawfly, including ichneumonid and chalcid Hymenoptera and, probably most important, tachinid flies (Alford et al., 2003a). Holland and Oakley (2007) listed two species of parasitoid, the ichneumonid *Perilissus lutescens* and the tachinid *Meigenia bisignata* but it is unclear whether these have been reared from turnip sawfly in the UK. Parasitism rates of up to 80% have been recorded in Europe (Alford et al., 2003a) indicating that parasitoids may have a strong controlling influence on populations.

Turnip sawfly larvae are vulnerable to generalist epigaeic predators such as carabid beetles, staphylinid beetles and spiders when they fall to the ground to pupate (Buchs, 2003b; Buchs and Alford, 2003). The larvae are known to sequester glucosinolates from their food plants for their own defence and this is likely to give them some protection from generalist predators (Hopkins et al., 2009).

There appears to be potential for control of turnip sawfly using nematodes. High rates of larval parasitism by *Mermis albicans* have been reported and sprays of suspensions of *Steinernema* *carpocapae* have resulted in 40% mortality of larvae on leaves and 67% mortality of developmental stages in the soil (Hokkanen et al., 2003).

8.10.9. Cultural control and conservation biological control

Tillage

In some seasons, turnip sawfly is likely to be vulnerable to soil tillage, depending upon the relationship between the phenology of pupation / overwintering and the timing of cultivations.

Trap cropping

The turnip sawfly is a brassica specialist that sequesters glucosinolates for defence and thus it is almost certainly attracted by the volatile break-down products of glucosinolates in host finding and host selection behaviour (Hopkins et al., 2009). This offers potential for behavioural manipulation in control strategies such as trap cropping (Cook et al., 2007b). It has been suggested that after harvest of oilseed rape, shed seed can be allowed to germinate to act as a trap crop for egg-laying turnip sawfly and that the plants should be ploughed in a month later to destroy the larvae and to act as a green manure (Sáringer, 1989).

Genetic resources

The effects on the performance of turnip sawfly larvae of different levels and types of glucosinolates in various Brassicaceae have recently been investigated (Mueller, 2009). However, given the tolerance of the larvae for high concentrations of glucosinolates, it is not clear whether this offers hope for the breeding of resistant cultivars suitable for the food chain.

8.10.10. Factors potentially influencing future risk

There is a risk that turnip sawfly may become a more frequent and serious pest in the UK if global climate change leads to warmer summers in north-west Europe. Warm summers and autumns allow turnip sawfly to have three generations per year in the UK and they increase the likelihood of mass migrations from the continent. Moreover, such conditions allow them to continue flying in the autumn even though their flight temperature threshold is higher than most pests of oilseed rape at 17.6 °C (Green and Oakley, 2006; Jones and Jones, 1984; Láska and Kocourek, 1991). Milder winters may also increase their overwintering survival (Holland and Oakley, 2007). Evans (2012) used the CLIMEX model to test the suitability for various pests of the projected climate in Scotland in 2050-2099. He listed turnip sawfly as an example of a pest likely to become more severe in oilseed rape and vegetable brassicas.

8.10.11. Recommendations for research and other actions

1. Keep a watching brief on the incidence and severity of turnip sawfly damage for any changing trend.
2. Advice on the most appropriate method and timing of monitoring for turnip sawfly is needed.
3. A control threshold for turnip sawfly on winter oilseed rape in the UK is needed, taking into account plant growth stage and vigour at the time of sawfly immigration.
4. If turnip sawfly continues to be sporadic, it may be more practical to base advanced warnings to growers on the observations of experts and agronomists in continental Europe and the UK, rather than attempting to develop a phenological model.
5. Assess the risk of resistance using the outputs of AHDB project RD-2012-3780 ‘Combating insecticide resistance in major UK pests’ when available.

8.11. Cabbage root fly

8.11.1. Description

The cabbage root fly, *Delia radicum*, as its name suggest is a fly, similar in appearance and size to a slender house fly, but dark grey in colour(Jones and Jones, 1984; Gratwick, 1992; Finch and Thompson, 1992). Males are smaller (5-6mm) than females (6-7mm). The larvae are white or cream coloured maggots, which burrow in to stems of growing seedlings of brassicas, including oilseed rape, especially in early sown crops in the autumn (Holland and Oakley, 2007). They grow up to 8 mm long before leaving the crops to pupate. Pupae are dark brown, sub-elliptical in shape with smoothly rounded sides

8.11.2. Distribution

Cabbage root flies are a widespread pest in the northern hemisphere, generally attacking cruciferous vegetable crops (Jones and Jones, 1984) rather than broad acre crops, but they do occasionally damage oilseed rape, especially in central Europe. For example, in a recent survey in the MASTER project, it was targeted for control in oilseed rape only in Germany, by 12% of growers (reviewed in Williams, 2010; Bayer Pestspotter, 2014), suggesting that it was a relatively minor pest in the other countries surveyed (Poland, Sweden and the UK). However, in autumn 2013 damage to oilseed rape was reported in Somerset (http://cropphotoupdate.com/2013/11/27/oilseed-rape-cabbage-root-fly-shows-up-in-somerset/), and some local epidemics have been reported anecdotally in oilseed rape East Anglia in 2015.

8.11.3. Life cycle

This pest usually has two generations per year in the UK, but this can vary from one generation in northern Europe to as many as five in parts of Canada and the USA (Finch and Thompson, 1992). In the UK, the first generation of flies emerges in April to early May, and the second in late June and July. Occasionally a third generation is produced sporadically in the south and the Midlands in some, presumably, warmer years (Kennedy and Collier, 2008). Adults emerge in autumn and are attracted to early-sown oilseed rape crops, especially crops that emerge in August. Females lay 50-70 white eggs in the soil around the stems of young brassica plants. They hatch in 3-7 days, and the larvae burrow down into the soil and colonise the tap roots. After about 23 days of feeding and having passed through three instars, the larvae reach maximum size (about 8 mm) and leave the plant to pupate in the soil nearby. The pupal stage lasts 15-35 days in summer before the second generation emerges. The second generation will normally go into diapause in the pupal stage through the autumn and winter, emerging the following year, but in some years a proportion of adults will emerge in September, mate and lay their eggs, forming a partial third generation. These may be the individuals that cause damage to newly-emerged autumn-sown oilseed rape crops.

8.11.4. Monitoring and forecasting

There are no forecasting systems for cabbage root fly that are applicable to oilseed rape crops, but in vegetable brassica crops, adults can be monitored using yellow water traps or sticky traps, with or without volatile chemical attractants (Kenny and Collier, 2008). Eggs can also be sampled from suspected infested fields using soil cores and standard extraction methods involving flotation.

A weather-based forecast of cabbage root fly activity is available through AHDB Horticulture and Syngenta (Kennedy and Collier, 2008; Syngenta 2016), which helps growers to decide on timings for control measures in established crops. If it becomes necessary, it may also be useful to guide growers with problems in oilseed rape. In 2013 the forecasted pattern of egg-laying at five sites in Cornwall, Kent, Lincolnshire, Lancashire and Scotland showed two peaks, in June and in July/August, with a small amount of egg-laying in late September (Syngenta 2016). The forecast of egg-laying predicted by the model (operated by Plantsystems Ltd) compared very accurately with the number of eggs actually laid in a brassica crop at Wellesbourne, Warwickshire.

8.11.5. Damage

Damage to brassicas varies with crop species and the growth stage at which it is attacked (Gratwick, 1992; Finch and Thompson, 1992). Oilseed rape plants attacked at the seedling stage often wilt or die. Less severe attacks stunt plants to varying degrees, making them more vulnerable to frost and diseases or to attack by pigeons. Reports from Germany suggest that damage by this pest often only becomes visible after severe frosts, which kill weakened plants. Therefore more damage may be occurring than formerly suspected because it is not apparent when plants are not stressed by cold. Yield losses due to poor root systems may be occurring without the grower’s knowledge. It may be that previously-used seed treatments have given some unmeasured level of control of this pest and, in the absence of these treatments in the future, cabbage root fly may become a more common problem.

It is unlikely that the generation of flies that emerges in April can cause much damage to a mature, flowering winter-sown oilseed rape crop, but the flies may damage spring-sown rape, although there is little documented evidence of this (Lane and Gladders, 2000; Holland and Oakley, 2007).

8.11.6. Thresholds for control

Reliable thresholds for cabbage root fly are not available for use in vegetable brassicas (Kennedy and Collier, 2008) so it is unlikely that they will be available for use in oilseed rape, either autumn- or spring-sown.

8.11.7. Control measures

The control measure formerly recommended for cabbage root fly in vegetable brassicas was to apply insecticides to the soil surface, including carbamate granules such as carbofuran, or organophosphate sprays such as chlorfenvinphos (Jones and Jones, 1984), but all of the products have now been banned or withdrawn. Of the products listed for cabbage root fly control in the Pest and Disease Control handbook in 2008 (Alford, 2008), including carbosulfan and phorate granules, chlorpyrifos and dimethoate mixture granules, and chlorpyrifos sprays or drenches, none are still available for use by growers of vegetable brassicas. The neonicotinoid dressings that were applied to oilseed rape seeds until 2013 may have had an influence on cabbage root fly larvae, if any were present, but there is no published evidence for this. In any case, following the ban on neonicotinoid seed treatments imposed by the European Commission in 2013, this is no longer an option, at least in the short term (EU, 2013).

8.11.8. Resistance

Evidence of the development of resistance in cabbage root flies has been recorded in the past (Finch and Thompson, 1992; Gratwick, 1992). Care to avoid the overuse of insecticides in both vegetable brassicas and oilseed rape is therefore advisable.

8.11.9. Biological control

Cabbage root fly are preyed upon by many natural enemies. These include 30 species of beetle, mostly carabids and staphylinids, and two species of predatory mites, which eat the eggs, larvae and pupae (reviewed by Jones and Jones, 1984), causing up to 90% mortality in some experiments (Gratwick, 1992). Larvae and pupae can also be parasitised by several species of parasitoids (Jones and Jones, 1984). Attempts have been made in Belgium and Denmark to breed the staphylinid, *Aleochara bilineata,* whose larvae are parasitoids of root fly larvae (Finch and

Collier, 2000), for augmentative release in high value crops, but so far with no commercial success (Alford et al., 2003). It is thus unlikely that such a strategy will be viable in relatively low value oilseed rape crops. However, use of soil cultivations that conserve natural enemies in the soil, for example minimum tillage, may help to reduce the potential for cabbage root flies to cause harm.

8.11.10. Cultural and conservation biological control

High value brassica crops can be covered with fleece or fine mesh to exclude adult cabbage root fly at the time of egg-laying (Kennedy and Collier 2008). This is not a viable strategy with broad acre crops, however. The encouragement of local parasitoid and predator populations by minimising cultivations and through landscape and margin management for biodiversity is likely to be a useful strategy for all brassica crops.

8.11.11. Recommendations for further research

Given the lack of evidence of serious problems in the UK caused by cabbage root fly, the only recommendation is to keep a watching brief on the situation in Germany, and respond to changes, should they occur in the UK.

8.12. Leaf blotch miner

The leaf blotch miner, *Scaptomyza flava*, is a drosophilid fly that is widespread across Britain and elsewhere in Europe (Pitkin et al., 2011) but has only recently been reported as a noteworthy pest on cruciferous crops. The fly was abundant in 2009 and 2010, and severe symptoms were observed in winter oilseed rape in autumn, causing concern at the time. However, infestations did not ultimately result in economic damage, due to compensatory plant growth, and they did not require an insecticide treatment directly targeted at *S. flava* (ADAS, 2011b). However, the situation was much more severe in baby-leaf salad crops in those years, resulting in severe crop losses (ADAS, 2011b; Bennison et al., 2013; Lole et al., 2011).

8.12.1. Life cycle

Adult flies are pale brown in colour with indistinct longitudinal stripes on the thorax and red eyes. They are small (2-3 mm in length) with wings that are 50% longer than the length of the head and thorax combined. Following courtship and mating, females make punctures within the lower leaf surface with their ovipositor and deposit an egg inside each; they can begin egg-laying within 4 h of adult emergence from the pupa and live approximately 12 days. Larvae mine the leaves, initially moving towards the midrib and creating a corridor-like mine; after they reach the midrib, the mine becomes a large irregular excavation or blotch (hence their name) in the upper leaf surface. The host range of these flies is large (over 100 species of cultivated and wild plants from six families) but some are preferred over others. For example, individual flies lay more eggs on turnip than cauliflower and their development time is longer on cauliflower than turnip. There are three larval instars, the largest reaching 4 – 5 mm in length and several larvae can be found feeding in the same mine (six or more). Larvae exit from the plant and fall to the ground to pupate, although sometimes a separate pupation mine is used. Adults are active from April to September but it is unclear how many overlapping generations there are in a year. This life cycle is summarised from a number of different references (ADAS, 2011; Bayer Pest Spotter, 2014; Lole et al., 2011; Pitkin et al., 2011; Seraj, 1994).

8.12.2. Damage

The feeding mines are obvious, appearing white or silvery in the leaf. The larvae do not spread beyond the attacked leaf to stalks, stems or growing tips, limiting damage by one larva to an individual leaf. In oilseed rape the plant can grow away from such damage easily with no resulting yield loss, but in baby-leaf salads the entire crop can be lost as the leaf punctures alone are sufficient for the retailer to reject the product (ADAS 2011b; Lole et al., 2011).

8.12.3. Thresholds for control, monitoring and forecasting

There are no available thresholds for treatment of oilseed rape as leaf blotch miner is not considered a significant enough pest for targeted applications. In baby-leaf salads it had not been targeted specifically in the past but was controlled incidentally by a range of insecticides, particularly pyrethroids, targeted at caterpillars (ADAS, 2011b; Lole et al., 2011). With the likelihood of resistance to pyrethroids (see below) growers of baby-leaf salads are now asked to use white sticky traps to monitor population size and to use crop covers, and not insecticides, if the population pressure is high (Bennison et al., 2013).

8.12.4. Control with insecticides

As oilseed rape plants can tolerate loss of older leaves and grow away from any leaf blotch miner damage, treatment with insecticides is not normally considered to be necessary. Baby-leaf salads receive repeated insecticide applications, many more than oilseed rape. From 1999 to 2007, treatments were dominated by pyrethroids and, with sequential planting, annual insecticide use was very high. Even though the leaf blotch miner was not the target of these applications, multiple generations of them would have been coincident with the repeated treatments over the year, placing them under heavy selection pressure for resistance and severely disrupting their natural enemies. Although further confirmation is still required, initial tests suggested that the leaf blotch miner on baby-leaf salads had developed resistance to pyrethroids and that this was the cause of the outbreaks in 2009 and 2010 (Lole et al., 2011). Furthermore, without the knock-down activity of pyrethroids, the remaining insecticides used for pest control in baby-leaf salads did not prevent adult puncture damage (Bennison et al., 2013). For this reason growers are advised to monitor for leaf blotch miner with sticky traps and, if the population pressure is high, to cover the crops to prevent the miner from entering, rather than apply insecticides (Bennison et al., 2013). This also provides incidental control of other pests (ADAS, 2011b). None of the neonicotoinoid seed treatments used in oilseed rape until December 2013 had any effect on the incidence of leaf mining in young seedlings in field trials, which was surprising, as the same active ingredients in sugar beet gave excellent control of beet leaf miner, *Pegomya betae (hyoscyami)* (Alan Dewar pers.comm.).

8.12.5. Cultural control

With the potential onset of insecticide resistance, plant covers have been used successfully to protect baby-leaf salad crops when leaf blotch miner is abundant. Growers are also advised not to grow their baby-leaf salad adjacent to oilseed rape, as it is a host plant (Bennison et al., 2013; Lole et al., 2011). Likewise, avoiding sowing winter oilseed rape close to baby-leaf salad crops is likely to reduce autumn populations in the rape crop.

8.12.6. Biological control

Eight species of chalcid parasitoids have been recorded from the leaf blotch miner in the UK (Pitkin et al., 2011) but there have been very few studies on their role in population regulation in UK, even though anecdotal evidence suggests they could be important (ADAS, 2011b). Their beneficial impact can be disrupted by insecticide use, adults being particularly sensitive as they are free-flying, unlike the immature stages that are protected from contact with insecticide within the host or its mine (Martin and MacDonald, 2009). It is likely that other predatory species and pathogens are also active against leaf blotch miner but they are under-reported (ADAS, 2011b).

8.12.7. Plant breeding for resistance

To the best of our knowledge there have been no plant breeding programmes targeted at resistance to leaf blotch miner and there are no oilseed rape varieties in the AHDB Recommended List (2016) with a specific indication of resistance to leaf blotch miner.

8.12.8. Recommendations for research

Given the lack of evidence for any significant impact of this pest on oilseed rape, research recommendations are few.

1. Maintain a watching brief in case insecticide-resistant populations of leaf blotch miner from baby-leaf salads become more widespread and abundant with the potential to impact on oilseed rape seedlings.
2. More research on the biology and encouragement of the natural enemies of leaf blotch miner would aid resistance management.

9. Discussion and conclusions

There have been remarkable developments affecting the management of invertebrate pests of cereals and oilseed rape in the UK in the years since these pests were last comprehensively reviewed for AHDB Cereals & Oilseeds by Holland and Oakley in 2007 (RR64), and since invertebrate pest thresholds were reviewed by Ellis et al. in 2009 (RR73). Many of these changes have been driven by resistance to insecticides or the need to manage the risk of resistance and by regulatory restrictions on the use of insecticides. However, changing cropping and agronomic practices have had an impact and there are indications that weather patterns that may be linked to climate change have also had an effect. Indeed, climate change impacts are only likely to increase, with important implications for UK and global food security. Recent climate modelling predicts that many of the most agriculturally productive parts of the world will suffer reduced potential for production but north-western Europe will be one of the least affected and may even increase output (though cropping patterns may change) (Wheeler and von Braun, 2013). As world commodity prices rise, this will increase the pressure to reconcile productivity with long-term sustainability in the agricultural environment.

Of the five research recommendations most frequently made in relation to pests in this review, three relate directly to chemical control with pesticides: the need for new insecticide actives or synergists; the need to monitor and assess the risk of insecticide resistance; and the need for improved control thresholds. These recommendations reflect the fact that pesticides remain the mainstay of pest management (and are likely to remain so) and the need to conserve the effectiveness of the pesticides available by using them strictly according to need, thus avoiding pest resistance or managing it. Significant steps are being taken as part of recent and ongoing research projects on pollen beetle thresholds and decision support systems funded by AHDB, Defra and others (Cook et al., 2013a; DEFRA, 2013; Ellis and Berry, 2012). However, for many pest species, urgent needs remain for improved monitoring techniques, for treatment thresholds in which farmers can have confidence, and for phenological models and surveys that can provide regional or local risk forecasts.

Plant breeding for pest resistance (antibiosis or antixenosis) or pest tolerance also repeatedly featured as a recommendation for further research effort. There is often evidence of resistance-conferring characters that might be introgressed from related taxa, although the variety of life histories of the pests and their division between specialists and generalists is likely to demand a tailored approach for each pest. While recognising that the sporadic nature of many pests makes interpretation of field infestation levels difficult, we recommend that routine screening of breeders' lines for pest resistance (as well as for disease resistance) should be encouraged.

The need for more knowledge of natural enemies, and how to conserve them and encourage their role in pest management, also featured as a research recommendation for most pests considered in this review. This reflects a continuing interest in the potential for natural enemies to contribute very significantly to pest management in broad-acre crops, as indicated by the extensive recent literature on the topic (e.g. Ferguson and Alomar, 2010; Griffiths et al., 2008; Jonsson et al., 2014; Rusch et al., 2010; Williams, 2010) and recent or current Defra-funded projects aiming to optimize the value of agri-environment schemes for biological control (Cook, 2014; Cook et al., 2016; DEFRA, 2009, 2012, 2013). It is consistent with recent EU CAP reform which places increasing emphasis on encouraging farmers to protect and enhance the environment by paying them for the provision of wider societal goods, i.e. environmental or ecosystem services, including biological control services and, by extension, reduced use of insecticides. The withdrawal of insecticide actives, and the inevitable selective pressure for resistance that this places on those remaining, increases the urgency of making the best use of natural enemies, some of which can deliver 50%

or more pest mortality. Such remarkable potential cannot be ignored if valuable insecticide chemistries are to be saved for when they are truly needed.

It would appear, however, that relatively slow progress has been made in influencing on-farm practice to optimise the role of natural enemies in pest management. Since the review by Holland and Oakley (2007) directly addressed this topic, pest management has remained heavily reliant upon chemical control. In part this reflects the complexity of the ecology of natural enemies that must be better understood if their potential is to be achieved. However, equally important, few studies have attempted to demonstrate that conservation biological control delivers yield benefits, the bottom line for farmers (Rusch et al., 2010). It is not enough to cite the strong evidence that conservation biological control increases natural enemies and the evidence that it can reduce pest populations in crops (see reviews by Bianchi et al., 2006; Ferguson and Alomar, 2010). If efforts to promote conservation biological control are to succeed, research must be accompanied by appropriate measurements to judge and demonstrate success (Gurr et al., 2000; Griffiths et al., 2008). Designing trials to quantify the effect of conservation biological control on yield is more difficult than for chemical control but it is a challenge that should not be avoided.

It is clear that modelling has much potential to offer pest management, whether in the form of forecasting modules in decision support systems or by enabling management strategies to be tested *in silico*. Based on historical data of pest occurrence in relation to weather data, phenological models have been used in the UK for forecasting the risk of oilseed rape diseases for some time (Rothamsted Research, 2014 a, b). Although a model forecasting the risk of spread of crop viruses by aphid vectors is also available (AHDB Cereals & Oilseeds, 2014a), in general attempts to introduce forecasting models for risk prediction for invertebrate pests have met with limited success (Walters et al., 2003). This is beginning to change. In the springs of 2013 and 2014, Bayer CropScience has made its ‘Bayer Pollen Beetle Predictor’ freely available via their website (Bayer CropScience, 2014). This internet-based tool uses modelling technology developed by proPlant GmbH to forecast the start, peaks and progress of pollen beetle migration into winter oilseed rape crops. Forecasting models for a number of insect pests of oilseed rape are marketed across Europe by proPlant (Johnen et al., 2013). Such models represent powerful tools, boosting farmer confidence in decision support systems, reducing monitoring effort and encouraging the use of control thresholds.

Modelling *in silico* has the potential to address complex and multi-factorial real-world problems, and to compare strategies and refine options so that more resource-intensive field tests are more effectively deployed. Such models are already in use for exploring resistance management strategies in major UK pests (AHDB project RD-2012-3780; Paveley, 2013). Recent advances in the analysis of statistically noisy datasets in relation to geographic information enable the

movement of pests and their natural enemies in complex real landscapes to be modelled. This could be used to develop conservation biological control or cultural control strategies, e.g. by testing different arrangements of crop and non-crop habitats that might be fostered through agri-environment schemes. The ultimate goal is to design a sustainable and productive landscape that maximizes the value of the ecosystem services provided by natural enemies for pest management. Modelling has the additional advantage of allowing a holistic approach to landscape planning, taking into account other public goods such as biodiversity, amenity value and watershed management. For example, the model, ‘InVEST’ is currently being used in the Wessex BESS Project to to model multiple ecosystem services, including pest control, in the Wessex region under potential future land use scenarios (Natural Capital Project, 2014; Wessex BESS, 2014).
It should be noted that all pest management models rely on fundamental biological and ecological information on the pests and their natural enemies and this is still lacking for some species. For the more sporadic or currently less severe pests, the knowledge gaps around natural enemies are often the rather basic issues of their identity and potential. For the more established pests, the knowledge gaps often relate to spatial ecology, both of the pests and their natural enemies.

Finally, it is important to maintain vigilance for every pest species in order to observe changes in their incidence and severity and to recognise and respond to new problems while they may still be tractable. This is most obviously true for the development of insecticide resistance and for responses to climate change. In the light of the risks identified in this review, we recommend that a high priority should be assigned to maintaining existing survey capacity in the UK, together with the invertebrate ecology, agronomy and modelling skills needed to design practical responses to new pest management challenges.

10. References

Abdel-Aal E-SM, Hucl P, Sosulski FW, Graf R, Gillott C and Pietrzak L (2001) Screening spring wheat for midge resistance in relation to ferulic acid content. Journal of Agriculture and Food Chemistry 49: 3559-3566.

Adam NM (2009) Pest and virus control in winter oilseed rape in northern Europe using a clothianidin -based seed treatment. *Seed Production and Treatment in a Changing Environment, BCPC Symposium Proceedings No. 83*, pp 37-42.

Adam NM, Hopkinson D (2006) Clothianidin: a new insecticide seed treatment for cereals. Proceedings of Crop Protection in Northern Britain Conference 2006**,** 131-136.

Adam NM, Hopkinson D (2008) Crop establishment improvements and foliar pest control in winter oilseed rape using a new clothianidin-based seed treatment. Proceedings of the Crop Protection in Northern Britain Conference 2008, 151-156.

