Section 1. Biological control of crop pests through the manipulation of the farm ecological infrastructure and modification of the tillage regime

The scope of this report focuses on identifying both novel and age-old techniques used to sustainably manage the pests of key crops within the UK. Five crops have been selected, based on the proportion of our land area, as of June 2014 (DEFRA, 2015).

- Cereals (3179 thousand ha) or (3362 thousand ha including maize)
- Oilseed rape (675 thousand ha)
- Potatoes (141 thousand ha)
- Peas & field beans (139 thousand ha)
- Vegetables grown outdoors (116 thousand ha)

It should be noted that there is a much greater weighting toward cereal and oilseed crops than in other crops, due to the proportionate size of the areas cultivated. It is also essential to remember that there is no one-size-fits-all approach to biological control of crop pests. In light of this, a combination of approaches may be required, so please bear in mind that techniques used to control some pests may also be relevant to pests of other crops, yet this still may not be suitable for all farming systems.

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Contents

SECTION 1. Cereals: biological control strategies

1.1. Aphids (Aphididae spp.)

1.1.1. Introduction & life history

Three aphid species are important pests within cereal crops; *Rhopalosiphum padi* Linnaeus, *Sitobion avenae* Fabricius, and *Metopolophium dirhodum* Walker (all Hemiptera: Aphididae). All have relatively similar life histories, as can be seen in Table 1.1.1.1.

Table 1.1.1.1. Life histories of the two pest aphid species of OSR (HGCA, 2014).

Aphid species	Autumn	Winter	Spring	Summer
Rhopalosiphum padi (**bird cherry-oat aphid**)	Winged adults migrate back to bird cherry trees. Asexual forms in mild conditions can remain and feed in crop (**Sep-Nov**).	Eggs overwinter on bird cherry trees, *Prunus padus* (**Dec-Mar**).	Eggs hatch (**Apr**) and winged adults migrate to cereals and grasses (**May-Jun**).	Winged adults migrate to cereals and grasses (**May-Jun**). Multiple generations occur, first infesting the lower leaves and stem (**Jul-Aug**).
Sitobion avenae (**grain aphid**)	BYDV is a risk (**Sep-Mar**) (pre-GS31).	Adults overwinter on crops and grasses, with no alternative host (**Dec-Mar**) BYDV is a risk (**Sep-Mar**) (pre-GS31).	Fresh migrations infest crops (**Apr**), and during dry, calm weather, populations can increase dramatically when feeding (**Apr-Aug**).	Direct crop feeding (**Apr- Aug**).
Metopolophium dirhodum (**rose-grain aphid**)	Very frost-resistant eggs are laid on wild and garden roses (**Oct-Nov**).	Overwintering of eggs on roses (**Dec-Feb**), and adults on grasses (**Dec-Apr**).	Winged adults migrate to crops (**Mar-Apr**).	Feeding on crops and grasses occurs (**May-Sep**).

1.1.2. Damage/presence

The three species are known to colonize different host plant organs from one another (Brabec et al., 2014) (for more information see Section 2.1.3). Even at low densities, the aphid species that attack cereals in the UK can cause economic damage acting as vectors of viruses. *S. avenae* is the most prominent vector of the barley yellow dwarf virus (BYDV), causing losses up to 2.5 t/ha particularly in the east, middle, and north of the UK. *R. padi* is also a vector, particularly in the south west of England. As *M. dirhodum* overwinters as eggs on roses, this species is not regarded as an important vector of BYDV (HGCA, 2014) but nevertheless, it is still a vector of the virus (Jarošová et al., 2013).

R. padi is the only aphid species that does not cause direct damage through feeding, whereas, *S. avanae* and *M. dirhodum* can cause direct feeding yield loss. *M. dirhodum*, when thresholds are exceeded, can cause yield losses of up to 4 t/ha, though usually damage equates to 0.25-1 t/ha (HGCA, 2014).

1.1.3. Pest thresholds

Information regarding the monitoring of migration, BYDV transmitted damage, and direct feeding-induced yield loss cereals for all three aphid species can be in AHDB Aphid News (HGCA, 2014). For monitoring direct feeding damage, cereal leaves should be checked for *S. avenae* and *D. dirhodum* about the time that cereals are coming into ear. *S. avenae* then move up into the stem to the ears during grain filling and feed from the phloem that supplies the grain (HGCA, 2014). *R. dirhodum* does not move onto the ear, but will collect on the top leaves in the later growth stages (HGCA, 2014).

No thresholds exist for treatment to avoid BYDV-caused yield loss in cereals. There are however thresholds for control of *S. avenae* and *M. dirhodum*, which cause yield losses via direct feeding, as can be seen below.

BYDV transmission thresholds (HGCA, 2014) (by R. padi and S. avenae)

It should be assumed that all *R. padi* and *S. avenae* carry BYDV, and therefore, their presence represents a risk of disease transmission.

Direct feeding thresholds (HGCA, 2014) (by S. avenae and *M. dirhodum)*

i. Before the *start of flowering (GS61)*: half of tillers infested
ii. *Start of flowering (GS61) – Grain watery ripe (71)*: two thirds of tillers infested with increasing populations
iii. *Start of flowering (GS61)* – two weeks before the *end of grain filling (GS87)*: two thirds of tillers infested from stem extension to flag-emergence

1.1.4. Potential for control

1.1.4.1. Chemical control

Clayson et al. (2014) found that significantly reduced concentrations of malathion*, and organophosphate, can cause aphid mortality when these aphids are stressed by crowding or plant resistance, than aphids grown in more favourable conditions. Aphid size at maturity can be affected by colony density (Dewar, 1976) and thus crowding (dense populations) can be used as a stressor to compare performances under optimal (uncrowded) and sub-optimal (crowded conditions) (Clayson et al. 2014). In laboratory conditions, Clayson et al. (2014) found that *M. dirhodum* development on the wheat cultivar 'Rapier' (partially resistant) substantially reduced the topical LC_{50} (lethal concentration required to kill 50% of population in a given time frame) of malathion by 37.8 and 34.8 % under high (stressed) and low density conditions respectively. This suggests that plant antibiosis by 'Rapier' increased malathion susceptibility. Although the detrimental effects of crowding on aphid populations will only occur at high aphid population densities, the adverse influence of plant resistance on aphid populations can be exhibited throughout aphid development, independent of population densities, and will improve the efficacy of insecticides when used in conjunction (Clayson et al. 2014). These findings could be harnessed to alleviate the pesticide impact on natural enemies, by reducing the pesticide input onto cereals, if coupled with other stressors such as more resistant cultivars.

1.1.4.2. Biological control

- *Identify potential biological control agents*

Primary and secondary parasitoids are known biological control agents of aphids within cereal fields. Host specialist parasitoids such as *Aphidius uzbekistanicus* Luzhetski and *A. rhopalosyphi* DeStefani-Peres (both Hymenoptera: Braconidae) are mostly restricted to *R. padi, S. avenae*, and *M. dihordum* (Hawro et al., 2015). Polyphagous parasitoids, such as *Ephedrus plagiator* Nees and *Praon volucre* Haliday, are known to attack aphids associated with forest edges and orchards, but also on herbaceous plants (Rakhshani and Talebi, 2006).

Some argue against the common hypothesis of specialist natural enemy dominance over generalist natural enemies, as generalists like spiders can limit aphids more effectively due to their earlier

*Malathion is no longer approved

appearance in crop fields during the growing season (Snyder and Ives, 2003). Van Rijn et al. (2008) found that hoverflies, lacewings, and parasitoids are likely to be the most important natural enemies of aphids within cereal fields. Aggregative behaviour in carabids have been shown to be correlated with aphid abundances (Monsrud and Toft, 1999). Hassan et al. (2013) found that aphid (*S. avenae* and *M. dirhodum*) and carabid abundances were always significantly correlated with each other, but to varying extent depending on landscape heterogeneity. Abundances of carabids and aphids were positively correlated in the homogenous landscape, but negatively correlated in the heterogeneous landscape (Hassan et al., 2013). Significantly fewer carabids were caught in the heterogeneous landscape also (Hassan et al., 2013). Indeed, related abundances does not necessarily represent biological control. Particularly as Hassan et al. (2013) found that the dominant carabid species (*Poecilus cupreus* and *Pterostichus melanarius*) were less abundant in heterogeneous landscapes, assumed to be due to the larger proportions of hedgerows in this landscape class. The two carabids are adapted to living in open plains (Diwo and Rougon, 2004) and therefore, hedgerows may act as a barrier to their movement (Mauremooto et al., 1995). It may therefore be important to ascertain which predatory species dominate (Hassan et al., 2013), to tailor management to those species. Overall however, the biological control potential that carabids impose on aphids is not deemed to be large.

- *Evidence of biological control directly impacting the pest*

Common hypotheses suggest that high primary parasitoid abundances in **complex landscapes** should increase **parasitism rates** and hence reduce pest numbers (Altieri and Letourneau, 1982), such as reported by Gagic et al. (2011) where localities of greater diversity in vegetation increased aphid parasitism, with similar results experienced by Salvo et al. (2005). Semi-natural habitats have been postulated to be of importance for parasitoid communities (Gagic et al., 2011; Rand et al., 2012). The proximity of perennial herbaceous and wooded patches surrounding arable fields may be of benefit, particularly as the longevity and fecundity of parasitoids with access to semi-natural habitats are enhanced, by shelter provision from agricultural disturbances (Araj et al., 2008).