ADAS Report (2009) Pest, disease and weed incidence in harvest year 2008. pp152.

ADAS Report (2010) Pest, disease and weed incidence in harvest year 2009. pp 166.

ADAS Report (2011) Pest, disease and weed incidence in harvest year 2010. pp 163.

ADAS (2011b) Review of factors including pest biology and control strategies that may explain the increased importance of the leaf miner *Scaptomyza flava*. Final Report Defra Research Project PS2718. pp 22.

ADAS Report (2013) Pest, disease and weed incidence in harvest year 2012. pp 140

AHDB (2013) Validation of an integrated pest management (IPM) strategy for pollen beetle to minimise the development of insecticide resistance. Project 214-0005 web summary. http://cereals.ahdb.org.uk/media/355413/214-0005-project-overview.pdf Accessed April 2014.

AHDB (2014a) Oilseed rape guide Updated 2014. http://cereals.ahdb.org.uk/media/305093/g55-oilseed-rape-guide-jan-2014-update.pdf

AHDB (2014b) http://cereals.ahdb.org.uk/markets/market-news/2014/march/28/adas-arable-crop-report-march-2014.aspx

AHDB (2014c) Encyclopaedia of pests and natural enemies in field crops. AHDB 2014, 200pp.

AHDB (2015) Area of oilseed rape grown in 2015. http://cereals.ahdb.org.uk/media/683680/planting-and-variety-survey-2015-final-results.pdf

AHDB (2015a) Controlling aphids and virus diseases in cereals and oilseed rape. AHDB Information Sheet 42

AHDB (2015b) Pyrethroid resistance in cabbage stem flea beetle is widespread – AHDB Cereals & Oilseeds calls for more samples. http://cereals.ahdb.org.uk/press/2014/september/15/widespread-resistance-in-cabbage-stem-flea-beetle-%E2%80%93-ahdb-cereals-oilseeds-calls-for-more-samples.aspx

AHDB (2016) Integrated slug control. Spring 2016. AHDB Information Sheet 04.

AHDB (2016a) Orange wheat blossom midge. Summer 2016. AHDB Information Sheet 53.

AHDB (2016b) Wheat bulb fly. Summer 2016. AHDB Information Sheet 51.

AHDB (2016c) Cabbage stem flea beetle. Summer 2016. AHDB Information Sheet 55.

Affolter F (1990) Structure and dynamics of the parasitoid complex of the wheat midges *Sitodiplosis mosellana* (Géhin) and *Contarinia tritici* (Kirby) (Diptera: Cecidomyiidae). CAB International Institute of Biological Control, Delemont, Switzerland. Final Report 108 pp.

Ahuja I, Rohloff J, Bones AM (2010) Defence mechanisms of Brassicaceae: implications for plant-insect interactions and potential for integrated pest management. A review. Agronomy for Sustainable Development 30, 311-348.

Alford DV (1979) Observations on the cabbage stem flea beetle, *Psylliodes chrysocephala,* on winter oilseed rape in Cambridgeshire. Annals of Applied Biology 93, 117-123.

Alford DV (2003) The oilseed rape crop: Biocontrol of Oilseed Rape Pests (ed. DV Alford) Blackwell Publishing, Oxford, pp. 1-8.

Alford DV, Ballanger Y and Kromp B (2003a) Parasitoids of miscellaneous pests: Biocontrol of oilseed rape pests (ed. DV Alford) Blackwell Science, pp. 139-144.

Alford DV, Nilsson C and Ulber B (2003b) Insect pests of oilseed rape crops: Biocontrol of oilseed rape pests (ed. DV Alford) Blackwell Science, Oxford, pp. 9-42.

Alford DV, Walters KFA, Williams IH and Murchie AK (1996) A commercially viable low-cost strategy for the management of seed weevil populations on winter oilseed rape in the UK: Brighton Crop Protection Conference, Pests & Diseases, Brighton, pp. 609-614.

Aljmli F (2007) Classification of oilseed rape visiting insects in relation to the sulphur supply. Landbauforschung Völkenrode - FAL Agricultural Research, Special Issue 312: 232 pp.

Allison R (2010) Gall midge outbreak may force re-think on 2010 cropping plans. Farmers Weekly. http://www.fwi.co.uk/Articles/30/07/2010/122574/Gall-midge-outbreak-may-force-rethink-on-2010-cropping.htm

Allison R (2013) New aphid control option for OSR this autumn. Farmers Weekly, 11 September 2013. http://www.fwi.co.uk/articles/11/09/2013/140989/new-aphid-control-option-for-osr-this-autumn.htm

Alves L, Wynn S and Stopps J (2016) Cabbage stem flea beetle live incidence and severity monitoring 2015. Project report No. 551. http://cereals.ahdb.org.uk/media/799228/pr551-final-project-report.pdf

Anon (2009) Agri-environment schemes in England, 2009: A review of results and effectiveness. NE194. Natural England Publications, UK.

Anon (2011) Faible pression pour les ravageurs de printemps en 2011. Arvalis Choisir 2011, 170.

Ansari MA, Evans M and Butt TM (2009) Identification of pathogenic strains of entomopathogenic nematodes and fungi for wireworm control. Crop Protection 28: 269-272. doi:http://dx.doi.org/10.1016/j.cropro.2008.11.003.

Ansari MA and Butt TM (2012) Evaluation of entomopathogenic fungi and a nematode against the soil-dwelling stages of the crane fly *Tipula paludosa*. Pest Management Science 68: 1337-1344.

Antico J, Colon C, Banks T, Ramonell KM (2012) Insights into the role of jasmonic acid-mediates defences against necrtrophic and biotrophic fingal pathogens. Frontiers in Biology 7(1): 48-56.

Arzani A, Peng JH and Lapitan NLV (2004) DNA and morphological markers for a Russian wheat aphid resistance gene. Euphytica 139: 167-172.

Axelsen J (1995) The winter mortality and emergence of *Dasineura brassicae* in Denmark. IOBC/wprs Bulletin 18(4): 81-87.

Axelsen JA, Fink R and Kjær C (1997) Global solar radiation as the factor controlling induction of diapause in the pod midge (*Dasyneura brassicae* Winn.). Oecologia 111: 178-182. doi:10.1007/s004420050223.

Ayala L, van Ginkel M, Khairallah M, Keller B and Henry M (2001) Expression of *Thinopyrum intermedium*-derived Barley yellow dwarf virus resistance in elite bread wheat backgrounds. Phytopathology 91: 55–62.

Bailey SER, Cordon S & Hutchinson S (1989) Why don't slugs eat more bait? A behavioural study of early meal termination produced by methiocarb and metaldehyde baits in *Derocera caruanae.* In: Henderson IF (Ed) *Slugs and Snails in World Agriculture.* Monograph No 41. BCPC, Thornton Heath, pp 385-390.

Bailey A, et al. (2009) ReBugging the system: Promoting adoption of alternative pest management strategies in field crop systems. Full Research Report, ESRC End of Award Report, RES-224-25-0093-A. Swindon: ESRC.

Balachowsky AS (1963) Entomologie Appliquée à l'Agriculture. Volume 2, Coleoptera. Masson, Paris.

Bale JS, Harrington R, Clough M (1988) Low temperature mortality of the peach potato aphid, *Myzus persicae*. Ecological Entomology 13: 121-129.

Bale JS and Hayward SAL (2010) Insect overwintering in a changing climate. The Journal of Experimental Biology 213: 980-994. doi:10.1242/jeb.037911.

Banks PM, Larkin PJ, Bariana HS, Lagudah ES, Appels R, Waterhouse PM, Bretell RIS, Chen X, Xu HJ, Xin ZY, Qian YT, Zhou XM, Cheng ZM and Zhou GH (1995) The use of cell culture for subchromosomal introgressions of Barley yellow dwarf virus resistance from *Thinopyrum intermedium* to wheat. Genome 38: 395–405.

Barari H, Cook SM, Clark SJ and Williams IH (2005) Effect of a turnip rape (*Brassica rapa*) trap crop on stem-mining pests and their parasitoids in winter oilseed rape (*Brassica napus*). BioControl 50: 69-86. doi:10.1007/s10526-004-0895-0.

Barker GM (2002) Ed. *Molluscs as Crop Pests*. Cabi Publishing, Wallingford, Oxon.

Barker PS and McKenzie RIH (1996) Possible sources of resistance to the wheat midge in wheat. Canadian Journal of Plant Science 76: 688-695.

Barnes, H.F. (1956). Gall midges of economic importance. Volume VII Gall midges of cereal crops. London: Crosby Lockwood & Sons, Ltd. pp. 29-82.

Barsics F, Haubruge E & Verheggen FJ (2011) Attraction of wireworms to root-emitted volatile organic compounds of barley. IOBC/wprs Bulletin 66: 475-478.

Barsics F, Haubruge E and Verheggen FJ (2013) Wireworms' management: an overview of the existing methods, with particular regards to *Agriotes* spp. (Coleoptera: Elateridae). Insects 4: 117-152.

Basedow T (1986) Die Abundanzdynamik der Sattelmücke, *Haplodiplosis marginata* (von Roser) Dipt., Cecidomyiidae), bei Fruchtwechsel, bei wiederholtem and bei permanentem Anbau von Weizen. Journal of Applied Entomology 102: 11-19.

Bass C, Puinean AM, Zimmer CT, Denholm I, Field LM, Foster SP, Gutbrod O, Nauen R, Slater R and Williamson MS (2014) The evolution of insecticide resistance in the peach-potato aphid, *Myzus persicae*. Insect Biochemistry and Molecular Biology 51: 41-51.

Baverstock, J. and Pell, J.K. (2011) Management of habitat diversity on arable farmland to maximize control of crop pests by communities of natural enemies. Defra Project IF0126. Final Report available at: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=14947

Bayer (2014) Methiocarb withdrawal dates announced. http://www.bayercropscience.co.uk/news-and-opinion/articles/2014/03/methiocarb-withdrawal-dates-announced/

Bayer Pest Spotter (2014) http://bayer.warinteractive.com/

Bayer CropScience (2014) Pollen beetle predictor. http://www.bayercropscience.co.uk/tools-and-services/agronomy-online-tools-and-services/pollen-beetle-predictor/

Beale MH, Birkett MA, Bruce TBA, Chamberlain K, Field JM, Huttly AK, Martin JL, Parker R, Phillips AL, Pickett JA, Prosser AM, Shewry PR, Smart LE, Wadhams LJ, Woodcok CM and Zhang Y (2006) Aphid alarm pheromone produced by transgenic plants affects aphid and parasitoid behaviour. Proceedings of National Acadamy of Science USA 103: 10 509 - 10 513. (doi:10.1073/pnas.0603998103)

Bell JR, Alderson L, Izera D, Kruger T, Parker S, Pickup J, Shortall CR, Taylor MS, Verrier P and Harrington R (2015) Long-term phenological trends, species accumulation rates, aphid traits and climate: five decades of change in migrating aphids. Journal of Animal Ecology 84: 21-34.

Benefer C, Andrew P, Blackshaw R, Ellis J & Knight M (2010) The spatial distribution of phytophagous insect larvae in grassland soils. Applied Soil Ecology 45: 269-274. doi:http://dx.doi.org/10.1016/j.apsoil.2010.05.002.

Benefer CM (2011) The Molecular and behavioural ecology of click beetles (Coleoptera: Elateridae) in agricultural land. PhD thesis, University of Plymouth, UK, 266 pp.

Benefer CM & Blackshaw RP (2014) Molecular approaches for studying root herbivores. Advances in Insect Physiology 45: 219-255.

Benefer CM, Herk WG, Ellis JS, Blackshaw RP, Vernon RS & Knight ME (2013) The molecular identification and genetic diversity of economically important wireworm species (Coleoptera: Elateridae) in Canada. Journal of Pest Science 86: 19-27. doi:10.1007/s10340-012-0454-x.

Bennison J, Pope T, Hough G, Maulden K, Kerley J and Drummond R (2013) Baby-leaf Cruciferae and watercress: Improved control of *Scaptomyza flava*. Final Report AHDB Horticulture Research Project FV 408. pp 26.

Benson RB (1952) Hymenoptera 2. Symphyta. Section (b). Handbooks for the Identification of British Insects 6.2(b): 51-137.

Beres PK (2011) Usefulness of selected seed dressing insecticides for integrated maize (*Zea mays* L.) protection against frit fly (*Oscinella frit* L.). Acta Scientiarum Polonorum – Agricultura 10: 15-23.

Berry P, Cook S, Ellis S, Gladders P and Roques S (2012) Oilseed rape guide, summer 2012. AHDB, 32 pp. http://www.hgca.com/media/177572/g55_oilseed_rape_guide.pdf.

Berzonsky WA, Ding H, Haley SD, Harris MO, Lamb RJ, McKenzie RIH, Ohm HW, Patterson FL, Pearis FB, Porter DR, Ratcliffe RK and Shanower TG (2003) Breeding wheat for resistance to insects. In: *Plant Breeding Reviews*, Vol. 22. Edited by Jules Janick, John Wiley & Sons Inc., Hoboken, New Jersey, 221-296.

Bianchi FJJ, Booij CJH and Tscharnke T (2006) Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proceedings of the Royal Society B 273: 1715-1727. doi:10.1098/rspb.2006.3530

Birch PA and Nicholson T (2001) A new insecticidal seed treatment for oilseed rape. In: A J Biddle, ed. Seed treatment: Challenges and Opportunities. BCPC Symposium Proceedings No. 76, BCPC Publications, 27-32.

Birkett MA, Campbell CAM, Chamberlain K, Guerrieri E, Hick AJ, Martin JL, Matthes M, Napier JA, Pettersson J, Pickett JA, Poppy GM, Pow EM, Pye BJ, Smart LE, Wadhams GH, Wadhams LJ & Woodcock CM (2000) New roles for cis-jasmone as an insect semiochemical and in plant defense. Proceedings of the National Academy of Sciences of the United States of America 97(16): 9329-9334.

Birkett MA, Bruce TJA, Martin JL, Smart LE, Oakley J and Wadhams LJ (2004) Responses of female orange wheat blossom midge, *Sitodiplosis mosellana* to wheat panicle volatiles. Journal of Chemical Ecology 30: 1319-1328.

Birkett MA and Pickett JA (2014) Prospects of genetic engineering for robust insect resistance. Current Opinion in Plant Biology 19: 59-67.

Blackman RL, Eastop VF (2007) Taxonomic issues. Chapter 1 *in Aphids as crop pests.* (eds) HR van Emden and R Harrington. CAB International. pp1-30.

Blackshaw RP (1983) The annual leatherjacket survey in Northern Ireland,1965-1982, and some factors affecting populations. Plant Pathology 32: 345-349.

Blackshaw RP (1988) Effects of cultivations and previous cropping on leatherjacket populations in spring barley. Research and Development in Agriculture 5: 35-37.

Blackshaw RP (1990a) Application of a sequential sampling technique to DIY assessment of leatherjacket (Diptera: Tipulidae) populations in grassland. Grass and Forage Science 45: 257-262.

Blackshaw RP (1990b) Observations on the distribution of leatherjackets in Northern Ireland. Annals of Applied Biology 116: 21-26.

Blackshaw RP (1991) Leatherjackets in grassland. In: Strategies for weed, disease and pest control in grassland: practical implications of recent developments and future trends. Proceedings of the British Grassland Society Conference held on 27th February 1991 at Hatherley Manor Hotel, Gloucester. Pp 6.1-6.12.

Blackshaw RP (1999) Behaviour mediated population regulation? Aspects of Applied Biology 53: 125-130.

Blackshaw RP (2009) A comparison of management options for leatherjacket populations in organic crop rotations using mathematical models. Agricultural and Forest Entomology 11: 197-203.

Blackshaw RP and Coll C (1999) Economically important leatherjackets of grassland and cereals: biology, impact and control. Integrated Pest Management Reviews 4: 143-160.

Blackshaw RP and Hicks (2013) Distribution of adult stages of soil insect pests across an agricultural landscape. Journal of Pest Science 86: 53-62.

Blackshaw RP and Kerry BR (2008) Root herbivory in agricultural ecosystems. In: Root Feeders: An Ecosystem Perspective. Eds. Johnson, S.N. and Murray, P.J. 35-53

Blackshaw RP and Vernon RS (2008) Spatial relationships between two *Agriotes* click-beetle species and wireworms in agricultural fields. Agricultural and Forest Entomology 10: 1-11. doi:10.1111/j.1461-9563.2007.00351.x.

Blackshaw RP and Moore JP (2012) Within-generation dynamics of leatherjackets (*Tipula paludosa* Meig.). Journal of Applied Entomology 136: 605-613.

Blackshaw RP and Perry JN (1994) Predicting leatherjacket population frequency in Northern Ireland. Annals of Applied Biology 124: 213-219.

Blackshaw RP and Petrovskii SV (2007) Limitation and regulation of ecological populations: a meta-analysis of *Tipula paludosa* field data. Mathematical Modelling of Natural Phenomena 2: 46-62.

Blackshaw RP and Vernon RS (2006) Spatiotemporal stability of two beetle populations in non-farmed habitats in an agricultural landscape. Journal of Applied Ecology 43: 680-689. doi:10.1111/j.1365-2664.2006.01167.x.

Blackshaw RP, Stewart RM, Humphreys IC and Coll C (1994) Preventing leatherjacket damage in cereals. Association of Applied Biologists conference on "*Sampling to make decisions*". Cambridge 22-23 March 1994, pp 189-196.

Blackshaw RP, Coll C, Humphreys IC and Stewart RM (1996) The epidemiology of a new leatherjacket pest (*Tipula oleracea*) of winter cereals in northern Britain. AHDB Cereals & Oilseeds Project Report No. 120, pp 129.

Blackshaw RP, Hicks H and Vernon RS (2009) Sex pheromone traps for predicting wireworm populations: limitations to interpretation. IOBC/WPRS Bulletin 51: 17-21.

Blake AJ, Dosdall LM and Keddie BA (2010) Plant nutrients and the spatiotemporal distribution dynamics of *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae) and its parasitoids. Environmental Entomology 39: 1195-1205. doi:10.1603/EN09217.

Blake AJ, Dosdall LM and Keddie BA (2011) Bottom-up effects of *Brassica napus* nutrition on the oviposition preference and larval performance of *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae). Arthropod-Plant Interactions 5: 39-48. doi:10.1007/s11829-010-9114-3.

Blake JJ, Spink JH and Dyer C (2003) Factors affecting cereal establishment and its prediction. Research Review 51, AHDB Cereals & Oilseeds, 53 pp.

Blassioli Moraws MC, Birkett MA, Gordon-Weeks R, Smart L, Martin JL, Pye BJ, Bromilow R and Pickett JA (2008) *cis*- Jasmone induces accumulation of defence compounds in wheat, *Triticum eastivum*. Phytochemistry 69: 9-17.

Bohan DA, Bohan AC, Glen DM, Symondson WOC, Wiltshire CWW, and Hughes L (2000) Spatial dynamics of predation by carabid beetles on slugs, Journal of Animal Ecology 69: 367–79.

Bonnemaison L (1957) Le charancon des siliques (*Ceuthorrhynchus assimilis* Payk.): Biologie et methodes de lutte. Annales des Epiphyties 4: 387-543.

Borg A (1996) Oviposition behaviour of two pollen beetles (*Meligethes aeneus* and M. *viridescens*) on different host plants. Växtskyddnotiser 60: 27–31.

Bowden J and Jones MG (1979) Monitoring wheat bulb fly, *Delia coarctata* (Fall.)(Diptera: Anthomyiididae) with light traps. Bulletin of Entomological Research 69: 129.

Bromand B ((1983) Possibility of continuous rearing of *Meligethes aeneus* Fabr. (Col.) Journal of Applied Entomology 96: 419-422.

Brooks DR, Bohan DA, Champion GT, Haughton AJ, Hawes C, Heard MS, Clark SJ, Dewar AM, Firbank LG, Perry JN, Rothery P, Scott RJ, Woiwod IP, Birchall C, Skellern MP, Walker JH, Baker P, Bell D, Browne EL, Dewar AJG, Fairfax CM, Garner BH, Haylock LA, Horne SL, Hulmes SE, Mason NS, Norton LR, Nuttall P, Randle Z, Rossall MJ, Sands RJN, Singer EJ and Walker MJ (2003) Invertebrate responses to the management of weeds in genetically modified herbicide-tolerant and conventional crops. 1. Soil surface active invertebrates. Philosophical Transactions of the Royal Society B, 358: 1847-1862.

Brown C and Beulke S (2010) Higher tier modeling to estimate concentrations of metaldehyde in three rivers following agricultural use and transport via drain flow. FERA study No T6ZB1000.

Bruce TJA and Smart LE (2009) Orange wheat blossom midge, *Sitodiplosis mosellana*, management. Outlooks on Pest Management 20: 89-92.

Bruce TJA, Martin JL, Pye BJ, Smart LE and Wadhams LJ (2002) Semiochemicals for the control of cereal pests. The BCPC Conference: Pests and Diseases, Brighton, pp 685-690.

Bruce TJA, Martin JL, Pickett JA, Pye BJ, Smart LE and Wadhams LJ (2003) cis- Jasmone treatment induces resistance in wheat plants against the grain aphid, *Sitobion avenae* (Fabricius) (Homoptera: Aphididae). Pest Management Science 59(9): 1031- 1036.

Bruce TJA, Hooper AM, Ireland L, Jones OT, Martin JL, Smart LE, Oakley J and Wadhams LJ (2007) Development of a pheromone trap monitoring system for orange wheat blossom midge, *Sitodiplosis mosellana*, in the U.K. Pest Management Science 63: 49-56.

Bryson R, Alford J and Oakley J (2005) Development of guidelines for improved control of gout fly (*Chlorops pumilionis*) in winter wheat. AHDB Cereals & Oilseeds Project Report No 372, pp 66.

Büchi R (1986) Biologie und Bekämpfung des Schwarzen Triebrüßlers,*Ceutorhynchus picitarsis* Gyll. (Col., Curculionidae). Anzeiger für Schädlingskunde, Pflanzenschutz, Umweltschutz 59: 51-56. doi:10.1007/BF01905922.

Büchi R (2002) Mortality of pollen beetle (*Meligethes* spp.) larvae due to predators and parasitoids in rape fields and the effect of conservation strips. Agriculture, Ecosystems & Environment 90: 255-263.

Büchi R and Roos-Humbel S (1991). Nützlinge reduzieren die Zahlder Rapsschädlinge. Landwirtschaft Schweiz 4 (3): 69–73.

Buchs W (2003a) Impact of on-farm landscape structures and farming systems on predators. In: *Biocontrol of Oilseed Rape Pests* (ed. by D Alford) Blackwell Publishing, Oxford, pp. 245-278.

Buchs W (2003b) Predators as biocontrol agents of oilseed rape pests. In: *Biocontrol of Oilseed Rape Pests* (ed. by D Alford) Blackwell Publishing, Oxford, pp. 279-298.

Buchs W and Alford DV (2003) Predators of oilseed rape pests. In *Biocontrol of oilseed rape pests* (ed. by DV Alford) Blackwell Publishing, pp. 181-199.

Buchs W and Nuss H (2000) First steps to assess the importance of epigaeic active polyphagous predators on oilseed rape insect pests with soil pupating larvae. IOBC/wprs Bulletin 23: 151-163.

Buntin GD, Flanders KL, Slaughter RW and DeLamar ZD (2004) Damage loss assessment and control of the cereal leaf beetle (Coleoptera: Chrysomelidae) in winter wheat. Journal of Economic Entomology 97: 374-382.

Butt TM (2011) Exploiting synergies to optimise the impact of entomopathogenic fungi. IOBC/WPRS Bulletin 66: 11-17.

Burghause F (2008) Der Schwarze Kohltriebrüssler, Vereinzelte Vorkommen oder Ausbreitunstendenz? [The rape winter stem weevil, local occurrance only or is it spreading?]. Raps: 202-203.

Byers GW and Arnaud PH (2011) *Tipula oleracea* Linnaeus in west-central California (Diptera: Tipulidae). Journal of the Kansas Entomological Society 84: 153-154.

Caillaud CM, Dedryver CA, Simon J-C (1994) Development and reproductive potential of the cereal aphid *Sitobion avenae* on resistant wheat lines (*Triticum monococcum).* Annals of Applied Biology 125: 219–232.

Cao H-H, Zhang M, Zhao H, Zhang Y, Wang X-X, Guo S-S, et al. (2014) Deciphering the Mechanism of *β*-Aminobutyric Acid-Induced resistance in wheat to the grain aphid, *Sitobion avenae*. PLoS ONE 9(3): e91768. doi:10.1371/journal.pone.0091768

Cambier V, Hance T and De Hoffmann E (2001) Effects of 1,4-benzoxazin-3-one derivatives from maize on survival and fecundity of Metopolophium dirhodum (Walker) on artificial diet. Journal of Chemical Ecology 27: 359–370.

Campbell AJ, Biesmeijer JC, Varma V and Wackers FJ (2012) Realising multiple ecosystem services based on the response of three beneficial insect groups to floral traits and trait diversity. Basic and Applied Ecology 13: 363 – 370.

Cárcamo HA, Dunn R, Dosdall LM and Olfert O (2007) Managing cabbage seedpod weevil in canola using a trap crop—A commercial field scale study in western Canada. Crop Protection 26: 1325-1334. doi:http://dx.doi.org/10.1016/j.cropro.2006.11.007.

Carreck NL, Butt TM, Clark SJ, Ibrahim L, Isger EA, Pell JK and Williams IH (2007) Honey bees can disseminate a microbial control agent to more than one influescence pest of oilseed rape. Biocontrol Science and Technology 17(2): 179-191.
DOI: 10.1080/09583150600937485

Carrie RJG, George DR and Wackers FL (2012) Selection of floral resources to optimize conservation of agriculturally-functional insect groups. Journal of Insect Conservation 16: 635-640.

Carroll MJ, Dennis P, Pearce-Higgins JW and Thomas CD (2011) Maintaining northern peatland ecosystems in a changing climate: effects of soil moisture, drainage and drain blocking on craneflies. Global Change Biology 17: 2991-3001.

Case P (2011) Saddle gall midge outbreaks seen for a second year. Farmers Weekly. http://www.fwi.co.uk/Articles/10/05/2011/126724/Saddle-gall-midge-outbreaks-seen-for-second-year.htm

Censier F, Chavalle S, Wittouck D, De Proft M and Bodson B (2012) Chemical control of *Haplodiplosis marginata* von Roser (Diptera: Cecidomyiidae). Communications in Agricultural and Applied Biological Sciences 77(4): 667-675.

Censier F, Chavalle S, San Martin y Gomez G, De Proft M and Bodson B (2015) Targeted control of the saddle gall midge, *Haplodiplosis marginata* (von Roser) (Diptera: Cecidomyiidae), and the benefits of good control of this pest to winter wheat yield. Pest Management Science 72(4): 731-737. DOI: 10.1002/ps.4046

Censier F, De Proft M and Bodson B (2015) The saddle gall midge, *Haplodiplsois marginata* (von Roser) (Diptera: Cecidomyiidae): Population dynamics and integrated management. Crop Protection 78: 137-145.

Censier F, Heuskin S, San Martin y Gomez G, Michels F, Fauconnier M-L, De Proft M, Lognay GC and Bodson B (2016) A pheromone trap monitoring system for the saddle gall midge, *Haplodiplosis marginata* (von Roser) (Diptera: Cecidomyiidae) Crop Protection **80**: 1-6.

CETIOM (2014a) Le charançon du bourgeon terminal. CETIOM. http://www.cetiom.fr/colza/cultiver-du-colza/ravageurs/insectes/insectes-automne/#c53584. Accessed February 2014.

CETIOM (2014b) Tenthrède de la rave. CETIOM. http://www.cetiom.fr/colza/cultiver-du-colza/ravageurs/insectes/insectes-automne/. Accessed February 2014.

Chain F, Riault G, Trottet M and Jacquot E (2005) Analysis of accumulation patterns of Barley yellow dwarf virus-PAV (BYDV-PAV) in two resistant wheat lines. European Journal of Plant Pathology 113: 343–355.

Chain F, Riault G, Trottet M and Jacquot E (2007) Evaluation of the durability of the *Barley yellow dwarf*- resistant *Zhong* and *TC14* wheat lines. European Journal of Plant Pathology 117: 35-43.

Chaplin-Kramer R and Kremen C (2012) Pest control experiments show benefits of complexity at landscape and local scales. Ecological Applications 22: 1936 – 1948.

Chaplin-Kramer R, de Valpine P, Mills NJ and Kremen C (2013) Detecting pest control services across spatial and temporal scales. Agriculture Ecosystems and Environment 181: 206 - 212.

Chapman PA (1994) Control of leatherjackets by natural enemies: the potential role of the ground beetle *Pterostichus melanarius*. Proceedings of the Brighton Crop Protection Conference, Pests and Diseases, Brighton, U.K., 21-24 November 1994. Volume 2. pp 933-934.

Ciepiela A, Sempbruch C and Czerniewicz P (2001) Relationship between the content of some protein fractions and population density of grain aphid (*Sitobion avenae* F.) on the winter triticale treated with Chwastox D 179 SL. Aphids and Other Homopterous Insects **8**: 195–204.

Chiverton PA and Sotherton NW (1991) The effect on beneficial arthropods of the exclusion of herbicides from cereal crop edges. Journal of Applied Ecology 28: 1027 – 1039.

Clark J, Wynn S, Twining S, Berry P Cook S, Ellis S and Gladders P (2009) Pestcide availability for cereals and oilseeds folowing revison of Directive 91/414/EEC: effects of losses and new rearch priorities. AHDB Cereals & Oilseeds Research Review 70, 127 pp.

Clements R, Bentley B and Asteraki E (1990) Origin of frit fly (*Oscinella* spp.) attack on newly sown grass, effect of pesticide on frit-fly larvae and benefit of using glyphosate herbicide pre-ploughing. Crop Protection 9: 105-110.

Coats SA, Coats JR and Ellis CR (1979) Selectivity of three synthetic pyrethroids to eight coccinellids, a eulopid parasitoid and two pest chrysomelids. Environmental Entomology 8: 720-722.

Coll C and Blackshaw RP (1996) Leatherjackets in winter cereals: a self-inflicted problem? Rotations and cropping systems. Aspects of Applied Biology 47: 145-151.

Coll C, Greenhorn JG and Blackshaw RP (1993a) The influence of oilseed rape (*Brassica napus*) on the occurrence of leatherjackets (*Tipula* spp.) in winter cereals. Proceedings of Crop Protection in Northern Britain. Dundee, pp 79-84.

Coll C, Blackshaw RP, Humphreys IC and Stewart RG (1993b) The epidemiology of *T. oleracea* in winter cereals in northern Britain. ANPP Third International Conference on Pests in Agriculture, Montpellier, pp 1059-1066.

Collier RH and Finch S (2007) IPM Case studies: Brassicas Chapter 21 In: van Emden H and Harrington R (eds) *Aphids as Crop Pests.* CABI, Wallingford, Oxon. Pp 549-559.

Collins KL, Boatman ND, Wilcox A, Holland JM and Chaney K (2002) Influence of beetle banks on cereal aphid predation in winter wheat. Agriculture Ecosystems and Environment 93: 337-35.

Cook SM (2009) Insect pests in oilseed rape: possibilities for control through genetic improvement? Presentation given at Oilseed Rape Genetic Improvement Network (OREGIN) 7th Stakeholder Forum meeting, JIC, Norwich, 27 November 2009. http://www.oregin.info/stakeholders/meetings/shf07-Nov2009/Cook_RRES_OREGIN_SHF7_Nov2009_InsectPests.pdf. Accessed February 2014.

Cook SM (2012) Field margin management for biocontrol and biodiversity across crop rotations. Defra Project IF01122. Proposal Summary can be found at: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=2&ProjectID=17807

Cook SM (2014) Oilseed rape crop and field margin management to encourage natural enemies and biodiversity in arable rotations. Defra Project IF0139, Final Report.

Cook SM, Baverstock J, Skellern MP and Pell JK (2016) Field margins for biocontrol and biodiversity across crop rotations. Final Project report for Defra project IF01122. 52 pp.

Cook SM, Döring TF, Ferguson AW, Martin JL, Skellern MP, Smart LE, Watts NP, Welham SJ, Woodcock C and Pickett JA (2013a) Development of an integrated pest management strategy for control of pollen beetles in winter oilseed rape. Project Report No. 504. AHDB Cereals & Oilseeds, 138 pp. http://publications.hgca.com/publications/documents/PR504_no_front110213.pdf. Accessed February 2014.

Cook SM, Khan ZR and Pickett JA (2007a) The use of push-pull strategies in integrated pest management. Annual Review of Entomology 52: 375-400. doi:10.1146/annurev.ento.52.110405.091407.

Cook SM, Rasmussen HB, Birkett MA, Murray DA, Pye BJ, Watts NP and Williams IH (2007b) Behavioural and chemical ecology underlying the success of turnip rape (*Brassica rapa*) trap crops in protecting oilseed rape (*Brassica napus*) from the pollen beetle (*Meligethes aeneus*). Arthropod-Plant Interactions 1(1): 57–67. doi:10.1007/s11829-007-9004-5

Cook SM, Skellern MP, Döring TF and Pickett JA (2013b) Red oilseed rape? The potential for manipulation of petal colour in control strategies for the pollen beetle (*Meligethes aeneus*). Arthropod-Plant Interactions 7: 249-258. doi:10.1007/s11829-013-9252-5.

Cook SM, Smart LE, Martin JL, Murray DA, Watts NP and Williams IH (2006) Exploitation of host plant preferences in pest management strategies for oilseed rape (*Brassica napus*). Entomologia Experimentalis et Applicata 119: 221-229. doi:10.1111/j.1570-7458.2006.00419.x.

Cook SM, Watts NP, Hunter F, Smart LE & Williams IH (2004) Effects of a turnip rape trap crop on the spatial distribution of *Meligethes aeneus* and *Ceutorhynchus assimilis* in oilseed rape. IOBC/WPRS Bulletin 27: 199-206.

Crop Monitor (2114) http://www.cropmonitor.co.uk/

Crespo Herrera, LA (2012) Reistance to aphids in wheat. Introductory paper at the Faculty of Landscape Planning, Horticulture and Agricultural Science 2012: 6, 36 pp.

D'Arcy CJ (1995) Symptomatology and host range of barley yellow dwarf, virus. In: C.J. D'Arcy, P.A. Burnett (Eds.), *Barley Yellow Dwarf, 40 Years of Progress*. APS Press St Paul MN USA, 1995, pp. 9–28.

Daamen RA and Stol W (1993) Surveys of cereal diseases and pests in the Netherlands. 6. Occurrence of insect pests in winter wheat. Netherlands Journal of Plant Pathology 99 (Supplement 3): 51-56.

Dawson LA, Grayston SJ, Murray PJ and Pratt SM (2002) Root feeding behavior of *Tipula paludosa* (Meig) (Diptera: Tipulidae) on *Lolium perenne* (L.) and *Trifolium repens* (L.). Soil Biology and Biochemistry 34: 609-615.

Dean GJ (1974) The overwintering abundance of cereal aphids. Annals of Applied Biology 76: 1-7.

Decourtye A, Mader E and Desneux N (2010) Landscape scale enhancement of floral resources for honey bees in agro-ecosystems. Apidologie 41: 264 – 277.

Dedryver CA, Le Gallic JF, Gauthier JP, Simon JC (1998b) Life cycle of the cereal aphid *Sitobion avenae* F.: polymorphism and comparison of life history traits associated with sexuality. Ecological Entomology 23:123–132.

Dedryver C-A, Hullé M, Le Gallic J-F, Caillaud MC and Simon J-C (2001) Coexistence in space and time of sexual and asexual populations of the cereal aphid *Sitobion avenae*. Oecologia 128: 379-388.

Dedryver CA (2004) Resistance of Poaceae to virus vectors. In: H. Lappierre, P. Signoret (Eds): *Virus Diseases of Poaceae.* **É**ditions INRA 2004. Pp 198-204.

Dedryver C.-A and Harrington R (2004) BYDV epidemiology and forecasting, in: H. Lapierre, P. Signoret (Eds.), *Viruses and Virus Diseases of Poaceae.* Editions INRA, France, 2004, pp. 155–170.

Dedryver C-A, Le Ralec A and Fabre F (2010) Conflicting relationships between aphids and men: A review of aphid damage and control strategies. Comptus Rendus Biologies 333: 539-553.

DEFRA (2009) Oilseed rape ecology - crop and margin management to encourage natural enemies for crop protection and biodiversity - Project IF0139. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=2&ProjectID=15611. Accessed February 2014.

DEFRA (2010) A review of slug control in winter cereals and oilseed rape. Project number PS2803. http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17215. Accessed March 2016.

DEFRA (2012) Field margins for biocontrol and biodiversity across crop rotation - DEFRA Project IF01122. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=2&ProjectID=17807. Accessed February 2014.

DEFRA (2013) Integrated pest management of pollen beetles in oilseed rape: the way forward. DEFRA Research Project PS2141. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=18590&FromSearch=Y&Publisher=1&SearchText=oilseed%20rape&GridPage=7&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description Accessed April 2014.

DEFRA (2015) 2015/2016 Survey: Autumn Pest Assessment 2015. Results of cabbage stem flea beetle larval assessment in the autumn of 2015. http://www.cropmonitor.co.uk/wosr/surveys/wosrPestAssLab.cfm?year=2015/2016&season=Autumn

DEFRA (2016) 2015/2016 Survey: Autumn Pest Assessment 2015. Results of cabbage stem flea beetle larval assessment in the spring of 2016. http://www.cropmonitor.co.uk/wosr/surveys/wosrPestAssLab.cfm?year=2015/2016&season=Spring

DEFRA Project PS2136. A novel approach for the control of dipteran pests of UK agriculture and horticulture using RNA interference. 2010 – 2012: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17610

Delaney KJ, Wawrzyniak M, Lemanczyk G, Wrzesinska D and Piesik D (2013) Synthetic cis-jasmone exposure induces wheat and barley volatiles that repel the pest cereal leaf beetle, *Oulema melanopus* L.. Journal of Chemical Ecology 39: 620-629.

Deligeorgidis PN, Deligeorgidis NP, Ipsilandis CG, Vardiabasis A, Vayopoulou,M, Giakalis L and Sidiropoulos G (2012) Four common insects of durum wheat cultivations in Western Macedonia, Greece. ISRN Agronomy 2012: article ID 781012, 1-4.

DePauw RM, Knox RE, Thomas JB, Smith M, Clarke JM, Clark FR, McCaig TN and Fernandez MR (2009) Goodeve hard red spring wheat. Canadian Journal of Plant Science 89: 937-944.

DePauw RM, Knox RE, Humphreys DG, Thomas JB, Fox SL, Brown PD, Singh AK, Pozniak C, Randhawa HS, Fowler DB, Graf RJ and Hucl P (2011) New breeding tools impact Canadian commercial farmer fields. Czech Journal of Genetics and Plant Breeding 47: S28-S34.

Desneux N, Decourtye A and Delpuech J-M (2007) The sublethal effects of pesticides on beneficial arthropods. Annual Review of Entomology **52**: 81–106.

Dewar AM (2007) Chemical control. In: van Emden, H. and Harrington, R. (eds) *Aphids as Crop Pests*. CABI Publishing, UK, pp. 391-422.

Dewar AM (2012) Ecology and control of saddle gall midge*, Haplodiplosis marginata von Roser* (Diptera; Cecidomyiidae). AHDB Cereals & Oilseeds Research Review No. 76, 15 pp.

Dewar AM (2014a) Alternative insecticides to control grain aphids, *Sitobion avenae,* that are resistant to pyrethroids. AHDB project report 532, 23 pp.

Dewar AM (2014b) Alternative insecticides to control pollen beetles, *Meligethes aeneus,* that are resistant to pyrethroids. Proceedings of the Crop Protection in Northern Britain Conference 2014, (in Press).

Dewar AM and Carter N (1984) Decision trees to assess the risk of cereal aphid (Hemiptera, Aphididae) outbreaks in summer in England. Bulletin of Entomological Research 74: 387-398.

Dewar AM, Dewar AJG, Haylock SP, Foster SP and Williamson MS (2014) Alternative insecticides to control cereal aphids, *Sitobion avenae*, that are resistant to pyrethroids. Proceedings of the Crop Protection in Northern Britain Conference 2014, 131-136.

Dewar AM and Evans J (2014) Controlling aphids and turnip yellows virus in oilseed rape in a post-neonicotinoid world. Aspects of Applied Biology 127*, Crop Protection in Southern Britain 2014*, pp. 21-28.

Dewar AM, Haylock LA, Bean KM and Ecclestone PMJ (2000) Novel seed treatments to control soil pests of sugar beet. The British Crop Protection Conference: Pests and Diseases. Volume 3. Brighton, UK. 2000. pp 907-912.

Dewar AM, Moores GD, Gifford MJ and Johnston M (2015) Ecofriendly synergists for insecticide formulations (EcoSyn): Improvements in the efficacy of pyrethroids in controlling pyrethroid-resistant pollen beetles, *Meligethes aeneus,* in spring oilseed rape. Proceedings of Resistance 2015 Conference held at Rothamsted Research, Harpenden UK September 2015.

Dewar AM, Tait M F and Stevens M (2011) Efficacy of thiamethoxam seed treatment against aphids and turnip yellows virus in oilseed rape. Aspects of Applied Biology 106*,* Crop Protection in Southern Britain 2011, pp. 195–202.

Dewar AM, Woiwod IP and Chopin de Janvry E (l980) Aerial migrations of the Rose-grain aphid, *Metopolophium dirhodum*, over Europe in l979. Plant Pathology 29, 101-109.

Dimitrijevic B, Lelie M and Lomovic S (1999) The effect of mineral nutrition on the damage degree of spring wheat by *Lema melanopus* L. (Coleoptera: Chrysomelidae). Acta Entomologia Serbic 4: 49-55.

Ding H and Lamb RJ (1999) Oviposition and larval establishment of *Sitodiplosis mosellana* (Diptera: Cecidomyiidae) on wheat (Graminae) at different growth stages. The Canadian Entomologist 151: 475-481.

Ding H, Lamb RJ and Ames N (2000). Inducible production of phenolic acids in wheat and antibiotic resistance to *Sitodiplosis mosellana*. Journal of Chemical Ecology, 26: 969-985.

Dmoch J (1965) The dynamics of a population of the cabbage seedpod weevil (*Ceuthorrhynchus assimilis* Payk.) and the development of winter rape. Part 1. Ekologia Polska, Seria A 8: 249-287.

Doane JF, DeClerck-Floate R, Arthur AP and Affolter F (1989) Description of the life stages of *Macroglenes penetrans* (Kirby) (Hymenoptera: Chalcidoidea, Pteromalidae) a parasite of the wheat midge *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae). The Canadian Entomologist 121: 1041-1048.

Dobson RM (1961) Observations on natural mortality, parasites and predators of wheat bulb fly, *Leptohylemyia coarctata* (Fall). Bulletin of Entomological Research 52: 281-91.

D**ö**ring TF, Skellern MP, Watts NP and Cook SM (2012) Colour choice behaviour in the pollen beetle, *Meligethes aeneus* (Coleoptera: Nitidulidae). Physiological Entomology 37(4): 360-378. DOI: 10.1111/j.1365-3032.2012.00850.x

Dosdall LM, Cárcamo H, Olfert O, Meers S, Hartley S and Gavloski J (2011) Insect invasions of agroecosystems in the western Canadian prairies: case histories, patterns, and implications for ecosystem function. Biological Invasions 13: 1135-1149.

Dosdall LM and Kott LS (2006) Introgression of resistance to cabbage seedpod weevil to canola from yellow mustard. Crop Science 46: 2437-2445. doi:10.2135/cropsci2006.02.0132.

DOW Information Leaflet 1 (2014) Wheat blossom midge: The threat to cereal crops. http://msdssearch.dow.com/PublishedLiteratureDAS/dh_0050/0901b80380050c69.pdf?filepath=/uk/pdfs/noreg/011-01380.pdf&fromPage=GetDoc

DOW Information Leaflet 2 (2014) Frit fly. http://msdssearch.dow.com/PublishedLiteratureDAS/dh_0041/0901b803800415e6.pdf?filepath=uk/pdfs/noreg/011-01014.pdf&fromPage=GetDoc

DOW Information Leaflet 3 (2014) Leatherjackets: The threat to cereals and grassland. http://msdssearch.dow.com/PublishedLiteratureDAS/dh_0061/0901b80380061a92.pdf?filepath=/uk/pdfs/noreg/011-01337.pdf&fromPage=GetDoc

DOW Cereals Pestwatch (2014) http://www.dowagro.com/united_kingdom/services/pestwatch2012.htm

DOW Webpage (2014) Problems. http://www.dowagro.com/united_kingdom/problems/Problems_index2.htm

Drake CM (1993) A review of the British Opomyzidae. British Journal of Entomology and Natural History 6: 159-176.

Dunn BL, Carver BF, Baker CA and Porter DR (2007) Rapid phenotypic assessment of bird cherry-oat aphid resistance in winter wheat. Plant Breeding 126(3): 240-243.

Dunn B, Porter D, Baker C and Carver B (2011) Screening USDA-ARS Wheat Germplasm for Bird Cherry-Oat Aphid Tolerance. Journal of Crop Improvement 25(2): 176-182.

EFSA (2013a) Conclusion on the peer review of the pesticide risk assessment for bees for the active substances clothianidin, thiamethoxam, imidacloprid. EFSA Journal 11: 3066–3068.

EFSA (2013b) https://secure.pesticides.gov.uk/pestreg/ProdSearch.asp

Ehlers R-U, Strauch O and Peters A (2010) Use of *Bacillus thuringiensis* against the larvae of *Tipula paludosa*. Julius Kühn-Archiv 428: 221.

Eickermann M, Junk J, Görgen K, Hoffmann L and Beyer M (2013) Ensemble-based analysis of regional climate change effects on the pod midge (*Dasineura brassicae* Winn.) in oilseed rape. IOBC/WPRS Bulletin 96: 23-28.

Eickermann M and Ulber B (2010) Screening of oilseed rape and other brassicaceous genotypes for susceptibility to *Ceutorhynchus pallidactylus* (Mrsh.). Journal of Applied Entomology 134: 542-550. doi:10.1111/j.1439-0418.2009.01449.x.

Eickermann M and Ulber B (2011) Effect of plant architecture on infestation of *Brassica* genotypes by cabbage stem weevil, *Ceutorhynchus pallidactylus* (Mrsh.): 13th International Rapeseed Congress, Prague, Czech Republic, June 05-09, 2011 (ed., Prague, Czech Republic, pp. 1162-1165.

Eickermann M, Ulber B and Vidal S (2011) Resynthesized lines and cultivars of *Brassica napus* L. provide sources of resistance to the cabbage stem weevil (*Ceutorhynchus pallidactylus* (Mrsh.)). Bulletin of Entomological Research 101: 287-294. doi:10.1017/s0007485310000489.

Eilenberg J, Hajek AE, Lomer C (2001) Suggestions for unifying the terminology in biological control. BioControl 46: 387-400.

Ekbom B (2010) Pests and their enemies in spring oilseed rape in Europe and challenges to integrated pest management: Biocontrol-Based Integrated Management of Oilseed Rape Pests (ed. by IH Williams) Springer Science+Business Media B.V., pp. 151-165.

Ekbom B and Borg A (1996) Pollen beetles (*Meligethes aeneus*) oviposition and feeding preference on different host plant species. Entomologia Experimentalis et Applicata 78: 291-299.

Elliott RH, Mann L and Olfert O (2009a) Calendar and degree-day requirements for emergence of adult wheat midges, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), in Saskatchewan, Canada. Crop Protection 28: 588-594.

Elliott R, Olfert O and Hartley S (2011) Management practices for wheat midges, *Sitodiplosis mosellana* (Gehin). Prairie Soils and Crops Journal 4: 8-13.

Ellis JS, Blackshaw R, Parker W, Hicks H and Knight ME (2009) Genetic identification of morphologically cryptic agricultural pests. Agricultural and Forest Entomology 11: 115-121. doi:10.1111/j.1461-9563.2008.00420.x.

Ellis S (2010) Wheat bulb fly: Survey of incidence in England; risk assessment as the basis for autumn 2010 seed treatment usage. Home Grown Cereals Authority, London.

Ellis S (2012) Autumn survey of wheat bulb fly incidence (2011-2013) AHDB Cereals & Oilseeds 15 pp. http://cereals.ahdb.org.uk/media/167014/wheat-bulb-fly-survey-autumn-2012-report.pdf

Ellis S and Berry P (2012) Re-evaluating thresholds for pollen beetle in oilseed rape. AHDB Cereals & Oilseeds Project Report No. 495. 17 pp.

Ellis SA, Ashlee NJ and Maulden KA (2014) Improving risk assessment and control of saddle gall midge (*Haplodiplosis marginata*). *Aspects of Applied Biology* **127**: 29-24.

Ellis S, Berry P and Walters K (2009a) A review of invertebrate pest thresholds. Research Review No. 73. AHDB Cereals & Oilseeds, 68pp.

Ellis SA, Bruce TJA, Smart LE, Martin JA, Snape J and Self M (2009b) Integrated management strategies for varieties tolerant and susceptible to wheat blossom midge. AHDB Cereals & Oilseeds Project Report 451, 151 pp.

Ellis SA, Bruce TJA, Smart LE, Martin JA, Snape J and Self M (2009c) Integrated management strategies for varieties tolerant and susceptible to wheat blossom midge. AHDB Cereals & Oilseeds Project Report 451, 138 pp.

Ellis SA, Berry PM and Kendall S (2012) Assessing tolerance to slugs in winter wheat and oilseed rape by simulating pest damage. Defra Project PS2805. (see DEFRA 2012).

Ellis SA, Oakley JN, Parker WE and Raw K (1999) The development of an action threshold for cabbage aphid (*Brevicoryne brassicae*) in oilseed rape in the UK. Annals of Applied Biology 134: 153-162.

El-Wakeil N, Sallam AA and Volkmar C (2009) Ecological studies on frit fly *Oscinella frit* (L.) and its control on summer wheat in Central Germany. Mitt. Deutsche Gesellschaft für allgemeine und angewandte Entomologie 17: 215-220.

El-Wakeil N, Gaafer N and Volkmar C (2010a) Susceptibility of spring wheat to infestation with wheat blossom midge and thrips. Journal of Plant Diseases and Protection 117: 261-267.

El-Wakeil NE, Volkmar C and Sallam AA (1010b) Jasmonic acid induces resistance to economically important insect pests in winter wheat. Pest Management Science 66: 549-554.

El-Wakeil N and Volkmar C (2011) Effect of weather conditions on frit fly (*Oscinella frit*, Diptera: Chloropidae) activity and infestation levels in spring wheat in central Germany. Gesunde Pflanzen 63: 159-165.

El-Wakeil N, Abdel-Moniem ASH, Gaafar N and Volkmar C (2013) Effectiveness of some insecticides on wheat blossom midge in winter wheat. Gesunde Pflanzen 65: 7-13.

El-Wakeil N and Volkmar C (2013) Efficacy of entomopathogenic nematodes against the frit fly *Oscinella frit* (L.) (Diptera: Choropidae) on spring wheat. Journal fur Kulturpflanzen 65: 9-18.

ENDURE (2009) Review of factors influencing success of biological control and recomendations. ENDURE Project deliverable DR4.7, 1 December 2009. http://www.endure-network.eu/endure_publications/deliverables. Accessed February 2014.

EPPO (2007) Report 07/13763 Ad hoc EPPO Workshop on insecticide resistance of *Meligethes* spp. (pollen beetle) on oilseed rape BBA, Berlin-Dahlem, 2007-09-03/05 http://archives.eppo.int/MEETINGS/2007_meetings/meligethes/18Brandes/18Brandes.pdf?utm_source=archives.eppo.org&utm_medium=int_redirect

Ester A and Huiting H (2007) Controlling wireworms (*Agriotes* spp.) in a potato crop with biologicals. IOBC/WPRS Bulletin 30(1).

European Food Safety Authority (EFSA) (2012) Conclusion of the peer review on the pesticide risk assessment of confirmatory data submitted for the active substance methiocarb. EFSA Journal 10(7): 2758. doi:10.2903/j.efsa.2012.2758. 14pp.

European Commission (EU) (2013) Commission Implementing Regulation (EU) No 485/2013. Official Journal of the European Union. http://ec.europa.eu/food/animal/liveanimals/bees/neonicotinoids_en.htm

Evans A (2007) Stem boring pests of winter oilseed rape. Techical Note 584. SAC, 3 pp. http://www.sruc.ac.uk/downloads/file/1341/tn584_stem_boaring_pests_of_winter_oilseed_rape. Accessed February 2014.

Evans EW, Karren JP and Israelsen CE (2006) Interactions over time between cereal leaf beetles (Coleoptera: Chrysomelidae) and larval parasitoid *Tetrastichus julis* (Hymenoptera: Eulophidae) in Utah. Journal of Economic Entomology 99: 1967-1973.

Evans EW, Anderson MR and Bowling PD (2010) Targeted sugar provision promotes parasitism of the cereal leaf beetle, *Oulema melanopus*. Agricultural and Forest Entomology 12: 41-47.

Evans EW, Carlile NR, Innes MB and Pitigala N (2013) Warm springs reduce parasitism of the cereal leaf beetle through phonological mismatch. Journal of Applied Entomology 137: 383-391.

Evans KA (2003) Wheat bulb fly and other pests of cereal: Technical note 552. Scottish Agricultural College, London

Evans KA (2012) Do we need to be worried about the potential threat of invasive species to crops as the climate changes?: Proceedings of the Dundee Conference on Crop Protection in Northern Britain 2012, Dundee, Scotland, pp. 55-60.

Evans KA and Allen-Williams LJ (1989a) Location and infestation of winter oilseed rape by the brassica pod midge *Dasineura brassicae* Winn. (Diptera: Cecidomyiidae). Mededelingen van de Faculteit landbouwwetenschappen - Rijksuniversiteit Gent 54(3a): 717-725.

Evans KA and Allen-Williams LJ (1989b) The response of the cabbage seed weevil (*Ceutorhynchus assimilis* Payk.) and the brassica pod midge (*Dasineura brassicae* Winn.) to flower colour and volatiles of oilseed rape. Aspects of Applied Biology 23: 347-353.

Fabre F, Mieuzet L, Plantegenest M, Dedryver CA, Leterrier JL, Jacquot E (2006) Spatial and temporal patterns in the frequency of *Rhopalosiphum padi* bearing barley yellow dwarf viruses and its epidemiological significance, Agriculture, Ecosystems and Environment. 106: 49-55.

FAOStat (2010) http://faostat3.fao.org/home/E

Fenton B, Margaritopoulos JT, Malloch GL and Foster SP (2010) Micro-evolutionary change in relation to insecticide resistance in the peach-potato aphid, *Myzus persicae*. Ecological Entomology 35: 131-146.

Ferguson AW and Alomar O (2010) Landscape studies for conservation biological control research: status and future needs. A meta-review from the EU NoE project ENDURE. IOBC/WPRS Bulletin 56: 41-44.

Ferguson AW, Barari H, Warner DJ, Campbell JM, Smith ET, Watts NP and Williams IH (2006) Distributions and interactions of the stem miners *Psylliodes chrysocephala* and *Ceutorhynchus pallidactylus* and their parasitoids in a crop of winter oilseed rape (*Brassica napus*). Entomologia Experimentalis et Applicata 119: 81-92. doi:10.1111/j.1570-7458.2006.00404.x.

Ferguson AW, Campbell JM, Warner DJ, Watts NP, Schmidt JEU and Williams IH (2004) Phenology and spatial distributions of *Dasineura brassicae* and its parasitoids in a crop of winter oilseed rape: implications for integrated pest management. IOBC/WPRS Bulletin 27: 243-251.

Ferguson AW, Holdgate R, Mason NS, Clark SJ and Williams IH (2013) Phenologies and diel periodicities of within-crop flight by pests and parasitoids in winter oilseed rape in the UK. IOBC/WPRS Bulletin 92: 45-54.

Ferguson AW, Klukowski Z, Walczak B, Clark SJ, Mugglestone MA, Perry JN and Williams IH (2003) Spatial distribution of pest insects in oilseed rape: implications for integrated pest management. Agriculture Ecosystems and Environment 95: 509-521.

Ferguson AW, Klukowski Z, Walczak B, Perry JN, Mugglestone MA, Clark SJ and Williams IH (2000) The spatio-temporal distribution of adult *Ceutorynhus assimilis* in a crop of winter oilseed rape in relation to the distribution of their larvae and that of the parasitoid *Trichomalus perfectus*. Entomologia Experimentalis et Applicata 95: 161-171.

Finch S and Thompson AR (1992) Pests of Cruciferous Crops. In: McKinley RG (ed) *Vegetable Crop Pests.* Macmillan, Basingstoke, pp. 87-138.

Fletcher MR, Hunter K, Quick MP, Thompson HM and Greig- Smith PW (1991) Pesticide poisoning of animals. Ministry of Agriculture Fishing and Food (MAFF) Publications, London, UK, pp 30.

Fletcher M, Hunter K and Barnet EA (1994) Pesticide poisoning of animals. Ministry of Agriculture Fishing and Food (MAFF) Publications, London, UK, pp 52.

Floate KD, Doane JF and Gillott C (1990) Carabid predators of the wheat midge (Diptera: Cecidomyiidae) in Saskatchewan. Environmental Entomology 19: 1503-1511.

Foster SP, Paul VL, Slater R, Warren A, Denholm I, Field LM and Williamson MS (2013) A mutation (L1014F) in the voltage-gated sodium channel of the grain aphid. *Sitobion avenae,* is associated with resistance to pyrethroid insecticides. Pest Management Science 70(8): 1249-1253. doi: 10.1002/ps.3683.

Fox CJS & MacLellan CR (1956) Some Carabidae and Staphylinidae shown to feed on a wireworm, *Agriotes sputator* (L.), by the precipitin test. Canadian Entomologist 88: 228-283.

Francki MG, Ohm HW and Anderson JM (2001) Novel germsplasm providing resistance to barley yellow dwarf virus in wheat. Australian Journal of Agricultural Research 52:1375- 1382.

Frank T, Drapela T, Moser D and Zaller JG (2010) Insect pests and spiders in oilseed rape and their response to site and landscape factors*: Biocontrol-based integrated management of oilseed rape pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 285-304.

Franzen LD, Gutsche AR, Heng-Moss TM, Higley LG and Macedo TB (2008) Physiological responses of wheat and barley to Russian wheat aphid, *Diuraphis noxia* (Mordvilko) and bird cherry-oat aphid, *Rhopalosiphum padi* (L.) (Hemiptera: Aphididae). *Arthropod-Plant Interactions* 2(4): 227-235.

Free JB and Williams IH (1979a) The distribution of insect pests on crops of oil-seed rape (*Brassica napus* L.) and the damage they cause. Journal of Agricultural Science, Cambridge 92: 139-149.

Free JB and Williams IH (1979b) The infestation of crops of oil-seed rape (*Brassica napus* L.) by insect pests. Journal of Agricultural Science, Cambridge 92: 203-218.

French N, Nichols DBR, Wright AJ, Green DI, Green DB and Fenlon JS (1988) Chemical control of the frit fly on winter cereals sown after grass. Annals of Applied Biology 113: 245-251.

Frost MJ, Elsworth SG and Moran A (1994) Tefluthrin: A cereal seed treatment for the control of wheat bulb fly (*Delia coarctata*). Brighton Crop Protection Conference: Pests and Disease 1-3, 217–222.

Furlan L (2007) Management and biological control of wireworm populations in Europe: current possibilities and future perspectives. IOBC/WPRS Bulletin 30(7): 11-16.

Furlan L, Bonetto C, Finotto A, Lazzeri L, Malaguti L, Patalano G & Parker W (2010) The efficacy of biofumigant meals and plants to control wireworm populations. Industrial Crops and Products 31: 245-254. doi:http://dx.doi.org/10.1016/j.indcrop.2009.10.012

Gaafar N, El-Wakeil N and Volkmar C (2011) Assessment of wheat ear insects in winter wheat varieties in central Germany. Journal of Pest Science 84: 49-59.

Galushka V and Gray R (2012) The privatization of British wheat breeding: what can Canada learn? Report prepared within the scope of the Canadian Triticum Advancement through Genomics (CTAG) Initiative, 58 pp.

Ganehiarachchi GASM and Harris MO (2007) Oviposition behavior of orange wheat blossom midge on low vs. high-ranked grass seed heads. Entomologia Experimentalis et Applicata 123: 287-297.

Garthwaite DG, Thomas MR, Parrish G, Heywood E and Battersby A (2007) Pesticide usage survey report 213. Arable crops in Great Britain 2006. DEFRA and SEERAD National Statistics, 116 pp.

Garthwaite DG, Thomas MR, Parrish G, Smith L and Barker I (2009) Pesticide usage survey report 224. Arable crops in Great Britain 2008. DEFRA and SEERAD National Statistics, 99 pp.

Garthwaite DG, Barker I, Parrish G, Smith L, Chippindale C and Pietravalle S (2011a) Pesticide usage survey report 235 - arable crops in the United Kingdom 2010. DEFRA National Statistics, 89pp.

Garthwaite DG, Thomas MR, Heywood E and Battersby A (2011b) Pesticide usage survey report 213. Arable crops in Great Britain 2006. DEFRA and SEERAD National Statistics, 120 pp.

Garthwaite DG, Hudson S, Barker I, Parrish G, Smith L and Pietravalle S (2013) Pesticide usage survey report 250 - arable crops in the United Kingdom 2012. DEFRA National Statistics, 92pp. http://www.fera.defra.gov.uk/landUseSustainability/surveys/documents/arable2012v2.pdf

Garthwaite D G, Hudson S, Barker I, Parrish G, Smith L and Pietravalle S (2013) Pesticide Usage Survey Report 255. Grassland and fodder crops in the United Kingdom in 2013. http://www.fera.defra.gov.uk/landUseSustainability/surveys/documents/grasslandFodder2013.pdf

Garthwaite DG, Barker I, Laybourn R, Huntly A, Parrish GP, Hudson S and Thygesen H (2015) Pesticide usage survey report 263 - arable crops in the United Kingdom 2014. DEFRA National Statistics, 87pp. https://secure.fera.defra.gov.uk/pusstats/surveys/documents/arable2014v2.pdf

Gengotti S, Censi D and Curto G (2008) Evaluation of active ingredients and nematodes against slugs and snails in organic lettuce. 16th IFOAM Organic World `congress, Modena Italy 2008.

George KS and Gair R (1979) Crop loss assessment on winter wheat attacked by the grain aphid, *Sitobion avenae*, (F.), 1974-77. Plant Pathology 28: 143-149.

Gharalari AH, Fox SL, Smith MAH and Lamb RJ (2009a) Oviposition deterrence in spring wheat, *Triticum aestivum*, against orange wheat blossom midge, *Sitodiplosis mosellana*: implications for inheritance of deterrence. Entomologia Experimentalis et Applicata 133: 74-83.

Gharalari AH, Smith MAH, Fox SL and Lamb RJ (2009b) The relationship between morphological traits of the spring wheat spike and oviposition deterrence in orange wheat blossom midge. Entomologia Experimentalis et Applicata 132: 182-190.

Gill RJ, Ramos-Rodriguez O and Raine NE (2012) Combined pesticide exposure severely affects individual- and colony-level traits in bees. Nature 491: 105-119. doi: 10.1038/nature11585.

Girard C, Bonadé-Bottino M, Pham-Delegue M-H and Jouanin L (1998) Two strains of cabbage seed weevil (Coleoptera: Curculionidae) exhibit differential susceptibility to a transgenic oilseed rape expressing oryzacystatin I. Journal of Insect Physiology 44: 569-577. doi:http://dx.doi.org/10.1016/S0022-1910(98)00050-X.

Givovich A, Niemeyer H, Sandström J and Pettersson J (1994) Presence of hydroxamic acid glucosides in wheat phloem sap, and its consequences for the performance of *Rhopalosiphum padi* (L.) (Homoptera: Aphididae). Journal of Chemical Ecology 20, 1923-1930.

Givovich A and Niemeyer HM (1995) Comparison of the effect of hydroxamic acids from wheat on five species of cereal aphids. Entomologia Experimentalis et Applicata 74: 115–119.

Gladbach DJ, Holzschuh A, Scherber C, Thies C, Dormann CF and Tscharntke T (2011) Crop-noncrop spillover: arable fields affect trophic interactions on wild plants in surrounding habitats. Oecologia 166: 433-441.

Glattkowski H, Saggau B and Goebel G (2008) Experiences in controlling resistant pollen beetle by type I ether pyrethroid Trebon 30 EC in Germany. Eppo Bulletin 38: 79 – 84.

Glen DM (2000) The effects of cultural measures on cereal pests and their role in integrated pest management. Integrated Pest management Reviews 5: 25-40.

Glen DM, Wiltshire CW, Hughes L, Ester A, van Rozen K, Castillejo J, Iglesias J, Speiser B, Coupland J and Gwynn R (2000) The use of slug-parasitic nematodes and other techniques for control of slug and snail damage in horticultural crops. Brighton Crop Protection Conference (BCPC) Pests and Diseases, 345–350.

Glen D (2002) Integrated control of slug damage. Pesticide Outlook, August 2002: 137-141.

Glen DM and Moens R (2002) Agriolimacidae, Arionidae and Milacidae as pests in west European cereals. In: Barker, G.M. (Ed.), *Molluscs as Crop Pests*. CABI Publishing, Wallingford, pp. 271–300.

Glen DM and Symondson WOC (2002) Influence of soil tillage on slugs and their natural enemies. In: *Soil Tillage in Agroecosystems* (Ed. A. El Titi) CRC Press, Boca Raton, USA.

Glen D, Bamber G, Batchelor C, Bohan D, Fisher J, Foster V, Godfrey M, Green D, Gussin E, Meredith R, Oakley J, Port G and Wiltshire C (2006) Integrated slug control in arable crops: Risk assessment, trapping, agronomy and chemical control. AHDB Cereals & Oilseeds Project Report No. 393. Home-Grown Cereals Authority, London.

Gomez P and Rodriguez-Hernandez AM (2009) Genetic resistance for the sustainable control of plant virus diseases: breeding, mechanisms and durability. European Journal of Plant Pathology 125: 1-22.

Gong Z-J, Wu Y-Q, Miao J, Duan Y, Jiang YL and Li T (2013) Global transcriptome analysis of orange wheat blossom midge *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae) to identify candidate transcripts regulating diapause. PLoS ONE 8 (8): e71564.doi:10.1371/journal.pone.0071564

Gough HC, Woods A, Maskell FE and Towler MJ (1961) Field experiments on the control of wheat bulb fly, *Leptohylemyia coarctata* (Fall.). Bulletin of Entomological Research 52: 621–634.

Goulson D (2013) An overview of the environmental crisis posed by neonicotoinoid insecticides. Journal of Applied Ecology 50 (4): 977-987. doi: 10.1111/1365-2664.12111

Golightly WH and Woodville HC (1974) Studies of recent outbreaks of saddle gall midge. Annals of Applied Biology 77**:** 97-101.

Graichen K and Peterka H (1999) Generation of oilseed rape with resistance to turnip yellows luteovirus. In *10th International Rapeseed Congress - New Horizons from an Old Crop*, pp 148.

Gratwick, M (1992) Ed. *Crop Pests in the UK. Collected edition of MAFF leaflets*. Chapman and Hall, London.

Gray L (2013) Millions of ‘killer slugs’ set to take over our gardens. http://www.telegraph.co.uk/gardening/9791458/Millions-of-killer-slugs-set-to-take-over-gardens.html).

Green DB (2007) Revised thresholds for economic cabbage stem flea beetle control. AHDB Cereals & Oilseeds Topic Sheet 98.

Green DB (2008) Revised thresholds for cabbage stem flea beetle on oilseed rape. AHDB Cereals & Oilseeds Project Report No. 428. http://cereals.ahdb.org.uk/media/366225/pr428_final_project_report.pdf

Green DB and Oakley JN (2006) Turnip sawfly. AHDB Cereals & Oilseeds press release statement 28 September 2006. 2pp. http://archive.hgca.com/publications/documents/news/turnip_sawfly_-_hgca_press_release_28_sept_06.pdf. Accessed February 2014.

Green DB, Corbett SJ, Jackson AW and Nowak KJ (1992) Surface versus admixed applciations of slug pellets to winter wheat. Proceedings of the Britsh Crop Protection Conference - Pests and Diseases. BCPC, Thornton Heath, pp. 587-592.

Gries R, Gries G, Khaskin G, King S, Olfert O and Kominski A (2000) Sex pheromone of the orange wheat blossom midge, *Sitodiplosis mosellana*. Naturwissenschaften 87: 450-454.

Griffiths GJK, Holland JM, Bailey A and Thomas MB (2008) Efficacy and economics of shelter habitats for conservation biological control. Biological Control 45: 200-209. doi:10.1016/j.biocontrol.2007.09.002.

Griffiths S, Simmonds J, Leverington M, Wang Y, Fish L, Sayers E, Alibert L, Orford S, Wingen L, Herry L, Faure S, Laurie D, Bilham L and Snape J (2009) Meta-QTL analysis of the genetic control of ear emergence in elite European winter wheat germplasm. Theoretical and Applied Genetics 119: 383-395.

Gunning RV and Forrester NW (1984) Cyclodiene lindane resistance in *Agrypnus variabilis* (Candéze) (Coleoptera: Elateridae) in northern New South Wales. Australian Journal of Entomology 23: 247-248. doi:10.1111/j.1440-6055.1984.tb01955.x.

Gurr GM, Wratten SD and Luna JM (2003) Multi-function agricultural biodiversity: Pest management and other benefits. Basic and Applied Ecology 4: 107-116.

Hall DR, Amarawardana L, Cross JV, Francke W, Boddum T and Hillbur Y (2012) The Chemical Ecology of Cecidomyiid Midges (Diptera: Cecidomyiidae). Journal of Chemical Ecology 38: 2-22. doi:10.1007/s10886-011-0053-y.

Hallmann CA, Foppen RPB, van Turnhout CAM, de Kroon H and Jongejans E (2014) Declines in insectivorous birds are associated with high neonicotoinoid concentrations. Nature 511: 341-350. doi:10.1038/nature13531

Hamilton RH (1964) Metabolism of herbicides: tolerance of several grass species to 2-chloro-s-triazine herbicides in relation to degradation and content of benzoxazinone derivatives. Journal of Agricultural and Food Chemistry 12: 14–17.

Hand SC, Wratten SD (1985) Production of sexual morphs by the monoecious cereal aphid Sitobion avenae. Entomologia Experimentalis et Applicata 38:239–247.

Hansen LM (2003) Insecticide-resistant pollen beetles (*Meligethes aeneus* F.) found in Danish oilseed rape (*Brassica napus* L.) fields. Pest Management Science 59(9): 1057-1059.

Hansen LM (2006) Effect of 6-methoxybenzoxazolin-2-one (MBOA) on the reproductive rate of the grain aphid (*Sitobion avenae* F.). Journal of Agriculture and Food Chemistry 54: 1031-1035.

Hao YN, Miao J, Wu YQ, Gong ZT, Jiang YL, Duan Y, Li T, Cheng WN and Cui JX (2013) Flight performance of the orange wheat blossom midge (Diptera: Cecidomyiidae). Journal of Economic Entomology 106: 2043-2047.

Hardie J, Isaacs R, Pickett JA, Wadhams LJ and Woodcock CM (1994). Methyl salicylate and (-)-(1RS,5S)-Myrtenal are plant-derived repellents for black bean aphid, *Aphis fabae* Scop. (Homoptera, Aphididae). Journal of Chemical Ecology 20(11): 2847-2855.

Harrington R (2014) The Rothamsted Insect survey strikes gold. Antenna 38(3): 159-166.

Harrington R, Fleming RA and Woiwod IP (2001) Climate change impacts on insect management and conservation in temperate regions: can they be predicted? Agricultural and Forest Entomology 3: 233-240. doi:10.1046/j.1461-9555.2001.00120.x.

Harrington R, Hullé M and Plantagenest M (2007) Monitoring and forecasting. Chapter 19 In: *Aphids as Crop Pests.* CABI Wallingford. Oxon*.* Pp 515-536.

Harrington R, Tatchell GM and Bale JS (1990) Weather, life cycle strategy and spring populations of aphids. Acta Phytopathologica et Entomologia Hungarica 25: 423-432.

Harris CR (1972) Factors Influencing the effectiveness of soil insecticides. Annual Review of Entomology 17: 177-198. doi:doi:10.1146/annurev.en.17.010172.001141.

Harris D and Thompson A (2012) Chorpyrifis: efficacy of chlorpyrifos through air induction nozzles. Aspects of Applied Biology 117: 173-176.

Haschek C, Drapela T, Schuller N, Fiedler K and Frank T (2012) Carabid beetle condition, reproduction and density in winter oilseed rape affected by field and landscape parameters. Journal of Applied Entomology 136: 665-674. doi:10.1111/j.1439-0418.2011.01694.x.

Havlickova H (1997) Differences in level of tolerance to cereal aphids in five winter wheat cultivars. Rostlinna Vyroba 43(12): 593-596.

Havlickova H (2001) Screening of productive Czech winter wheat cultivars on resistance to aphids. Rostlinna Vyroba 47(7): 326-329.

Haye T, Mason PG, Dosdall LM and Kuhlmann U (2010) Mortality factors affecting the cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham), in its area of origin: A life table analysis. Biological Control 54: 331-341. doi:http://dx.doi.org/10.1016/j.biocontrol.2010.06.004.

Heimbach U and Müller A (2013) Incidence of pyrethroid-resistant oilseed rape pests in Germany. Pest Management Science 69: 209-216. doi:10.1002/ps.3351.

Heimbach U, Müller A and Thieme T (2006) First steps to analyse pyrethroid resistance of different oil seed rape pests in Germany. Nachrichtenblatt des Deutschen Pflanzenschutzdienstes 58: S1-S5.

Heldon AJ and Dixon AFG (2002) Life cycle variation in the aphid *Sitobion avenae*: costs and benefits of male reproduction. Ecological Entomology 27: 692-701.

Henderson I and Triebskorn R (2002) Chemical control of terrestrial slugs. Chapter 1 In: Barker, GM (Ed.), *Molluscs as Crop Pests*. CABI Publishing, Wallingford, pp. 1-33.

Henry M, George S, Arnold GM, Dedryver CA, Kendall DA, Robert Y and Smith BD (1993) Occurrence of Barley yellow dwarf virus (BYDV) isolates in different farmland habitats in western France and south-west England. Annals of Applied Biology 123: 315–329.

Henry M and McNab A (Eds (2002) Barley Yellow Dwarf Disease: Recent Advances and Future Strategies. Mexico, D.F.: CIMMYT. ISBN: 970-648-095-1

Henry M, Posadas G, Segura J and Rajaram S (2002) Evaluating resistance to BYDV-PAV, BYDV-MAV and CYDV-RPV in *Thinopyram intermedium*-derived wheat lines. Proceedings of conference on *Barley Yellow Dwarf Disease: Recent Advances and Future Strategies.* Mexico. Pp 64-66.

Henry M, Beguin M, Requier F, Rollin O, Odoux J-F, Aupinel P, Aptel J, Tchamitchian S and Decourtye A (2012) A common pesticide decreases foraging success and survival in honeybees. Science 336: 350–351.

Herbert DA and Van Duyn JW (2009) Cereal leaf beetle biology and management. Communications and marketing, College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University. Publication No 444-350. pp 8.

Hermann A, Brunner N, Hann P, Wrbka T and Kromp B (2013) Correlations between wireworm damages in potato fields and landscape structure at different scales. Journal of Pest Science 86: 41-51. doi:10.1007/s10340-012-0444-z.

Hesler LS, Riedell WE, Kieckhefer RW, Haley SD and Collins RD (1999) Resistance to *Rhopalosiphum padi* (Homoptera : Aphididae) in wheat germplasm accessions. Journal of Economic Entomology 92(5): 1234-1238.

Hesler LS (2005) Resistance to *Rhopalosiphum padi* (Homoptera: Aphididae) in three triticale accessions. Journal of Economic Entomology 98: 603–610.

Hesler LS, Haley SD, Nkongolo KK and Peairs FB (2007) Resistance to *Rhopalosiphum padi* (Homoptera : Aphididae) in triticale and triticale-derived wheat lines resistant to *Diuraphis noxia* (Homoptera : Aphididae). Journal of Entomological Science 42(2): 217-227.

AHDB Cereals & Oilseeds (2002) Arable cropping and the environment - a guide. AHDB Cereals & Oilseeds, 19 pp. *AHDB Archive.*

AHDB Cereals & Oilseeds (2003) Pest management in cereals and oilseed rape – a guide. pp24. *AHDB Archive.*

AHDB Cereals & Oilseeds (2005a) Slug pellet timing and placement in winter wheat and oilseed rape. Topic Sheet No. 88. *AHDB Archive.*

AHDB Cereals & Oilseeds (2005b) Integrated slug control in winter wheat. Topic Sheets No. 84. *AHDB Archive.*

AHDB Cereals & Oilseeds (2005c) Integrated slug control in oilseed rape. Topic Sheet No. 85. *AHDB Archive.*

AHDB Cereals & Oilseeds (2005d) Controlling gout fly in wheat. Topic Sheet No 87, 2pp. *AHDB Archive.*

AHDB Cereals & Oilseeds (2012a) Guide to growing oilseed rape. G55. *AHDB Archive.*

AHDB Cereals & Oilseeds (2012b) Controlling aphids and virus diseases in cereals and oilseed rape. Summer 2012. AHDB Cereals & Oilseeds Information Sheet 16*. AHDB Archive.*

AHDB Cereals & Oilseeds (2013a) Maximising control of cabbage stem flea beetles (CSFB) without neonicotinoid seed treatments: project overview. AHDB Cereals & Oilseeds

Project no. 214-009. http://www.hgca.com/media/355416/214-0009-project-overview.pdf Accessed April 2014.

AHDB Cereals & Oilseeds (2013c) Monitoring and control of pollen beetle in oilseed rape. Information Sheet 18, Spring 2013.

AHDB Cereals & Oilseeds (2014) Controlling aphids and virus diseases in cereals and oilseed rape. Information Sheet 32. *AHDB Archive.*

AHDB Cereals & Oilseeds Handout (2014) Neonicotinoids: key messages. pp 2.

AHDB Recommended Lists (2014). AHDB Recommended lists 2013/14 for cereals and oilseeds. 52 pp.

Hiiesaar K, Williams HI, Mänd M, Luik A, Jo˜gar K, Metspalu L, Svilponis E, Ploomi A and Kivimägi I (2011) Supercooling ability and cold hardiness of the pollen beetle *Meligethes aeneus*. Entomologia Experimentalis et Applicata138: 117–127.

Hilton MJ, Jarvis TD and Ricketts (2015) The degradation of thiamethoxam in European field studies. Pest Management Science 72(2): 388-397. DOI: 10.1002/ps.4024

Hoffman GD and Rao S (2011) Oviposition site selection on oats: the effect of plant architecture, plant and leaf age, tissue toughness, and hardness on cereal leaf beetle, *Oulema melanopus*. Entomologia Experimentalis et Applicata 141: 232-244.

Højland DH, Nauen R, Foster SP, and Williamson MS and Kristensen (2015) Incidence, spread and mechanisms of pyrethroid resistance in European populations of the cabbage stem flea beetle, *Psylliodes chrysocephala* L. (Colepotera: Chrysomelidae). PLoS ONE 10(12): e0146045. doi:10.1371/journal.pone.0146045

Hokkanen HMT (1993) Overwintering survival and spring emergence in *Meligethes aeneus*: effects of body weight, crowding, and soil treatment with *Beauveria bassiana*. Entomologia Experimentalis et Applicata 67: 241–246.

Hokkanen H, Menzler-Hokkanen I and Butt T (2003) Pathogens of oilseed rape pests. In: *Biocontrol of Oilseed Rape Pests* (ed. by D Alford) Blackwell Publishing, Oxford, pp. 299-322.

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture Ecosystems & Environment 103: 1-25. doi:10.1016/j.agee.2003.12.018.

Holland JM and Oakley J (2007) Importance of arthropod pests and their natural enemies in relation to recent farming practice changes in the UK. Research Review No. 64. AHDB Cereals & Oilseeds, 106pp.

Holland JM, Oaten H, Moreby S, Birkett T, Simper J, Southway S and Smith BM (2012) Agri-environment scheme enhancing ecosystem services: A demonstration of improved biological control in cereal crops. Agriculture, Ecosystems and Environment 155: 147-152.

Holland JM, Storkey J, Lutman PJW, Henderson I and Orson J (2013) Managing uncropped land in order to enhance biodiversity benefits of the arable farmed landscape: The Farm4bio project. AHDB Cereals & Oilseeds Final Report Project No. 508 pp 97.

Holland JM, Storkey J, Lutman PJW, Birkett TC, Simper J and Aebischer NJ (2014) Utilisation of agri-environment habitats to enhance invertebrate ecosystem service providers. Agriculture, Ecosystems and Environment 183: 103 – 109.

Holland JM, Thomas SR and Hewitt A (1996) Some effects of polyphagous predators on cereal aphid (*Sitobion avenae* F.) and orange wheat blossom midge (*Sitodiplosis mosellana* Géhin). Agriculture Ecosystems and Environment 59: 181-190.

Holland JM and Thomas SR (2003) Do polyphagous predators help control orange wheat blossom midge *Sitodiplosis mosellana* Géhin in winter wheat? Journal of Applied Entomology 124: 325-330.

Hollingsworth RG, Armstrong JW and Campbell E (2002) Caffeine as a repellent for slugs and snails. Nature **417**: 915-916. doi:10.1038/news020624-8

Huang T, Jander G, and de Vos M, (2011) Non-protein amino acids in plant defense against insect herbivores: representative cases and opportunities for further functional analysis. Phytochemistry 72(13): 1531-1537.

Homeida AM and Cooke RG (1982) Pharmacological aspects of metaldehyde poisoning in mice. Journal of Veterinary Pharmacology and Therapeutics 5: 77–82.

Hopkins RJ, van Dam NM and van Loon JJA (2009) Role of glucosinolates in insect-plant relationships and multitrophic interactions. Annual Review of Entomology 54: 57-83.

Horgan A (2011) Challenges asscoaited with controlling slugs in UK arable crops. Aspects of Applied Biology 106: 213-217. Crop Protection in Southern Britain 2011.

HSE (2016) http://content.govdelivery.com/accounts/UKHSE/bulletins/13567bb

Hu Q, Weiss A, Feng S and Braenziger PS (2006) Earlier heading dates and warmer springs in the U.S. Great Plains. Agricultural and Forest Meteorology 135: 290-294.

Hughes JM and Evans KA (2003) Lygid bug damage as a pod access mechanism *for Dasineura brassicae* (Dipt., Cecidomyiidae) oviposition. Journal of Applied Entomology 127: 116-118. doi:10.1046/j.1439-0418.2003.00658.x.

Humphreys DG, Townley-Smith TF, Lukow O, McCallum B, Gaudet D, Gilbert J, Fetch T, Menzies J, Brown D and Czarnecki E (2010) Burnside extra strong hard red spring wheat. Canadian Journal of Plant Sciences 90: 79-84.

Humphreys IC, Blackshaw RP, Stewart RM and Coll C (1993) Differences between larvae of *Tipula paludosa* and *Tipula oleracea* (Diptera: Tipulidae) using isoelectric focusing and their occurrence in grassland in northern Britain. Annals of Applied Biology 122: 1-8.

Impey L (2009) Watch out for lemon blossom midge in the south. May issue. Farmer's Weekly Article by Louise Impey. http://www.fwi.co.uk/articles/05/05/2009/115448/watch-out-for-lemon-blossom-midge-in-the-south.htm

IRAC (2016) Insecticide Resistance Action Committee http://www.irac-online.org/pests/meligethes-aeneus/

Irwin ME, Kampmeier GE and Weisser WW (2007**)** Process and Consequences. Ch. 7 in *Aphids as Crop Pests.* (eds) HR van Emden and R Harrington. CAB International. Pp 153-186.

Irwin ME and Thresh JM (1990) Epidemiology of barley yellow dwarf virus: a study in ecological complexity. Annual Review of Phytopathology 28: 393-424.

Jahier J, Chain F, Barloy D, Tanguy A-M, Lemoine J, Riault G, Margale E, Trottet M and Jacqot E (2009) Effect of combining two genes for partial resistance to *Barley yellow dwarf virus* – PAV (BYDV-PAV) derived from *Thinopyrum intermedium* in wheat. Plant Pathology 58: 807-814.

Jay CN, Rossall S and Smith HG (1999) Effects of beet western yellows virus on growth and yield of oilseed rape (*Brassica napus*). Journal of Agricultural Science, Cambridge 133: 131-139.

Jeschk P, Nauen R, Schindler M and Elbert A (2011) Overview of the status and global strategy for neonicotinoids. Journal of Agricultural and Food Chemistry 59: 2897–2908.

Jonasson T (1978) Studies on the biology of resistance to frit fly, *Oscinella frit*, in oats: A literature survey. Svenges Utsadesforenings Tidskrift 85: 37-57.

Johnen A and von Richthofen J-S (2013) The decision-support system proPlant expert: a computer-based tool for integrated pest management used in Europe. IOBC/WPRS Bulletin 96: 99-105.

Johnen A, Volk T and von Richthofen J-S (2013) The proPlant expert decision support system for pest and disease management in oilseed rape. IOBC/WPRS Bulletin 96: 107-111.

Johnen A, Williams IH, Nilsson C, Klukowski Z, Luik A and Ulber B (2010) The proPlant decision support system: phenological models for the major pests of oilseed rape and their key parasitoids in Europe. IN: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by I Williams) Springer Science+Business Media B.V., pp. 381-403.

Johnson RM, Wen Z, Schuler MA and Berenbaum MR (2006) Mediation of pyrethroid insecticide toxicity to honey bees (Hymenoptera: Apidae) by cytochrome P450 monooxygenases. Journal of Economic Entomology 99:1046–1050.

Jones MG (1975) The predators of wheat bulb fly. Annals of Applied Biology 80(1): 128-130.

Jones A, Harrington P and Turnbull G (2014) Neonicotinoids concentrations in arable soils after seed treatment applications in preceding years. Pest Management Science 70 (12): 1780-1784. doi: 10.1002/ps.3836.

Jones FGW and Jones MG (1984) *Pests of Field Crops*. 3 edn. Edward Arnold, London.

Jones RAC, Coutts BA and Hawkes J (2007) Yield-limiting potential of *Beet western yellows virus* in *Brassica napus*. Australian Journal of Agricultural Research **58**:788-801.

Jonsson M and Anderson P (2007) Emission of oilseed rape volatiles after pollen beetle infestation; behavioural and electrophysiological responses in the parasitoid *Phradis morionellus*. Chemoecology 17: 201-207.

Jonsson M, Bommarco R, Ekbom B, Smith HG, Bengtsson J, Caballero-Lopez B, Winqvist C and Olsson O (2014) Ecological production functions for biological control services in agricultural landscapes. Methods in Ecology and Evolution 5: 243 – 252.

Jourdheuil P (1960) Influence de quelques facteurs ecologiques sur les fluctuations de population d'une biocenose parasitaire. Annales des Epiphyties 11: 445-660.

Jung J, Racca P, Schmitt J and Kleinhenz B (2012) SIMAGRIO-W: Development of a prediction model for wireworms in relation to soil moisture, temperature and type. Journal of Applied Entomology 138(3): 183-194. n/a-n/a. doi:10.1111/jen.12021

Junk J, Eickermann M, Görgen K, Beyer M and Hoffmann L (2012) Ensemble-based analysis of regional climate change effects on the cabbage stem weevil (*Ceutorhynchus pallidactylus* (Mrsh.)) in winter oilseed rape (*Brassica napus* L.). The Journal of Agricultural Science 150: 191-202. doi:doi:10.1017/S0021859611000529.

Kabaluk JT and Ericsson JD (2007) Environmental and Behavioral Constraints on the Infection of Wireworms by *Metarhizium anisopliae*. Environmental Entomology 36: 1415-1420. doi:10.1603/0046-225X(2007)36[1415:EABCOT]2.0.CO;2.

Kabaluk JT, Vernon RS and Goettel MS (2007) Mortality and infection of wireworm, *Agriotes obscurus* [Coleoptera: Elateridae], with inundative field applications of *Metarhizium anisopliae*. Phytoprotection 88: 51-56.

Kaniuczak Z (2008) Distribution and effect of chemical control of gout fly (*Chlorops pumilionis* Bjerk.) on spring wheat in south-eastern Poland. Journal of Plant Protection Research 48: 453-460.

Kaniuczak Z (2011) Occurrence and range of damage on spring wheat and triticale cultivars caused by gout fly (*Chlorops pumilionis* Bjerk.) in south-eastern Poland. Acta Scientiarum Polonorum Poland, Agricultura 10: 97-106.

Kaniuczak Z (2013) Effect of some insecticides in leaf beetle larvae control in winter wheat and its influence on seed yield and economic indices. Acta Scientiarum Polonorum Agricultura 12: 45-53.

Kati A, Shufran KA, Taylor MS, Barjadze S, Eastop VF, Blackman RL and Harrington R (2013) Identity of *Schizaphis* species (Hemiptera: Aphididae) in the United Kingdom: are they a threat to crops? Bulletin of Entomological Research 103 (4): 425-440. doi:10.1017/S0007485312000909

Katis NI, Tsitsipis JA, Stevens M and Powell G (2007) Transmission of plant viruses. Chapter 14 in *Aphids as Crop Pests.* (eds) HR van Emden and R Harrington. CAB International. Pp 353-390.

Kearns HGH (1931) The larval and pupal anatomy of *Stenomalus micans* Ol. (Pteromalidae), a chalcid endoprasite of the gout fly of barley (*Chlorops taeniopus* Meig.), with some details of the life history of the summer generation. Parasitology 23(3): 380-395.

Kell G. (1988) Agro-environmental factors influencing leatherjacket (Diptera: Tipulidae) populations in grassland. PhD Thesis, The Queen's University of Belfast.

Kell GV and Blackshaw R (1988) The influence of agricultural practices on leatherjacket populations in Northern Ireland. Proceedings of the 12th General Meeting of the European Grassland Federation. pp 504-508.

Kelm M and Klukowski Z (2000) The effect of stem weevil (*Ceutorhynchus pallidactylus* Marsh.) infestation on oilseed rape yield. IOBC/WPRS Bulletin 23(6): 125-130.

Kendall DA (2002) Soil Tillage and Epigeal predatory arthropods. Chapter 11 In: *Soil Tillage in AgroEcosystems* (ed.) Adel El Titi. RCR Press pp 297-343.

Kendall DA, Brain P and Chinn NE (1992) A simulation model of the epdiemiology of barley yellow dwarf virus in winter sown cereals and its application to forecasting. Journal of Applied Ecology 29: 414-426.

Kennedy P and Collier R (2008) Pests and diseases of field vegetables. Chapter 7 in DV Alford (ed) *Pest and Disease Management Handbook* BCPC Enterprises. Pp 185-257. DOI: 10.1002/9780470690475.ch7

Kennedy TF and Connery J (2005) Grain yield reductions in spring barley due to barley yellow dwarf virus and aphid feeding. Irish journal of Agriculture & Food Research 44: 111-128.

Kennedy TF and Connery J (2012) Control of barley yellow dwarf virus in minimum-till and conventional-till autumn-sown cereals by insecticide seed and foliar spray treatments. Journal of Agricultural Science 150: 249-262.

Kerney (1999) *Atlas of the Land and Freshwater Molluscs of Britain and Ireland*. 264 pp. Harley Books.

Kher SV, Dosdall LM and Cárcamo HA (2011) The cereal leaf beetle: Distribution and prospects for control. Prairie Soils and Crops Journal 4: 32-41.

Kher SV, Dosdall LM, Carcamo HA and El-Bouhssini M (2013) Antibiosis resistance to cereal leaf beetle, *Oulema melanopus* (L.) (Coleoptera: Chrysomelidae) in central Asian wheat germplasm. Journal of Applied Entomology 137: 751-760.

Klueken AM, Poehling H-M and Hau B (2008) Attractiveness and host suitability of winter wheat cultivars for cereal aphids (Homoptera: Aphididae). Journal of Plant Diseases and Protection 115(3): 114-121.

Knodel J and Garichiarachchi M (2008) Integrated pest management of the wheat midge in North Dakota. NDSU Extension Service Publication 8 pp.

Konyspaevna SK (2012) Spring wheat resistance against cereal leaf beetle (*Oulema melanopus* Z.) in relation to leaf pubescence. Australian Journal of Basic and Applied Sciences 6: 515-518.

Kostov K (2001) Breeding wheat lines for host-plant resistance to cereal leaf beetle by using the cross-mutation method. Bulgarian Journal of Agricultural Science 7: 7-14.

Kovács G, Kaasik R, Metspalu L, Williams IH, Luik A and Veromann E (2013) Could *Brassica rapa*, *Brassica juncea* and *Sinapis alba* facilitate the control of the cabbage seed weevil in oilseed rape crops? Biological Control 65: 124-129. doi:http://dx.doi.org/10.1016/j.biocontrol.2013.01.011.

Kozina A, Čačija M, Igrc Barčić J & Bažok R (2013) Influence of climatic conditions on the distribution, abundance and activity of *Agriotes lineatus* L. adults in sex pheromone traps in Croatia. International Journal of Biometeorology 57: 509-519. doi:10.1007/s00484-012-0577-z.

Kozłowski J (2005) Host plants and harmfulness of the *Arion lusitanicus* Mabille, 1868 slug. Journal Plant Protection Research 45 (3): 221-233.

Kozłowski J (2012) The significance of alien and invasive slug species for plant communities in agrocenoses. Journal of Plant Protection Research 52 (1): 67-76.

Kozłowski J, Kaluski T, Jaskulska M and Kozlowska M (2010) Initial evaluation of the effectiveness of selected active substances in reducing damage to rape plants caused by *Arion lusitanicus* (Gastropoda, Pulmonata, Arionidae). Journal of Plant Protection Research 50(4): 520-526. DOI: 10.2478/v10045--□□010--□□0086--□□1

Kraus P and Kromp B (2002) Parasitization rates of the oilseed rape pests *Ceutorhynchus napi*, *Ceutorhynchus pallidactylus* (Coleoptera, Curculionidae) and *Meligethes aeneus* (Coleoptera, Nitulidae) by ichneumonids in several localities of Eastern Austria. IOBC/WPRS Bulletin 25(2): 117-122.

Kromp B (1999) Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. Agriculture Ecosystems & Environment 74: 187-228.

Krupke CH, Hunt GJ, Eitzer BD, Andino G and Given K (2012) Multiple routes of pesticide exposure for honey bees living near agricultural fields. PLoS One 7(1), e29268. doi:10.1371/journal.pone.0029268

Krusteva H, Karadjova O, Beschovski V and Ventsislovov V (2011) Studies on harmful dipterans on winter wheat in small grain regions of North Bulgaria. Plant Science 48: 308-315.

Krusteva H and Karadjova O (2011) Impacts of triticale crop sowing date on the insect pest species composition and damage caused. Bulgarian Journal of Agricultural Science 17: 411-416.

Krusteva H, Karadjova O and Ventsislovov V (2012) Monitoring methods and prognosis of *Opomyza florum* Fabr. (Diptera: Opomyzidae) – a pest of wheat in Bulgaria. Journal of Plant Protection Research 52: 472-478.

Kuhar TP, Speese Iii J, Whalen J, Alvarez JM, Alyokhin A, Ghidiu G and Spellman MR (2003) Current status of insecticidal control of wireworms in potatoes. Pesticide Outlook 14: 265-267. doi:10.1039/B314851N.

Kurppa S (1989) Susceptibility and reaction of wheat and barley varieties grown in Finland to damage by the orange wheat blossom midge, *Sitodiplosis mosellana* (Géhin). Annales

Agriculturale Fenniae 28: 371-383.

Kurppa SLA and Hursburg GS (1989) Control of orange wheat blossom midge (*Sitodiplosis mosellana*) (Géhin) with pyrethroids. Annales Agriculturale Fenniae 28: 103-111.

Kwon M, Hahm YI, Shin KY and Ahn YJ (1999) Evaluation of various potato cultivars for resistance to wireworms (Coleoptera: Elateridae). American Journal of Potato Research 76: 317-319. doi:10.1007/BF02853631.

Lamb RI, Wise IL, Gavloski JE, Kaminski LA and Olfert OO (2002) Making control decisions for *Sitodiplosis mosellana* (Diptera: Cecidomyiidae) in wheat (Gramineae) using sticky traps. The Canadian Entomologist 134: 851-854.

Lamb RJ and MacKay PA (1995) Tolerance of antibiotic and susceptible cereal seedlings to the aphids *Metopolophium dirhodum* and *Rhopalosiphum padi.* Annals of Applied Biology 127(3): 573-583.

Lambion J (2005) Limaces et escargots en agriculture biologique: quelle alternative au metaldehyde? AFPP 7th Conference Internationale sur les ravageurs en agriculture, Montpelier 2005.

Landé N, Sauzet G and Leterme P (2013) Is oilseed rape mixed cropping an efficient solution to reduce nitrogen fertilization, weed population, and damage caused by insects? GCIRC Technical Meeting 28 April to 1 May 2013, Agroscope Changins-Wädenswil, 1 p. http://www.cetiom.fr/fileadmin/cetiom/Innovations/couverts_associes/oilseed_rape_mixed_cropping_GCIRC_2013_abstract.pdf. Accessed February 2014.

Landis DA, Wratten SD and Gurr GM (2000) Habitat management to conserve natural enemies of arthropod pests in agriculture. Annual Review of Entomology 45: 175 – 201.

Landl M and Glauninger J (2013) Preliminary investigations into the use of trap crops to control *Agriotes* spp. (Coleoptera: Elateridae) in potato crops. Journal of Pest Science 86: 85-90. doi:10.1007/s10340-011-0348-3.

Lane A and Cooper DA (1989) Importance and control of insect pests of oilseed rape. Aspects of Applied Biology 23: 269-276.

Lane A and Gladders P (2000) Pests and diseases of oilseeds, brassica seed crops and field beans. In: *Pest and Disease Management Handbook* (ed. by DV Alford) Blackwell Science, Oxford.

Lane A and Walters KFA (1994) Pest control requirements of oilseed rape under reformed CAP. Aspects of Applied Biology 40: 171–181.

Lange W and Jochemsen G (1987) Leaf hairs in common wheat are no deterrent to attack by the saddle gall midge. Cereal Research Communications 15: 255-258.

Larsson HA (1984) Frit fly (*Oscinella frit* L.) damage in oats and its chemical control by synthetic pyrethroids. Zeitschrift für angewandte Entomologie 97(1□5): 470-480.

Larsson H (1992) Skadetroskel och bekampningstrojel forden gula vetmenyggan. In 33rd Swedish Crop Protection Conference, Uppsala, 29-30 January 1992. Pest and plant diseases. Uppsala, Sweden. Swedish University of Agricultural Sciences, 233-238.

Láska P and Kocourek F (1991) Monitoring of flight activity in some crucifer-feeding pests by means of yellow water-traps. Acta Entomologica Bohemoslovaca (CSFR) 88: 25-32.

Laznik Z, Toth T, Lakatos M, Vidrih M and Trdan S (2010) *Oulema melanopus* (L.) (Coleoptera: Chrysomelidae) adults are susceptible to entomopathogenic nematode (*Rhabditida*) attack: results from a lab study. Journal of Plant Disease Protection 117: 30-32.

Laznik Z, Vidrih M, Vucajnk F and Trdan S (2012) Is foliar application of entomopathogenic nematodes (*Rhabditida*) an effective alternative to thiamethoxam in controlling cereal leaf beetle (*Oulema melanopus* L.) on winter wheat. Journal of Food, Agriculture and Environment 10: 716-719.

LeSage L, Dobesberger EJ and Majka CG (2007) Introduced leaf beetles of the maritime provinces, 2. The cereal leaf beetle *Oulema melanopus* (Linnaeus) (Coleoptera: Chrysomelidae). Proceedings of the Entomological Society of Washington 109: 286-294.

Leach JE, Darby RJ, Williams IH, Fitt BDL and Rawlinson CJ (1994) Factors affecting growth and yield of winter oilseed rape (*Brassica napus*) 1985-1989. Journal of Agricultural Science 122: 405-413.

Leclercq-Le Quillec F, Tanguy S and Dedryver CA (1995) Aerial flow of barley yellow dwarf viruses and of their vectors in western France. Annals of Applied Biology 126: 75-90.

Leclercq-Le Quillec F, Plantagenest M, Riault G and Dedryver CA (2000) Analysing and modelling temporal diseases progress of barley yellow dwarf virus serotypes in barley fields. Phytopathology 90(8): 860-866.

Lee RW, Malchev IT, Rajcan I and Kott LS (2014) Identification of putative quantitative trait loci associated with a flavonoid related to resistance to cabbage seedpod weevil (*Ceutorhynchus obstrictus*) in canola derived from an intergeneric cross, *Sinapis alba* x *Brassica napus*. Theoretical and Applied Genetics 127: 419-428. doi:10.1007/s00122-013-2228-0.

Lehmhus J and Heimbach U (2012) Wheat blossom midge monitoring in Germany 2007-2010. Mitteilungen der Deutschen Gesellschaft fur Allegemeine und Angewandte Entomologie, BD18 18: 527-531.

Lei L, Stewart CN, Tang ZX and Wei W (2011) Dynamic expression of green fluorescent protein and *Bacillus thuringiensis* Cry1Ac endotaxin in interspecific hybrids and successive backcross generations (BC1 and BC2) between transgenic *Brassica napus* crop and wild *Brassica juncea*. Annals of Applied Biology 159: 212-219. doi:10.1111/j.1744-7348.2011.00486.x.

Leimu R and Koricheva J (2006) A meta-analysis of tradeoffs between plant tolerance and resistance to herbivores: combining the evidence from ecological and agricultural studies. *Oikos* 112(1): 1-9.

Lerin J (1991) Influence of host plant phenology on the reproduction of the rape weevil *Ceutorhynchus assimilis* Payk. Journal of Applied Entomology 111: 303-310.

Levie A, Legrand MA, Dogot P, Pels C, Baret P and Hance T (2005) Mass releases of *Aphidius rhopalosiphi* (Hymenoptera: Aphidiinae) and strip management to control wheat aphids. Agriculture Ecosystems and Environment 105: 17-21. doi:10.1016/j.agee.2004.06.004

Li D, Ma C, Liu S, Wu YQ and He YZ (2012) Trapping effects of sticky cards in different colors on adults of red wheat blossom midge *Sitodiplosis mosellana* (Géhin). Acta Phytophylacica Sinica 39: 390-394.

Li LH, Zheng DS, Yang XM, Li XQ, Liu SC and Song CH (1998) Diversity evaluation of wheat germplasm resources in China. Genetic Resources and Crop Evolution 45: 167–72.

Lindblad M (1997) Dynamics and forecasting of frit fly populations. Vaxtskyddsnotiser 61: 81-85.

Lindblad M (1999) Density and mortality of overwintering *Oscinella frit* and other oscinellids in Swedish grassland. International Journal of Pest Management 45: 23-28.

Lindblad M (2001) Development and evaluation of a logistic risk model: predicting frit fly infestation in oats. Ecological Applications 11: 1563-1572.

Lindblad M and Sigvald R (1996) A degree-day model for regional prediction of first occurrence of frit flies in oats in Sweden. Crop Protection 16: 559-565.

Lindblad M and Sigvald R (1999) Frit fly infestation of oats in relation to growth stage and weather conditions at oviposition. Crop Protection 18: 517-521.

Lindblad M and Solbreck C (1998) Predicting *Oscinella frit* population densities from suction trap catches and weather data. Journal of Applied Ecology 35: 871-881.

Lister RM and Ranieri R (1995) Distribution and economic importance of barley yellow dwarf. In: D'Arcy CJ, Burnett PA (eds) *Barley yellow dwarf: 40 years of progress*. APS Press, St. Paul, pp 29–53.

Liu X, Yang X, Wang C, Wang Y, Zhang H and Ji W (2011) Molecular mapping of resistance gene to English grain aphid (*Sitobion avenae* F.) in *Triticum* durum wheat line C273. Theoretical and Applied Genetics: 1-7.

Lole M (2009) Pest, disease and weed incidence report - harvest year 2008. ADAS, 152 pp.

Lole M (2010a) Pest, disease and weed incidence report - harvest year 2009. ADAS, 166 pp.

Lole M (2010b) Sustainable long term management of wireworms on potato. Report number 2010/09. AHDB Potatoes, 55 pp.

Lole M (2011) Pest, disease and weed incidence report - harvest year 2010. ADAS, 163 pp.

Lole M, Pope T and Roberts H (2011) Baby-leaf Cruciferae: Leaf miner identification, biology and control. Final Report AHDB Horticulture Research Project FV 376. pp 33.

Loxdale HD and Lushai G (2007) Population genetic issues: the unfolding story using molecular markers. Chapter 2 In: *Aphids as Crop Pests* (eds) HR van Emden and R Harrington. CAB International. Pp 31-68.

Lys J-A and Nentwif W (2002) Augmentation of beneficial arthropods by strip management 4. Surface activity, movements and density of abundant carabid beetles in a cereal field. Oecologia 92: 373-382.

Maercks H (1941) Das schadauftreten der wiessenschnaken (Tipuliden) in abhangigkeit von Klima, Witterung und Boden. Arbeiten Physiologische und Angewandle Entomologie aus Berlin-Dahlem 8: 261-275.

Maling T, Diggle AJ, Thackray DJ, Siddique KHM and Jones RAC (2010) An epidemiological model for externally acquired vector-borne viruses applied to *Beet western yellows virus* in *Brassica napus* crops in a Mediterranean-type environment. Crop and Pasture Science 61(2) 132-144.

Marriott C and Evans KA (2003) Host plant choice and location by larvae of the wheat bulb fly (*Delia coarctata*). Entomologia Experimentalis et Applicata 106: 1-6.

Marshall J (2012) Water UK Briefing Paper 31 October 2012. http://www.getpelletwise.co.uk/uploads/literature/pdf/FINAL_WaterUK_Metaldehyde_Briefing_31_Oct_2012.pdf.

Martin N and MacDonald F (2009) Evaluating the impact of insecticides on *Scaptomyza flava* and its parasitoid, *Asobara persimilis*. New Zealand Journal of Crop and Horticultural Science 37: 243-252.

Mauricio R, Rausher MD and Burdick DS (1997) Variation in the defense strategies of plants: Are resistance and tolerance mutually exclusive? Ecology 78(5): 1301-1311.

McCracken DI, Foster GF and Kelly A (1995) Factors affecting the size of leatherjacket (Diptera: Tipulidae) populations in pasture in the west of Scotland. Applied Soil Ecology 2: 203-213.

McKenzie RIH, Lamb RJ, Aung T, Wise IL, Barker P and Olfert OO (2002) Inheritance of resistance to wheat midge, *Sitodiplosis mosellana*, in spring wheat. Plant Breeding 121:1-6.

McKinlay RG and Franklin MF (1980) A comparison of a corer and a shovel for sampling populations of wheat bulb fly (*Delia coarctata)* eggs. Annals of Applied Biology 95: 279–282.

McKinley RG, Spaull AM and Straub RW (1992) Pests of Solanaceous Crops. Chapter 8 In: *Vegetable Crop Pests*: 263-289. (Ed) RG McKinley, Macmillan Academic and Professional Ltd., London.

McKirdy SJ and Jones RAC (1996) Use of imidacloprid and newer generation synthetic pyrethoids to control the spread of barley yellow dwarf luteovirus in cereals. Plant Disease 80: 895-901.

Meats A (1970) Susceptibility of the leatherjackets *Tipula oleracea* and *Tipula paludosa* to soil flooding. Annals of Applied Biology 65: 25-38.

Melander M, Ahman I, Kamnert I and Stromdahl AC (2003) Pea lectin expressed transgenically in oilseed rape reduces growth rate of pollen beetle larvae. Transgenic Research 12: 555-567.

Meredith RH, Heatherington PJ, Morris DB (2002) Clothianidin- a new chloronicotinyl seed treatment for use on sugar beet and cereals: field trial expereinces from Northern Europe. Proceedings of British Crop Protection Conference – Pest and Diseases 2002, Brighton. 691-699.

Meissle M, Knecht S Waldburger M and Romeis J (2012) Sensitivity of the cereal leaf beetle *Oulema melanopus* (Coleoptera: Chrysomelidae) to Bt maize-expressed Cry 3Bb1 and Cry 1Ab. Arthropod Plant Interactions 6: 203-211.

Micu LM, Petanec D, Cotuna O, Dicu M and Fazakas P (2013) Studies on the behaviour of wheat varieties to pests attack *Oulema melanopa* L. Research Journal of Agricultural Science 45: 188-192.

Migui SM and Lamb RJ (2003) Patterns of resistance to three cereal aphids among wheats in the genus *Triticum* (Poaceae). *Bulletin of Entomological Research* 93(4): 323-333.

Migui SM and Lamb RJ (2004) Seedling and adult plant resistance to *Sitobion avenae* (Hemiptera: Aphididae) in *Triticum monococcum* (Poaceae), an ancestor of wheat. Bulletin of Entomological Research 94(1): 35-46.

Miles EJ, Bluett DJ and Mann DH (2001) The influence of seed rate on the efficacy of imidacloprid seed treatment against BYDV in winter cereals. In: *Seed Treatment: Challenges and Opportunities. Proceedings of the 2001 British Crop Council Protection Symposium No. 76.* British Crop Protection Council, Farnham, pp. 47–52.

Miller WA, Liu A and Beckett R (2002) Barley yellow dwarf virus : *Luteoviridae* or *Tombusviridae?* Molecular Plant Pathology 3(4): 177-183.

Milne A, Laughlin R and Coggins RE (1965) The 1955 and 1959 population crashes in the leatherjacket *Tipula paludosa* Meigen in Northumberland. Journal of Animal Ecology 34: 529-544.

Moens R and Glen DM (2002) Agriolimacidae, Arionidae and Milacidae as pests in west European oilseed rape. In: Barker, G.M. (Ed.), *Molluscs as Crop Pests.* CABI Publishing, Wallingford, pp. 425–439.

Mölck G (2006) Erfahrung mit Prognose und Bekämpfung des Schadauftretens von Sattelmücken und Weizelgallmücken (Diptera: Cecidomyiidae) in Schleswig-Holstein. Deutsche Pflanzenschutz 55: 227.

Moores GD, Wegorek P, Zamojska J, Field L and Philippou D (2012) The effect of piperonyl butoxide/tau-fluvalinate mixture on pollen beetle (*Meligethes aeneus*) and honey bees (*Apis mellifera*). Pest Management Science 68: 795-800. DOI 10.1002/ps.2328

Moser D, Drapela T, Zaller JG and Frank T (2009) Interacting effects of wind direction and resource distribution on insect pest densities. Basic and Applied Ecology 10: 208-215. doi:http://dx.doi.org/10.1016/j.baae.2008.03.008.

Mueller C (2009) Interactions between glucosinolate- and myrosinase-containing plants and the sawfly *Athalia rosae*. Phytochemistry Reviews 8: 121-134.

Müller A, Heimbach U and Thieme T (2006) Pyrethroid sensitivity monitoring in Germany of oilseed rape pest insects other than pollen beetle. Bulletin OEPP/EPPO Bulletin 38: 85-90.

Murchie AK (1996) Parasitoids of Cabbage Seed Weevil and Brassica Pod Midge in Oilseed Rape, Vol. PhD: Keele University.

Murchie AK, Williams IH and Alford DV (1997) Effects of commercial insecticide treatments to winter oilseed rape on parasitism of *Ceutorhynchus assimilis* Paykull (Coleoptera: Curculionidae) by *Trichomalus perfectus* (Walker) (Hymenoptera: Pteromalidae). Crop Protection 16: 199-202.

Natural Capital Project (2014) Integrated valuation of environmental services and tradeoffs. http://www.naturalcapitalproject.org/InVEST.html. Accessed March 2016.

Nauen R (2011) Brief crop protection update and WG intro. 46th Meeting of IRAC International, Brussels, Belgium, Wednesday March 30th, 2011. http://www.irac-online.org/content/uploads/S3CropIntro_2011.pdf. Accessed February 2014.

Nauen R, Zimmer CT, Andrews M, Slater R, Bass C, Ekbom B, Gustaffson G, Hansen LM, Kristensen M, Zebotz, CPW and Williamson MS (2012) Target-site resistance to pyrethroids in European populations of pollen beetle, *Meligethes aeneus* F. Pesticide Biochemistry and Physiology 103: 173-180.

Nerad D, Vašák J, Zukalová H, Kuchtová P and Baranyk P (2004) Verification of protective sowing ability to concentrate insect pests and their parasitoids around oilseed rape field. IOBC/WPRS Bulletin 27(10): 253-262.

Neumann N, Schütz S, Eisenwiener U and Ulber B (2013) Influence of insecticide application on host finding of the cabbage stem weevil parasitoid *Tersilochus obscurator* (Hym.; Ichneumonidae) IOBC/WPRS Bulletin 92: 59-61.

Newman JA (2005) Climate change and the fate of cereal aphids in southern Britain. Global Change Biology: 940-944.

Nicholls CJ (2013) Implications of the restriction on the neonicotinoids: imidacloprid, clothianidin and thiamethoxam on crop protection in oilseeds and cereals in the UK. Research Review 77. AHDB Cereals & Oilseeds, 19 pp. http://archive.hgca.com/document.aspx?fn=load&media_id=8858&publicationId=9309. Accessed February 2014.

Nicholls CJ (2015) Assessing the impact of the restrictions on the use of neonicotinoid seed treatments. AHDB Project Report 541. pp 8.

Nicholls CJ (2016) A review of AHDB impact assessments following the neonicotioid seed treatment restrictions in winter oilseed rape. AHDB Research Review No. 84, 27pp.

Nicholls CJ and Cook SM (2012) An investigation into the development of monitoring and risk assessment systems for pollen beetle in winter oilseed rape. Aspects of Applied Biology 117: Crop Protection in Southern Britain 2012, 191-196.

Niehoff B and Stäblein (1998) Vergleichende Untersuchungen zum Schadpotential der Getreideblattlausarten, *Metopolophium dirhodum* (Wlk).) und *Sitobion avenae* (F) in Winterweizen. Journal of Applied Entomology 122: 223-229.

Nielsen O and Philipsen H (2005) Susceptibility of *Meligethes* spp. and *Dasyneura brassicae* to entomopathogenic nematodes during pupation in soil. BioControl 50: 623-634. doi:10.1007/s10526-004-8298-9.

Nijveldt WC and Hulshoff AJA (1968) Waarnemingen inzake de tarwestengelgalmug *Haplodiplosis equestris* Wagner in Nederland. Pflantenziektenkundige Dienst, Wageningen, Meded 144: 1-77.

Nilsson C (1988a) The pollen beetle (*Meligethes aeneus* F.) in winter and spring rape at Alnarp 1976–1978. II. Oviposition. Växtskyddsnotiser 52(6):139–144

Nilsson C (1988b) Pollen beetles (*Meligethes aeneus* F.) and flowering in rape. Swedish Journal of Agricultural Research 1: 113-118.

Nilsson C (1990) Yield losses in winter rape caused by cabbage stem flea beetle larvae (*Psylliodes chrysocephala*). IOBC /WPRS Bulletin 13(4): 53-55.

Nilsson C (2010) Impact of soil tillage on parasitoids of oilseed rape pests. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 305-311.

Nilsson C (2003) Parasitoids of the pollen beetles. In: Alford DV (ed) *Biocontrol of oilseed rape pests.* Blackwell, Oxford, UK.

Nilsson C, Vimarlund L and Gustafsson G (2004) Long term survival of Brassica Pod Midge (*Dasineura brassicae)* populations. IOBC/WPRS Bulletin 27: 297-302.

Nolte HW (1956) Flug und Eiablage von *Ceuthorrhynchus quadridens* Panz. in Abhangigkeit von der Witterung (Col., Curculionidae). Bericht uber die Hundertjahrfeier Deutschen Entomologischen Gesellschaft, Akademia Verlag, Berlin: 135-140.

Nordlander G (1978a) Parasitoids of the frit fly, *Oscinella frit* (L.) on oats. Norwegian Journal of Entomology 25: 89-90.

Nordlander G (1978b) Population ecology of the frit fly *Oscinella frit* L. Vaxtskyddsrapporter Jordbruk 1978: 41-51.

Oakley JN and Walters KFA (1994) A field evaluation of different criteria for determining the need to treat winter wheat against the grain aphid *Sitobion avenae* and the rose-grain aphid *Metopolophium dirhodum*. Annals of Applied Biology 124: 195-211.

Oakley JN (1994) Orange wheat blossom midge: a literature review and survey of the 1993 outbreak. AHDB Cereals & Oilseeds Research Review No. 28.

Oakley JN (2003) Pest management in cereals and oilseed rape – guide. AHDB Cereals & Oilseeds. London

Oakley JN (2008) Control needs for changing pest distributions. AHDB Cereals & Oilseeds Conference: Arable cropping in a changing climate. 24-25 Jan. 2008.

Oakley JN and Smart LE (2002) The use of baited and unbaited traps to monitor the orange wheat blossom midge *Sitodiplosis modellana* and its parasitoid *Macroglenes penetrans*. The British Crop Protection Conference: Pests and Diseases, Volumes 1 and 2. Brighton, 2002. pp 665-670.

Oakley JN, Cumbleton PC, Corbett SJ, Saunderat P, Green DI, Young JEB and Rodgers R (1998) Prediction of orange wheat blossom midge activity and risk of damage. Crop Protection 17: 145-149.

Oakley JN, Talbot G, Dyer C, Self MM, Freer JBS, Angus WJ, Barrett JM, Feuerhelm G, Snape J, Sayers L, Bruce TJA, Smart LE and Wadhams LJ (2005) Integrated control of wheat blossom midge: variety choice, use of pheromone traps and treatment thresholds. AHDB Cereals & Oilseeds Project Report No. 363.

Oberholzer F and Frank T (2003) Predation by the carabid beetle *Pterostichus melanarius* and *Poecilus cupreus* on slugs and slug eggs. Biocontrol Science and Technology 13(1): 99-110.

Oestergaard J, Belau C, Strauch O, Ester A, van Rozen K and Ehlers R-U (2006) Biological control of *Tipula paludosa* (Diptera: Nematocera) using entomopathogenic nematodes (*Steinernema* spp.) and *Bacillus thuringiensis* subsp. *israelensis*. Biological Control 39: 525-531.

Ohkawara Y, Akayama A, Matsuda K and Andersch W (2002) Clothianidin: a novel broad-spectrum neonicotinoid insecticide. Proceedings of British Crop Protection Conference – Pests and Diseases 2002, 51-58.

Olfert OO, Mukerji MK and Doane DF (1985) Relationships between infestation levels and yield loss caused by wheat midge *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae) in spring wheat in Saskatchewan. The Canadian Entomologist 117: 593-598.

Olfert O, Doane JF and Braun MP (2003) Establishment of *Platygaster tuberosula*, an introduced parasitoid of the wheat midge, *Sitodiplosis mosellana*. The Canadian Entomologist 135: 303-308.

Olfert O and Weiss RM (2006) Impact of climate change on potential distributions and relative abundances of *Oulema melanopus*, *Meligethes viridescens* and *Ceutorhynchus obstrictus* in Canada. Agriculture, Ecosystems & Environment 113: 295-301. doi:http://dx.doi.org/10.1016/j.agee.2005.10.017.

Olfert O, Elliott RH and Hartley S (2009) Non-native insects in agriculture: strategies to manage the economic and environmental impact of wheat midge, *Sitodiplosis mosellana*, in Saskatchewan. Biological Invasions 11: 127-133.

Osborne P (1964) Morphology of the immature stages of *Meligethes aeneus* (F.) and *M. viridescens* (F.) (Coleoptera, Nitidulidae). Bulletin of Entomological Research 55: 747-759.

Oxley S and Evans A (2009) Winter oilseed rape pests and diseases. Technical Note 20. SAC, 8pp.

Papp M and Mesterházy Á (1993) Resistance to bird cherry oat-aphid *Rhopalosiphum padi* (L.) in winter wheat accessions. Euphytica 67: 49–57.

Parker WE (1994) Evaluation of the use of food baits for detecting wireworms (*Agriotes* spp., Coleoptera: Elateridae) in fields intended for arable crop production. Crop Protection 13: 271-276. doi:http://dx.doi.org/10.1016/0261-2194(94)90014-0.

Parker WE (1996) The development of baiting techniques to detect wireworms (*Agriotes* spp., Coleoptera: Elateridae) in the field, and the relationship between bait-trap catches and wireworm damage to potato. Crop Protection 15: 521-527. doi:http://dx.doi.org/10.1016/0261-2194(96)00020-8.

Parker WE and Howard JJ (2001) The biology and management of wireworms (*Agriotes* spp.) on potato with particular reference to the U.K. Agricultural and Forest Entomology 3: 85-98. doi:10.1046/j.1461-9563.2001.00094.x.

Parker WE and Seeney FM (1997) An investigation into the use of multiple site characteristics to predict the presence and infestation level of wireworms (*Agriotes* spp., Coleoptera: Elateridae) in individual grass fields. Annals of Applied Biology 130: 409-425. doi:10.1111/j.1744-7348.1997.tb07671.x.

Parsche S, Fründ J and Tscharntke T (2011) Experimental environmental change and mutualistic vs. antagonistic plant flower–visitor interactions. Perspectives in Plant Ecology, Evolution and Systematics 13: 27-35. doi:http://dx.doi.org/10.1016/j.ppees.2010.12.001.

Paulsen HM, Schochow M, Ulber B and Kühne S (2006) Mixed cropping systems for biological control of weeds and pests in organic oilseed crops. COR 2006. Aspects of Applied Biology 79: 215-220.

Pavela R, Kazda J and Herda G (2009) Effectiveness of neem (*Azadirachta indica*) insecticides against brassica pod midge (*Dasineura brassicae* Winn.). Journal of Pest Science 82: 235-240. doi:10.1007/s10340-009-0244-2.

Paveley N (2013) Combating insecticide resistance in major UK pests. Web summary, AHDB Cereals & Oilseeds project RD-2012-3780. AHDB Cereals & Oilseeds, AHDB Potatoes, BBRO, PGRO, Rothamsted Research, Chemical Regulations Directorate. http://www.hgca.com/media/154662/3780_web_summary.pdf Accessed April 2014.

Peck DC, Olmstead D and Morales A (2008) Application timing and efficacy of alternatives for the insecticidal control of *Tipula paludosa* Meigen (Diptera: Tipulidae), a new invasive pest of turf in the U.S. Pest Management Science 64: 989-1000.

Peck DC, Olmstead DL and Petersen MJ (2010) Pest status of invasive crane flies in New York turfgrass and the repercussions for regional plant protection. Journal of Integrated Pest Management 1: 1-8.

Pell JK (2007) Ecological approaches to pest management using entomopathogenic fungi; concepts, theory, practice and opportunities. In: *Use of entomopathogenic fungi in pest management.* Eds. S. Ekesi and N. Maniania. Research Signpost 145-177, 333pp.

Pell JK, Hannam J and Steinkraus DC (2010) Conservation biological control using fungal entomopathogens. Biocontrol Special Issue 55: 187-198.

Perry KL, Kolb FL, Sammons B, Lawson C, Cisar G and Ohm H (2000) Yield effects of barley yellow dwarf virus in soft red wheat. Phytopathology 90(9): 1043-1048.

Pesho GR, Brauen SE and Goss RL (1981) European crane fly: Larval infestation in grass cultivars. Journal of Economic Entomology 74: 230-233.

Peters A and Ehlers R-U (1994) Susceptibility of leatherjackets (*Tipula paludosa* and *Tipula oleracea*: Tipulidae: Nematocera) to the entomopathogenic nematode *Steinernema feltiae*. Journal of Invertebrate Pathology 63: 163-171.

Petersen MJ and Peck DK (2013) Host plant resistance of cool-season (C3) turfgrasses to above- and belowground feeding by *Tipula paludosa* (Diptera: Tipulidae). Journal of Economic Entomology 106: 1463-1472.

Petersen MJ, Olmstead DL and Peck DC (2011) Best management practices for invasive crane flies in Northeastern Unites States sod production. Journal of Integrated Pest Management 2: C1-C6.

Petersen MJ, Seto M and Peck D (2013) Linking the spatio-temporal distribution of an edaphic crane fly to its heterogeneous soil environment. Ecological Entomology 38: 585-595.

Pettersson J, Pickett J, Pye B, Quiroz A, Smart L, Wadhams L and Woodcock C (1994). Winter host component reduces colonization by bird-cherry-oat aphid, *Rhopalosiphum padi* (L.) (Homoptera, Aphididae), and other aphids in cereal fields. Journal of Chemical Ecology 20(10): 2565-2574.

Philipou D, Field LM, Wegorek P, Zamojska J, Andrews MC, Slater R, Moores GD (2010) Characterising metabolic resistance in pyrethroid-insensitive pollen beetle (*Meligethes aeneus* F.) from Poland and Switzerland. Pest Management Science 67: 239-243. DOI 10.002/ps.2061.

Philips CR, Herbert DA, Kuhar TP, Reisig DD, Thomason WE and Malone S (2011) Fifty years of cereal leaf beetle in the US: An update on its biology, management and current research. Journal of Integrated Pest Management 2: 1-5.

Philips CR, Herbert DA, Kuhar TP, Reisig DD and Roberts EA (2012) Using degree-days to predict cereal leaf beetle (Coleoptera: Chrysomelidae) egg and larval peaks. Environmental Entomology 41: 761-767.

Pickett JA and Glinwood RT (2007). Chemical Ecology. In: Van Emden, H.F. and Harrington R. (Eds .) *Aphids as Crop Pests.* Wallingford, UK: Cabi Publishing. pp. 235-260.

Pickett JA, Arodottir GI, Birkett MA, Bruce TJA, Hooper AM, Midega CAO, Jones HD, Matthes MC, Napier JA, Pittchar JO, Smart LE, Woodcock CM and Khan ZR (2014) Delivering sustainable crop protection systems via the seed: exploiting natural constitutive and inducible defence pathways. Philosophical Transactions of the Royal Society B 369(1639): 20120281. doi: 10.1098/rstb.2012.0281

Piesik AW and Piesik D (1998) The spring cereals food preferences of *Oulema* spp. in pure and mixed crops. Electronic Journal of the Polish Agricultural Universities 1: 04. http://www.ejpau.media.pl/volume1/issue1/agronomy/art-04.html

Piesik D, Panka D, Delaney KJ, Skoczek A, Lamparski R and Weaver DK (2011) Cereal crop volatile organic compound induction after mechanical injury, beetle herbivory (*Oulema* spp.) or fungal infection (*Fusarium* spp.). Journal of Plant Physiology 168: 878-886.

Piesik D, Panka D, Jeske M, Wenda-Piesik A, Delaney KJ and Weaver DK (2013) Volatile induction of infected and neighbouring uninfected plants potentially influence attraction/ repellence of a cereal herbivore. Journal of Applied Entomology 137: 296-309.

Pitkin B, Ellis W, Plant C and Edmunds R (2011) The leaf and stem mines of British flies and other insects. http://ukflymines.co.uk/.

Pivnick KA and Labbé E (1993) Daily patterns of activity of the orange wheat blossom midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae). The Canadian Entomologist 125: 725-736.

Plantwise Technical Factsheet (2014) Frit fly (*Oscinella frit*) http://www.plantwise.org/KnowledgeBank/Datasheet.aspx?dsid=37996

Plecas M, Gagic V, Jancovik M, Petrovic-Obradovic O, Kavallieratos NG, Tomanovic Z, Thies C, Tscharntke T and Cetkovic A (2014) Landscape composition and configuration influence cereal aphid-parasitoid-hyperparasitoid interactions and biological control differently across years. Agriculture, Ecosystems & Environment 183: 1-10.

Plumb R (1976) Barley yellow dwarf virus in aphids caught in suction traps 1969-1973. Annals of Applied Biology 83: 53-59.

Plumb R (1983) Barley yellow dwarf virus: A global problem. PP 185-189 In *Plant Virus Epidemiology.* Eds. RT Plumb and JM Thresh . Blackwell Scientific Publications, Oxford.

Plumb R (1990) The epidemiology of barley yellow virus in Europe. In: *World Perspectives on Barley Yellow Dwarf.* Ed. PA Burnett International Maize and Wheat improvement Centre, Mexico. Pp 185-198.

Plumb RT (1995) Epidemiology of Barley Yellow Dwarf in Europe. In: DÕArcy CJ and Burnett PA (eds.), *Barley Yellow Dwarf, 40 years of progress*, St Paul, 107–127.

Poeling H-M, Freier B and Klüken AM (2007) IPM Studies: Grain. Chapter 25 In: *Aphids as Crop Pests* Ed HF van Emden and R Harrington Cabi International, Wallingford, Oxon.pp 597-612.

Popov C, Petcu L and Barbulescu A (1998) Researches on biology, ecology and control of saddle gall midge (*Haplodiplosis marginata* von Roser) in Romania. Romanian Agricultural Research 9-10: 67-77.

Porter DR, Harris MO, Hesler LS and Puterka GJ (2009) Insects which challenge gobal wheat production. Chapter 9 In: *Wheat Science and Trade* (Ed. BF Carver), Wiley Blackwell, Oxfod, UK. Doi: 10.1002/9780813818832.ch9.

AHDB Potatoes (2011) Wireworm factsheet. AHDB Potatoes' advice, AHDB Potatoes, 11 pp. http://www.potato.org.uk/sites/default/files/%5Bcurrent-page%3Aarg%3A%3F%5D/Growers%20Advice%20-%20Wireworm%20Factsheet.pdf

Powell W and Pell JK (2007) Biological Control. In: *Aphids as Crop Pests.* Eds H. van Emden and R. Harrington. CABI International 469-513 717pp.

Powell W, A'Hara S, Harling R, Holland JM, Northing P, Thomas CFG and Walters KFA (2004) Managing biodiversity in field margins to enhance integrated pest control in arable crops (3-D faming Project). AHDB Cereals & Oilseeds Final Report Project No 356 Part 1, 80pp.

Prior RNB (1976) Keys to the British species of *Metopolophium* (aphididae) with one new species. Systematic Entomology 1(4): 271-279.

Purves G and Bannon JW (1992) Non-target effects of repeated methiocarb slug pellet application on carabid beetle (Coleoptera, Carbidae) activity in winter-sown cereals. Annals of Applied Biology 121: 215–23.

Purvis G (1986) The influence of cabbage stem flea beetle (*Psylliodes chryosocephala*) (L.) on yields of oilseed rape. Proceedings of 1986 British Crop Protection Conference- Pests and Diseases, pp. 753–759.

Pywell R, Warman E, Carvell C, Sparks T, Dicks LV, Bennett D, Wright A, Critchley C and Sherwood A (2005) Providing forage resources for bumble bees in intensively farmed landscapes. Biological Conservation 121: 479-494.

Qian YT, Zhou GH and Zhou XM (1993) Screening for the sources of resistance to BYDV. Acta Phytophylacica Sinica 20: 71–5.

Quisenbury SS and Ni X (2007) Feeding Injury. Chapter 13 In: *Aphids as Crop Pests.* (eds) HR van Emden and R Harrington. CAB International. Pp 331-352.

Rae RG, Verdun C, Grewal PS, Robertson JF and Wilson MJ, (2007) Biological control of terrestrial molluscs using *Phasmarhabditis hermaphrodita*- progress and prospects. Pest Management Science 63: 1153-1164.

Rae RG, Robertson JF and Wilson MJ (2009) Chemo-attraction and host preference of the gastropod parasitic nematode *Phasmarhabditis hermaphrodita*. Journal of Parasitology 95: 517-526.

Rand TA, van Veen FJ and Tscharntke T (2012) landscape complexity differentially benefits generalized fourth, over specialized third, trophic level natural enemies. Ecography 35: 97-104.

Randhawa HS, Asif M, Pozniak C, Clarke JM, Graf RJ, Fox SL, Humphreys DG, Knox RE, DePauw RM, Singh AK, Cuthbert RD, Hucl P and Spaner D (2013) Application of molecular markers to wheat breeding in Canada. Plant Breeding 132: 458-471.

Rao S, Cossé AA, Zilkowski BW and Bartelt RJ (2003) Aggregation pheromone of the cereal leaf beetle: Field evaluation and emission from males in the laboratory. Journal of Chemical Ecology 29: 2165-2175.

Rattan RS (2010) Mechanism of action of insecticidal secondary metabolites of plant origin. Crop Protection 29: 913-920.

Raw F (1967) Some aspects of the wheat bulb fly problem. The fifth *Barnes Memorial Lecture.* Annals of Applied Biology 59: 155-173. DOI: 10.1111/j.1744-7348.1967.tb04426.x

Reay-Jones FPF (2012) Spatial analysis of the cereal leaf beetle (Coleoptera: Chrysomelidae) in wheat. Environmental Entomology 41: 1516-1526.

Reisig DD, Bacheler JS, Herbert DA, Kuhar T, Malone S, Philips C and Weisz R (2012) Efficacy and value of prophylactic vs integrated pest management approaches for management of cereal leaf beetle (Coleoptera: Chrysomelidae) in wheat and ramifications for adoption by growers. Journal of Economic Entomology 105: 1612-1619.

Rijsten EG (1967) Occurrence and control of *Haplodiplosis equestris* in Holland. Pflanzenschutz Nachrichten Bayer 1967(4): 674-680.

Robert C (2013) Field monitoring of cabbage stem flea beetle and rape winter stem weevil autumn flights. IOBC-Working Group Integrated Control in Oilseed Crops, Biannual Meeting 8-10 Ocotber 2013, Belvaux, Luxembourg. Abstract E05.

Roberts DA, Harris D, Corr I and Corrigan W (2014) Saddle gall midge *Haplodiplosis marginata*) in winter wheat. Proceedings Crop Protection in Northern Britain 2014, 125-130.

Roberts JJ and Foster JE (1983) Effect of leaf pubescence in wheat on the bird cherry-oat aphid (Homoptera: Aphididae). Journal of Economic Entomology 76(6): 1320-1322.

Rogers CD and Evans KA (2013) Wheat bulb fly (*Delia coarctata*, Fallén, Diptera: Anthomyiidae) larval response to hydroxamic acid constituents of host-plant root exudates. Bulletin of Entomological Research 103: 261–268.

Rogers CD and Evans KA (2014) Wheat bulb fly, *Delia coarctata*, Fallén (Diptera: Anthomyiidae), larval response to phenolic components of host-plant root exudates. Entomologia Experimentalis et Applicata 150: 166–173.

Rogers CD, Evans KA, Parker J and Pappa VA (2013) Behavioural response of wheat bulb fly (*Delia coarctata,* Diptera: Anthomyiidae) larvae to the primary plant metabolite carbon dioxide. Bulletin of Entomological Research 103: 675–682.

Rogers CD, Guimarães RML, Evans KA and Rogers SA (2014) Spatial and temporal analysis of wheat bulb fly (*Delia coarctata*, Fallén) oviposition: consequences for pest population monitoring. Journal of Pest Science 88(1): DOI 10.1007/s10340-014-0589-z

Rose PW and Oades L (2001) Effects of imidacloprid cereal seed treatments against wireworms and slugs. Proceedings No.76. British Crop Protection Conference: Seed Treatment – Challenges & Opportunities, pp191-196.

Ross DW, Brown J, McCaffrey JP, Harmon BL and Davis JB (2008) Cabbage seedpod weevil resistance in canola (*Brassica napus* L.) yellow mustard (*Sinapis alba* L.) and canola × yellow mustard hybrids. Canadian Journal of Plant Science 88: 239-245. doi:10.4141/P04-194.

Rothamsted Research (2014a) Light leaf spot forecast. http://www.rothamsted.ac.uk/light-leaf-spot-forecast. Accessed March 2016.

Rothamsted Research (2014b) Phoma leaf spot forecast. http://www.rothamsted.ac.uk/phoma-leaf-spot-forecast. Accessed March 2016.

Rothamsted Research (2015) Rothamsted Research scientists detect significant levels of pyrethroid resistance in Cabbage Stem Flea Beetles in South East England. http://www.rothamsted.ac.uk/news-views/update-pyrethroid-resistance-cabbage-stem-flea-beetles. Accessed March 2016.

Rouag N, Mekhlouf A and Makhlouf M (2012) Evaluation of infestation by cereal leaf beetles (*Oulema* spp.) on six varieties of durum wheat (*Triticum dirum*, Desf.) seedlings in arid conditions of Selif, Algeria. Agriculture and Biology Journal of North America 3: 525-528.

Rowley C, Cherrill A, Leather S, Nicholls C, Ellis S and Pope T (2016) A review of the biology, ecology and control of saddle gall midge, *Haplodiplosis marginata* (Diptera: Cecidomyiidae). Annals of Applied Biology (In Press).

M, Andersson GKS, Bommarco R, Fries I, Hederström V, Herbertsson L, Jonsson O, Klatt BK, Pedersen TR, Yourstone J and Smith HG (2015) Seed coating with a neonicotinoids insecticide negatively affects wild bees. Nature 521: 77-80.

Runham NW and Hunter PJ (1970) *Terrestrial slugs.* London Huthinson University Library. 184 pp.

Rusch A, Bommarco R, Jonsson M, Smith HG and Ekbom B (2013) Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale. Journal of Applied Ecology 50: 345 – 354.

Rusch A, Valantin-Morison M, Sarthou J-P and Roger-Estrade J (2010) Biological control of insect pests in agroecosystems: effects of crop management, farming systems, and seminatural habitats at the landscape scale: a review. Advances in Agronomy 109: 219-259.

Rusch A, Valantin-Morison M, Sarthou J-P and Roger-Estrade J (2011) Multi-scale effects of landscape complexity and crop management on pollen beetle parasitism rate. Landscape Ecology 26: 473-486. DOI 10.1007/s10980-011-9573-7

Rusch A, Valantin-Morison M, Roger-Estrade J and Sarthou J-P (2012) Using landscape indicators to predict high pest infestations and succesful natural control at the regional scale. Landscape and Urban Planning105(1-2): 62-73. doi:10.1016/j.landurbplan.2011.11.021

Ruther J and Thiemann K (1997) Response of the pollen beetle *Meligethes aeneus* to volatiles emitted by intact plants and conspecifics. Entomologia Experime ntalis et Applicata 84: 183-188.

Ryan MF (1973) The natural mortality of wheat-bulb fly eggs in bare fallow soils. Journal of Applied Ecology 10: 869–874.

Sánchez Chopa Cand Deschamps LR (2012) Composition and biological activity of essential oils against *Metopolophoium dirhodum* (Hemiptera: Aphididae) cereal crop pests. Pest Management Science 68: 1492-1500.

Saringer G (1984) Summer diapause of cabbage stem flea beetle, *Psylliodes chrysocephala* L. (Col. Chrysomelidae). Journal of Applied Entomology 98: 50-54.

Sáringer G (1989) Über eine insektizidfreie Methode zur Bekämpfung der Rübenblattwespe, *Athalia rosae* L. (Hym., Tenthredinidae). Anzeiger für Schädlingskunde, Pflanzenschutz, Umweltschutz 62: 31-33. doi:10.1007/BF01905963.

Schaefer-Koesterke HL and Ulber B (2013) Effects of various resyntheses, lines, and cultivars of oilseed rape on rape stem weevil (Ceutorhynchus napi Gyll.) infestation. IOBC-Working Group Integrated Control in Oilseed Crops, Biannual Meeting 8-10 Ocotber 2013, Belvaux, Luxembourg. Abstract E07.

Scheid BE, Thies C and Tscharntke T (2011) Enhancing rape pollen beetle parasitism within sown flower fields along a landscape complexity gradient. Agriculture and Forest Entomology 13: 173-179.

Schellhorn NA, Bianchi FJJA and Hsu CL (2014) Movement of entomophagous arthropods in agricultural landscapes: Links to pest suppression. Annual Review of Entomology 59: 559-581.

Schepers A (1989) Chemical control. Chapter 11 In: *World Crop Pests: Aphids, Their Biology*, *Natural Enemies and Control,* Vol 2C. (eds AK Minks & P Harrewijn) pp. 89-122. Elsevier, Amsterdam.

Scherney FV (1953) Zur Biology der an Raps vorkommenden Meligethesarten. Zeitschrift Pflanzenbau und Pflanzenchutz 4: 154-176.

Scholte E-J and Dicke M (2005) Effects of insect-resistant transgenic crops on non-target arthropods: first step in pre-market risk assessment studies. http://www.cogem.net/index.cfm/en/publications/publicatie/effects-of-insect-resistant-transgenic-crops-on-non-target-arthropods-first-step-in-pre-market-risk-assessment-studies. Accessed February 2014: Commissie Genetische Modificatie, p. 57.

Schüder I, Port G and Bennison J (2003) Barriers, repellents and antifeedants for slug and snail control. Crop Protection 22: 1033-1038.

Schulz R-R and Daebeler F (1984) Zum Schaden durch den Rapserdfloh (*Psylliodes chrysocephala* L.), insbesondere seiner Imagines. Nachrichtenblatt für den Pflanzenschutz in der DDR 38: 113-115.

Schütte F (1964) Zur Anfälligkeit einiger Getreide- und Gräserarten gengen *Haplodiplosis equestris* (Wagner). Anz. Scadlingskde 37: 129-132.

Schütte F (1983) Sattelmücke. Informationen zum intergrierten Pflanzenschutz. Nachrichtenblatt des Deutschen Pflanzenschutzdienstes 35: 109.

Scott GC and Greenway AR (1973) Effects of cereal extracts on attack on wheat by wheat bulb fly, *Leptohylemyia coarctata*. Entomologia Experimentalis et Applicata 16, 554–556.

Scott GC, Pickett JA, Smith MC, Woodcock CM, Harris PGW, Hammon RP and Koetecha HD (1984) Seed treatments for controlling slugs in winter wheat, In: Proceedings of the British Crop Protection Conference on Pests and Diseases. British Crop Protection Council, Farnham, UK, pp 133–8.

Seidenglanz M, Poslušná J and Hrudová E (2009) The importance of monitoring the *Ceutorhynchus pallidactylus* female flight activity for the timing of insecticidal treatment. Plant Protection Science 45: 103-112.

Seraj AA (1994) Biology and host plant relationships of *Scaptophaga flava* leaf miner. PhD Thesis, Massey University, New Zealand. pp 359

Shah PA and Pell JK (2003) Entomopathogenic fungi as biological control agents. Invited Mini-Review Applied Microbiology and Biotechnology 61: 413-423.

Shah SJA, Bashir M and Manzoor N (2012) A review of barley yellow dwarf virus. Chapter 29 in: M. Ashraf et al. (eds) *Crop Production for Agricutural Improvement*. DOI 10.1007/978-94-007-4116-4_29, © Springer Science+Business Media B.V. 2012

Shaw EJ, Fletcher RS, Dosdall LL and Kott LS (2009) Biochemical markers for cabbage seedpod weevil (*Ceutorhynchus obstrictus* (Marsham)) resistance in canola (*Brassica napus* L.). Euphytica 170: 297-308. doi:10.1007/s10681-009-9980-x.

Simard L, Bélair G, Gosselin ME and Dionne J (2006) Virulence of entomopathogenic nematodes (Rhabditida: Steinernematidae, Heterorhabditidae) against *Tipula paludosa* (Diptera: Tipulidae), a turfgrass pest on golf courses. Biocontrol Science and Technology 16: 789-801.

Simms LC, Mullins CE and Wilson MJ (2002) Seed dressings to control slug damage in oilseed rape. Pest Management Science 58: 687-94.

Simms LC, Glen D and Wilson M (2006) Mini-plot experiments using seed dressings to control slug damage to oilseed rape. Crop Protection 25: 890-892.

Singh RP, Burnett PA, Albarrán M and Rajaram S (1993) *Bdv1*: A gene for tolerance to Barley yellow dwarf virus in bread wheats. Crop Science 33: 231-234.

Sivinski J, Wahl D, Holler T, Al Dobai S and Sivinski R (2011) Conserving natural enemies with flowering plants: Estimating floral attractiveness to parasitic Hymenoptera and attraction's relationship to flower and plant morphology. Biological Control 58: 208-214.

Skuhravy V (1982) The saddle gall midge, *Haplodiplosis marginata* (von Roser) (Diptera, Cecidomyiidae), an important pest of wheat and barley in Czechoslovakia. Folia Fac. Scient. Nat. Univ. Purkynianae Brunensis, *23/Biol* 74(7): 133-135.

Skuhravy V, Skuhrava M and Brewer WJ (1983) Ecology of the saddle gall midge *Haplodiplosis marginata* (von Roser) (Diptera, Cecidomyiidae). Zietschrift für Angewandte Entomologie 96: 476-490.

Slater R, Ellis S, Genay JP, Heimbach U, Huart G, Sarazin M, Longhurst C, Müller A, Nauen R, Rison JL and Robin F (2011) Pyrethroid resistance monitoring in European populations of pollen beetle (*Meligethes* spp.): a coordinated approach through the Insecticide Resistance Action Committee (IRAC). Pest Management Science 67(6): 633-638. doi: 10.1002/ps.2101.

Smith CM, Havlickova H, Starkey S, Gill BS and Holubec V (2004b) Identification of *Aegilops* germplasm with multiple aphid resistance. Euphytica 135(3): 265-273.

Smith HG and Hinckes JA (1985) Studies on *Beet western yellows virus* in oilseed rape (*Brassica-napus* ssp. *oleifera*) and sugar beet (*Beta vulgaris*). Annals of Applied Biology 107: 473-484.

Smith MAH, Lamb RJ, Wise IL and Olfert OO (2004) An interspersed refuge for *Sitodiplosis mosellana* (Diptera: Cecidomyiidae) and a biocontrol agent *Macroglenes penetrans* (Hymenoptera: Pteromalidae) to manage crop resistance in wheat. Bulletin of Entomological Research 94: 179-188.

Smith MAH, Wise IL and Lamb RJ (2007) Survival of *Sitodiplosis mosellana* (Diptera: Cecidomyiidae) on wheat (Poaceae) with antibiosis resistance: implications for the evolution of virulence. The Canadian Entomologist 139: 133-140.

Snyder GB, Finke DL and Snyder WE (2008) Predator biodiversity strengthens aphid suppression across single and multiple-species prey communities. Biological Control 44: 52-60.

Sotherton NW (1995) Beetle banks - helping nature to control pests. Pesticide Outlook 6: 13-17.

Speiser B and Kistler C (2002) Field tests with a molluscicide containing iron phosphate. Crop Protection 21: 389-394.

Spink JH, Berry PM, Theobald C, Sparkes D, Wade AP and Roberts A (2004) Effects of location and management on the target drilling rate for winter wheat. AHDB Cereals & Oilseeds Project No. 361. AHDB Cereals & Oilseeds, London, 161 pp.

Spittler H (1969) Beiträge zur Morphologie und Ökologie des Sattelmückenparasitien *Platygaster equestris* nov. spec. (Hymenopt., Proctotrupoidea, Scelionidae) unter besonderer Berücksichtigung seines abundanzdynamischen Einflusses auf *Haplodiplosis euquestris* Wagner (Diptera, Cecidomyiidae). Zietschrift für Angewandte Entomologie 63: 353-381.

Stahnke GK, Antonelli AL, Miltner ED, Jones MJ, Corpus PR and Aviles MP (2005) Application timing for maximum efficiency of insecticides to control European and common crane fly larvae in the Pacific Northwest. International Turfgrass Society Research Journal 10: 779-783.

Staley JT, Hodgson CJ, Mortimer SR, Morecroft MD, Masters GJ, Brown VK and Taylor ME (2007) Effects of summer rainfall manipulations on the abundance and vertical distribution of herbivorous soil macro-invertebrates. European Journal of Soil Biology 43: 189-198. doi:10.1016/j.ejsobi.2007.02.010

Stevens M, McGrann G and Clark B (2008) Turnip yellows virus (syn. *Beet western yellows virus*): an emerging threat to European oilseed rape production? AHDB Cereals & Oilseeds Research Review 69, 36 pp.

Stevens M and Clark W (2009) The impact of *Turnip Yellows Virus* (TuYV) on winter oilseed rape-do we really appreciate the risk? Aspects of Applied Biology 91: 109-114.

Stewart RM and Kosicki KK (1987) DIY assessment of leatherjacket numbers in grassland. Proceedings of Crop Protection in Northern Britain 1987, pp 349-353.

Storkey J, Holland JM, Henderson IG, Lutman PJW, Orson J, Baverstock J and Pell JK (2014) Balancing food production and biodiversity in arable landscapes: Lessons from the farm4BIO Experiment. Outlooks on Pest Management 25(4): 252-256.

Stowe KA, Marquis RJ, Hochwender CG and Simms EL (2000) The evolutionary ecology of tolerance to consumer damage. Annual Review of Ecology and Systematics 31: 565-595.

Strauss SY and Agrawal AA (1999) The ecology and evolution of plant tolerance to herbivory. Trends in Ecology & Evolution 14(5): 179-185.

Sufyan M, Neuhoff D and Furlan L (2011) Assessment of the range of attraction of pheromone traps to *Agriotes lineatus* and *Agriotes obscurus*. Agricultural and Forest Entomology 13: 313-319. doi:10.1111/j.1461-9563.2011.00529.x.

Sufyan M, Neuhoff D and Furlan L (2013) Effect of male mass trapping of *Agriotes* species on wireworm abundance and potato tuber damage. Bulletin of Insectology 66: 135-142.

Sylvester-Bradley R, Berry P, Blake J, Kindred D, Spink J, Bingham I, McVittie J and Foulkes J (2008). *The wheat growth guide*. Spring 2008, second edition. AHDB Cereals & Oilseeds Booklet 30 pp.

Symondson WOC, Glen DM, Ives AR, Langdon CJ, and Wiltshire CW (2002a) Dynamics of the relationship between a generalist predator and slugs over five years. Ecology 83(1): 137-147.

Symondson WOC, Sunderland KD and Greenstone MH (2002b) Can generalist predators be effective biocontrol agents? Annual Review of Entomology 47: 561-594.

Symondson WOC, Cesarini S, Dodd PW, Harper GL, Bruford MW, Glen DM, Wiltshire CW and Harwood JD (2006) Biodiversity vs biocontrol: positive and negative effects of alternative prey on control of slugs by carabid beetles. Bulletin of Entomological Research 96(6): 637-645.

Syngenta (2016) AHDB Horticulture Pest Bulletin. https://www.syngenta.co.uk/ahdb-horticulture-pest-bulletin. Accessed April 2016.

Tait MF, Horak A and Dewar AM (2011) Control of pollen beetles, *Meligethes aeneus*, in oilseed rape using pymetrozine**.** Aspects of Applied Biology 106*,* Crop Protection in Southern Britain, pp. 187-194.

Tanaskovic S, Madic M, Durovic D, Knezevic D and Vukajlovic F (2012) Susceptibility of cereal leaf beetle (*Oulema melanopa* L.) in winter wheat to various foliar insecticides in western Serbia region. Romanian Agricultural Research 29: 361-366.

Tanguy S and Dedryver C-A (2008) Reduced BYDV-PAV transmission by the grain aphid in a *Triticum monococcum* line. European Journal of Plant Pathology 123: 281–289.

Taschereau E, Simard L, Brodeur J, Gelhaus J, Belair G and Dionne J (2009) Seasonal ecology of the European crane fly (*Tipula paludosa*) and species diversity of the family Tipulidae on golf courses in Quebec, Canada. International Turfgrass Society Research Journal 11: 681-693.

Tharp C, Blodgett SL and Johnson GD (2000) Efficacy of imidacloprid for control of cereal leaf beetle (Coleoptera: Chrysomelidae). Journal of Economic Entomology 93: 83-42.

Tansey JA, Dosdall LM, Keddie A, Fletcher RS and Kott LS (2010) Antixenosis and antibiosis resistance to *Ceutorhynchus obstrictus* in novel germplasm derived from *Sinapis alba* x *Brassica napus*. The Canadian Entomologist 142: 212-221. doi:doi:10.4039/n09-067.

Tatchell GM (1983) Compensation in spring-sown rape (*Brassica napus* L.) plants in response to injury to their flower buds and pods . Journal of Agricultural Science, Cambridge 101: 565-573.

Tatchell GM (1989) An estimate of the potential economic losses to some crops due to aphids in Britain. Crop Protection 8: 25–29.

Thieme T, Drbal U, Gloyna K and Hoffmann U (2008) Different methods of monitoring susceptibility of oilseed rape beetles to insecticides. EPPO Bulletin 38: 114–117.

Thieme T, Heimbach U and Müller A (2010) Chemical control of insect pests and insecticide resistance in oilseed rape: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 313-335.

Thomas JB, Fineberg N, Penner G, McCartney C, Aung T, Wise I and McCallum B (2005) Chromosome location and markers of Sm1: a gene of wheat that conditions antibiotic resistance in orange wheat blossom midge. Molecular Breeding 15: 183-192.

Thompson JM, Sibley JL, Wheeler GF, Keever GJ and Appel AG (2005) Effect of copper hydroxide on slug feeding. Journal of Environmental Horticology 23(4): 167-170.

Thomson LJ, Macfadyen S and Hoffmann AA (2010) Predicting the effects of climate change on natural enemies of agricultural pests. Biological Control 52: 296-306. doi:http://dx.doi.org/10.1016/j.biocontrol.2009.01.022.

Tiffin P (2000) Are tolerance, avoidance, and antibiosis evolutionarily and ecologically equivalent responses of plants to herbivores? American Naturalist 155(1): 128-138.

Toba HH, Lindegren JE, Turner JE and Vail PV (1983) Susceptibility of the Colorado Potato Beetle and the Sugarbeet Wireworm to *Steinernema feltiae* and *S. glaseri*. The Journal of Nematology 15: 597-601.

Toepfer S, Ellsbury MM, Eschen R and Kuhlmann U (2007) Spatial clustering of *Diabrotica virgifera virgifera* and *Agriotes ustulatus* in small-scale maize fields without topographic relief drift. Entomologia Experimentalis et Applicata 124: 61-75. doi:10.1111/j.1570-7458.2007.00549.x.

Toth P, Hrudova E, Zavadska E and Seidenglanz M (2013) Species of the genus *Meligethes* occurring in oil-seed crop fields in the Czech republic. Plant Protection Science 49(4): 177-186.

Traugott M, Schallhart N, Kaufmann R and Juen A (2008) The feeding ecology of elaterid larvae in central European arable land: New perspectives based on naturally occurring stable isotopes. Soil Biology and Biochemistry 40: 342-349. doi:10.1016/j.soilbio.2007.08.013

Traugott M, Schallhart N, Staudacher K & Wallinger C (2013) Understanding the ecology of wireworms and improving their control: a special issue. Journal of Pest Science 86: 1-2. doi:10.1007/s10340-013-0482-1.

Tremblay C, Cloutier C and Comeau A (1989) Resistance to the bird cherry-oat aphid, *Rhopalosiphum padi* L. (Homoptera: Aphididae), in perennial Gramineae and wheat x perennial Gramineae hybrids. Environmental Entomology 18(6): 921-923.

Tripathi AK, Upadhyay S, Bhuiyan M and Bhattacharya PR (2009) A review of essential oils as biopesticide in insect-pest management. Journal of Pharmacology and Phytotherapy 1: 52-63.

Tscharntke T, Bommarco R, Clough Y, Crist TO, Kleijn D, Rand TA, Tylianakis JM, van Nouhuys S and Vidal S (2007) Conservation biological control and enemy diversity at a landscape scale. Biological Control 43: 294-309.

Ulber B, Eickermann M and Mennerich D (2006a) The parasitism of ceutorhynchid stem weevils on *Brassica* host plants: Proceedings of the International Symposium on Integrated Pest

Management in Oilseed Rape, Göttingen, Germany, 3-5 April 2006 (ed. by DV Alford) BCPC, UK (CD).

Ulber B and Fischer K (2006) Effect of plant density and host plant architecture on the abundance and within-plant distribution of stem-mining pests and the level of parasitism: Proceedings of the International Symposium on Integrated Pest Management in Oilseed Rape, Göttingen, Germany, 3-5 April 2006 ((ed. by DV Alford) BCPC, UK (CD).

Ulber B, Fischer K, Klukowski Z, Veromann E, Luik A, Nilsson C, Ahman B, Williams IH, Ferguson AW, Piper R and Barari H (2006b) Identity of parasitoids and their potential for biocontrol of oilseed rape pests in Europe: Proceedings of the International Symposium on Integrated Pest Management in Oilseed Rape, Göttingen, Germany, 3-5 April 2006 (ed. by D Alford) BCPC, UK (CD).

Ulber B, Klukowski Z and Williams IH (2010a) Impact of insecticides on parasitoids of oilseed rape pests. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 337-355.

Ulber B, Williams IH, Klukowski Z, Luik A and Nilsson C (2010b) Parasitoids of oilseed rape pests in Europe: key species for conservation biocontrol. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by I Williams) Springer Science+Business Media B.V., pp. 45-76.

Ulmer BJ and Dosdall LM (2006) Glucosinolate profile and oviposition behavior in relation to the susceptibilities of Brassicaceae to the cabbage seedpod weevil. Entomologia Experimentalis et Applicata 121: 203-213. doi:10.1111/j.1570-8703.2006.00480.x.

Umuru PA, Bale JS, and Shorrocks B (1990) Predicting time of emergence of frit fly (*Oscinella frit* L.) (Dipt.: Chloropidae) in northern England. Journal of Applied Entomology 109: 377-384.

Umuru PA (1993) Parasitoids of frit fly *Oscinella frit* (Dipt., Chloropidae) and *Geomyza tripunctata* Fall. (Diptera., Opomyzidae) by hymenopterous parasitoids in northern England. Journal of Applied Entomology 116: 313-320.

USDA – APHIS Pest Assessment (2003) Cereal leaf beetle, *Oulema melanopus* (L.) (Coleoptera: Chrysomelidae) pp 7.

Valantin-Morison M (2012) Comment favoriser la régulation biologique des insectes de l’échelle de la parcelle à celle du paysage agricole, pour aboutir a des stratégies de protection intégrée sur le colza d’hiver? Oleagineux Corps Gras Lipides (OCL)19: 169-183. doi:10.1684/ocl.2012.0455

Valantin-Morison M, Meynard J-M and Dore´ T (2007) Effects of crop management and surrounding field environment on insect incidence in organic winter oilseed rape (*Brassica napus* L.). Crop Protection 26: 1108-1120.

Van Emden H (2007) Host Plant Resistance. Chapter 17 In: *Aphids as crop pests.* CAB International.

Van Emden HF, Harrington R (2007) Eds. *Aphids as crop pests.* CAB International.

Van Herk WG, Vernon RS and Roitberg BD (2008) Repellency of a Wireworm, *Agriotes obscurus* (Coleoptera: Elateridae), on exposure to synthetic insecticides in a soil-less bioassay. Environmental Entomology 37: 534-545. doi:10.1603/0046-225X(2008)37[534:ROAWAO]2.0.CO;2

van Rijn PCT, Kooijman J and Wackers FL (2013) The contribution of floral resources and honeydew to the performance of predatory hoverflies (Diptera: Syrphidae). Biological Control 67: 32-38.

Vera CL, Fox SL, DePauw RM, Smith MAH, Wise IL, Clarke FR, Procusier JD and Lukow OM (2013) Relative performance of resistant wheat varietal blends and susceptible wheat cultivars exposed to wheat midge *Sitodiplosis mosellana* (Géhin). Canadian Journal of Plant Science 93: 59-66.

Veres A, Petit S, Conord C and Lavign C (2013) Does landscape composition affect pest abundance and their conservation biological control? A review. Agriculture, Ecosystems and Environment 166: 110-117.

Vernon RS, van Herk WG, Blackshaw RP, Shimizu Y and Clodius M (2014) Mark–recapture of *Agriotes obscurus* and *Agriotes lineatus* with dense arrays of pheromone traps in an undisturbed grassland population reservoir. Agricultural and Forest Entomology 16(3): 217-325. doi:10.1111/afe.12045

Veromann E, Metspalu L, Williams IH, Hiiesaar K, Mand M, Kaasik R, Kovács G, Jogar K, Svilponis E, Kivimagi I, Ploomi A and Luik A (2012) Relative attractiveness of *Brassica napus, Brassica nigra, Eruca sativa* and *Raphanus sativus* for pollen beetle (*Meligethes aeneus*) and their potential for use in trap cropping. Arthropod-Plant Interactions 6: 385-394.

Veromann E, Toome M, Kännaste A, Kaasik R, Copolovici L, Flink J, Kovács G, Narits L, Luik A & Niinemets Ü (2013) Effects of nitrogen fertilization on insect pests, their parasitoids, plant diseases and volatile organic compounds in *Brassica napus*. Crop Protection 43: 79-88. doi:http://dx.doi.org/10.1016/j.cropro.2012.09.001.

Vickerman GP (1982) Distribution and abundance of adult *Opomyza florum* (Diptera: Opomyzidae) in cereal crops and grassland. Annals of Applied Biology 101: 441-447.

Vinatier F, Gosme M and Valantin-Morison M (2012) Mosaic-Pest, landscape model for pest management(I): model description and use for IPM strategies testing. Landscape Ecology 27: 1421-1433.

Vollhardt IMG, Bianchi FJJA, Wackers FL, Thies C and Tscharntke T (2010) Spatial distribution of flower vs honeydew resources in cereal fields may affect aphid parasitism. Biological Control 53: 204-213.

Volkmar C, Werner C and Matthes P (2008) On the occurrence and crop damage of wheat blossom midges (*Contarinia tritici* (Kby.) and *Sitodiplosis mosellana* (Géh.)) in Saxony-

Anhalt. Mitteilungen der Deutschen Gesellschaft für allgemeine und angewandte Entomologie 16: 305-308.

Von Burg SK (2011) Transgenic wheat and non-target impacts on insect herbivores and food webs. PhD thesis, University of Zurich, Faculty of Science. pp 116.

von Richthofen J-S, Johnen A and Volk T (2010) Neuerungen bei den proPlant expert. Pflanzenschutz-Beratungssystemen in Deutschland und Europa. [Improvements of proPlant expert decision support systems in Germany and Europe]. Julius-Kühn-Archiv 428: 135-136.

Waalwijk C, Dullermans A, Weigers G and Smits P (1992) Toxicity of *Bacillus thuringiensis* variety *israelensis* against tipulid larvae. Journal of Applied Entomology 114: 415-420.

Walczak B, Kelm M, Klukowski Z, Smart LE, Ferguson AW and Williams IH (1998) The effect of trap design and 2-phenylethyl isothiocyanate on catches of stem weevils (*Ceutorhynchus pallidactylus* Marsh. and *C. napi* Gyll.) in winter oilseed rape. IOBC/WPRS Bulletin 21: 141-146.

Waliwitiya R, Isman MB, Vernon RS and Riseman A (2005) Insecticidal Activity of Selected Monoterpenoids and Rosemary Oil to *Agriotes obscurus* (Coleoptera: Elateridae). Journal of Economic Entomology 98: 1560-1565. doi:10.1603/0022-0493-98.5.1560.

Walters KFA, Lane A, Cooper DA and Morgan D (2001) A commercially acceptable assessment technique for improved control of cabbage stem flea beetle feeding on winter oilseed rape. Crop Protection 20: 907-912.

Walters K, Young J, Kromp B and Cox P (2003) Management of oilseed rape pests. In: *Biocontrol of oilseed rape pests* (ed. By D. Alford). Blackwell Publishing, Oxford, pp. 43 – 72.

Warner DJ, Allen-Williams LJ, Ferguson AW and Williams IH (2000) Pest-predator spatial relationships in winter rape: implications for integrated crop management. Pest Management Science 56: 977-982.

Warner DJ, Allen-Williams LJ, Warrington S, Ferguson AW and Williams IH (2003) Mapping, characterisation, and comparison of the spatio- temporal distributions of cabbage stem flea beetle (*Psylliodes chrysocephala*), carabids, and Collembola in a crop of winter oilseed rape (*Brassica napus*). Entomologia Experimentalis et Applicata 109: 225-234.

Warner DJ, Allen-Williams LJ, Warrington S, Ferguson AW and Williams IH (2008) Implications for conservation biocontrol of spatio-temporal relationships between carabid beetles and coleopterous pests in winter oilseed rape. Agricultural and Forest Entomology 10: 375-387. doi:10.1111/j.1461-9563.2008.00391.x.

Wegorek P and Zamojska J (2008) Current status of resistance in pollen beetle (*Meligethes aeneus* F.) to selected active substances of insecticides in Poland. Bull OEPP/EPPO 38:91-94.

Weibull J (1994) Glutamic acid content of phloem sap is not a good predictor of plant resistance to *Rhopalosiphum padi*. Phytochemistry 35: 601–602.

Weidner H (1985) Die Sattelmücke *Haplodiplosis equestris* (Wagner, 1871), ein Gersten- und Weizenschadling in Nordost-Bayern in den Jahren 1692 und 1693 (Diptera, Cecidomyiidae). Anzeiger fur Schadlingskunde, Pflanzenschutz, Umweltschutz 58(4): 65-68.

Weisz R, Tarleton B, Murphy JP, Kolb FL (2005) Identifying soft red winter wheat cultivars tolerant to Barley yellow dwarf virus. Plant Disease 89: 170-6.

Wellings PW, Ward SA, Dixon AFG and Rabbinge R (1989) Crop loss assessment. In: A.K. Minks, P. Harrewijn (Eds.), *Aphids, their biology, natural enemies and control*, 2C, Elsevier, NL, 1989, pp. 49–69.

Wessex BESS (2014) Biodiversity and ecosystem services in current and future multifunctional landscapes. http://www.brc.ac.uk/wessexbess/News. Accessed March 2016.

WGIN Webpage (2014) www.wgin.org.uk

Wheeler T and von Braun J (2013) Climate change impacts on global food security. Science 341(6145): 508-513. DOI: 10.1126/science.1239402.

Williams IH (2006a) The EU project MASTER (Management Strategies for European Rape Pests): an update. IOBC/WPRS Bulletin 29: 39-42.

Williams IH (2006b) Integrating biological control within IPM for winter oilseed rape in Europe: an overview of the MASTER project. Proceedings of the Symposium on Integrated Pest Management in Oilseed Rape, 3-5 April 2006, Göttingen, Germany (ed. by D Alford) BCPC, UK (CD).

Williams IH (2010) The major insect pests of oilseed rape in Europe and their management: an overview. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 1-44.

Williams I, Büchi R and Ulber B (2003) Sampling, trapping and rearing oilseed rape pests and their parasitoids. In: *Biocontrol of Oilseed Rape Pests* (ed. by D Alford) Blackwell Publishing, Oxford, pp. 145-160.

Williams IH and Cook SM (2010) Crop location by oilseed rape pests and host location by their parasitoids. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 215-244.

Williams IH and Ferguson AW (2010) Spatio-temporal distributions of pests and their parasitoids on the oilseed rape crop. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests (*ed. by IH Williams) Springer Science+Business Media B.V., pp. 245-271.

Williams IH, Ferguson AW, Kruus M, Veromann E and Warner DJ (2010) Ground beetles as predators of oilseed rape pests: incidence, spatio-temporal distributions and feeding. In: *Biocontrol-Based Integrated Management of Oilseed Rape Pests* (ed. by IH Williams) Springer Science+Business Media B.V., pp. 115-149.

Williams IH, Frearson D, Barai H and McCartney A (2007) Migration to and dispersal from oilseed rape by the pollen beetle, *Meligethes aeneus*, in relation to wind direction. Agricultural and Forest Entomology 9(4): 279-286.

Williams IH and Free JB (1978) The feeding and mating behaviour of pollen beetles (*Meligethes aeneus* Fab.) and seed weevils (*Ceutorhynchus assimilis* Payk.) on oil-seed rape (*Brassica napus* L.). Journal of Agricultural Science 91: 453-459.

Williams IH and Free JB (1979) Compensation of oilseed rape *Brassica napus* L.) plants after damage to their buds and pods . Journal of agruicultural Science 92: 53-59.

Williams IH, Martin AP and Kelm M (1987a) The phenology of the emergence of brassica pod midge (*Dasineura brassicae* Winn.) and its infestation of spring oil-seed rape (*Brassica napus* L.). The Journal of Agricultural Science 109: 309-314. doi:doi:10.1017/S0021859600080734.

Williams IH, Martin AP and Kelm M (1987b) The phenology of the emergence of brassica pod midge (*Dasineura brassicae* Winn.) and its infestation of winter oil-seed rape (*Brassica napus* L.). Journal of Agricultural Science 108: 579-589. doi:10.1017/S0021859600079983.

Williams IS and Dixon AFG (2007) Life Cycles and Polymorphism. Chapter 3 in: *Aphids as Crop Pests.* (eds) HF van Emden and R Harrington. CAB International. Pp 69-86.

Wilson MJ, Glen DM and George SK (1993) The rhabditid nematode Phasmarhabditis hermaphrodita as a potential biological control agent for slugs. Biocontrol Science and Technology **3**: 503–511.

Winfield AL (1986) Field pests of oilseed rape: Oilseed Rape (ed. by DH Scarisbrick & RW Daniels) Collins, London, pp. 235-281.

Winfield AL (1992) Management of oilseed rape pests in Europe. Agricultural Zoology Reviews 5: 51-95.

Winkler K, Wackers FL, Termorshuizen AJ and van Lenteren JC (2010) Assessing the risks and benefits of floral supplements in conservation biological control. BioControl 55: 719-727.

Wise L, Lamb RJ and Smith MAH (2001) Domestication of wheats (Graminae) and their susceptibility to herbivory by *Sitodiplosis mosellana* (Diptera: Cecidomyiidae). The Canadian Entomologist 133: 255-267.

Woodville HC (1968) Saddle gall midge survey on barley 1967. Plant Pathology 17: 64-66.

Woodville HC (1970) Results of a three year survey of saddle gall midge (*Haplodiplosis equestris* (Wagn.)) on spring barley. Plant Pathology 19**:** 141-145.

Woodville HC (1973) Observations on saddle gall midge (*Haplodiplosis equestris* (Wagn.)) in Eastern England. Plant Pathology 22: 177-181.

Wratten SD, Gillespie M, Decourtye A, Mader E and Desneux N (2012) Pollinator habitat enhancement: Benefits for other ecosystem services. Agriculture Ecosystems and

Environment 159: 112-122.

Wu YQ, Jiang YL and Duan Y (2008) Monitoring methods of wheat blossom midge. Henan Journal of Agricultural Science 8: 98-100.

Wynn S, Ellis S and Alves L (2014) Cabbage stem flea beetle snapshot assessment – September 2014. http://cereals.ahdb.org.uk/media/507048/pr546-extension.pdf

Xu T, Dyer DG, McConnell LL, Bondarenko S and Allen R (2016) Clothianidin in agricultural soils and uptake into corn pollen and canola nectar after multi-year seed treatment applications. Environmental Toxicology and Chemistry 35(2): 311-321.

Young JE and Cochrane J (1993) Changes in wheat bulb fly (*Delia coarctata*) populations in East Anglia in relation to crop rotations, climatic data and damage forecasting. Annals of Applied Biology 123: 485-498.

Zadoks JC, Chang TT and Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Research 14: 415-421.

Zaller JG, Moser D, Drapela T, Schmöger C and Frank T (2008a) Effect of within-field and landscape factors on insect damage in winter oilseed rape. Agriculture, Ecosystems & Environment 123: 233-238. doi:http://dx.doi.org/10.1016/j.agee.2007.07.002.

Zaller JG, Moser D, Drapela T, Schmöger C and Frank T (2008b) Insect pests in winter oilseed rape affected by field and landscape characteristics. Basic and Applied Ecology 9: 682-690. doi:http://dx.doi.org/10.1016/j.baae.2007.10.004.

Zaller JG, Moser D, Drapela T, Schmöger C and Frank T (2009) Parasitism of stem weevils and pollen beetles in winter oilseed rape is differentially affected by crop management and landscape characteristics. Biocontrol 54(4): 505-514.

Zimmer CT and Nauen R (2011) Pyrethroid resistance and thiacloprid baseline susceptibility of European populations of *Meligethes aeneus* (Coleoptera: Nitidulidae) collected in winter oilseed rape. Pest Management Science 67(5): 599-608. doi: 10.1002/ps.2137

Zimmer CT, Köhler H and Nauen R (2014) Baseline susceptibility and insecticide resistance monitoring in European populations of *Meligethes aeneus* and *Ceutorhynchus assimilis* collected in winter oilseed rape. Entomologia Experimentalis et Applicata 150: 279-288. doi:10.1111/eea.12162.

Zimmer CT, Müller A, Heimbach U and Nauen R (2013) Target-site resistance to pyrethroid insecticides in German populations of the cabbage stem flea beetle, P*sylliodes chrysocephala* L. (Coleoptera: Chrysomelidae), Pesticide Biochemistry and Physiology 108: 1-7. doi:10.1016/j.pestbp.2013.11.005

Zhang Z, Zhang YH, Cheng DF, Sun JR, Jiang JW, Yang LX and Liang XZ (2012) Impacts of different tillage practices on population dynamics of the orange wheat blossom midge *Sitodiplosis mosellana* (Diptera: Cecidomyiidae). Acta Entomologica Sinica 55(2): 612-617.