However, a recent study by Hawro et al. (2015) demonstrated that across five different European regions, the species composition of aphids and their parasitoids, and their respective parasitism rates, depend not upon the landscape heterogeneity nor on agricultural intensification, but predominantly on the **geographical region**. There was a significant difference in the species composition of aphids, their parasitoids, or their respective parasitism rates between the five sites, despite no significant difference between the total numbers of aphids found. For example, the Swedish aphid communities were dominated by *R. padi* communities, in parallel with other research (Leather et al., 1989; Östman et al., 2001b) as *R. padi* is both known to favour colder climates (Gianoli, 1999) and *Prunus padus* (bird cherry) is abundant in Sweden (Hawro *et al*., 2015). Hawro et al. (2015) found that parasitoid communities and parasitism rates were mostly triggered by their host aphid availability, independent of landscape heterogeneity and agricultural intensification.

In a French study, Andrade et al. (2015) also found that parasitoid communities were driven by the geographical region, rather than local-scale variability. In contrast to Hawro et al. (2015), Andrade et al., 2015) found that parasitoid relative abundance patterns are not heavily linked to aphid availability, as varying aphid abundances were associated to fairly **constant parasitoid abundances**. However, there did appear to be host aphid preferences with regard to the parasitoids. *M. dirhodum* was most abundant among the parasitized aphid samples, than in the living aphid samples across most of the region-years. *M. dirhodum* is considered a ‘high risk, but high reward’ host (Andrade et al., 2015) whereby they exert greater behavioural defences (Chau and Mackauer, 2001) but have been shown to have a greater nutritional value (Bilde and Toft, 2008). This is of great importance, as the damage induced by *M. dirhodum* has been shown to surpass that of *S. avenae* in cultivated winter wheat (Niehoff and Stablein, 1998) *S. avenae* also posseses a greater rate of increase than *M. dirhodum* over a broad temperature range (Asin and Pons, 2001). Although the studied parasitoids clearly do parasitize aphids in-field, their potential as effective biological control agents of the most high risk aphids (potentially *S. avenae*) may be in doubt.

As with other UK pests, **entomopathogenic fungi** have been reported to be pathogenic against aphids that are pests within the UK, including *M. dirhodum* (Fadayivata et al., 2014). Murerwa et al. (2014) demonstrated that the isolate ICIPE 51 from the fungus, *Metarhizium anisopliae*, was pathogenic against both *R. padi* and *M. dirhodum* under laboratory conditions. The fecundity and intrinsic rate of increase of both aphid species declined with aphid maturity and dosage. As both *R. padi* and *M. dirhodum* were significantly more fecund in early adulthood, this stage should be targeted using the entomopathogenic fungal intervention (Murerwa et al., 2014). It is important to note that the conditions of the experiment were optimal for fungal growth, and therefore, it is important that field-based studies should also be considered for aphid control by the use of entomopathogens (Murerwa et al., 2014).

- *Evidence that a certain habitat and/or management practice improves actual biological control*

Aphid suppression is also facilitated by generalist predators, such as hoverfly larvae (Diptera: Syrphidae), lacewing larvae (Neuroptera: Chrysopidae), and aphidophagous ladybird adults and larvae (Coleoptera: Coccinellidae) (Brewer and Elliott, 2004) Many hoverfly larvae are aphidophagous, and after nectar and pollen resources for energy and sexual maturation and egg development, adults will oviposit near to aphid colonies (Hickman and Wratten, 1996). Hickman and Wratten (1996) found that in a UK study, significantly more hoverfly eggs were observed in *Phacelia tanacetifolia* than in control winter wheat fields, and when many third-instar hoverfly larvae were found in field, four weeks into the experiment, aphid presence was reduced when compared to the control fields. This highlights that the use of flowering margins of the likes of ***Phacelia* spp**., can be important for the regulation of pest aphids.

Tulli et al. (2013) demonstrated in a South American study, that in increasing the **non-crop structural complexity** surrounding wheat crops, smaller abundances of cereal aphids (including *S. avenae* and *M. dirhodum*) would occur as a result of enhanced abundances of *Eriopis connexa* Germar (Coleoptera: Coccinellidae). Although *E. connexa* were affected by cereal aphid abundance, perhaps more importantly, they were also related to plant diversity. Tulli et al. (2013) recorded an increase in the abundance of *E. connexa* earlier in the season within the diverse non-crop habitat than in the less diverse non-crop habitat. The ladybird density increase was not due to an increase in the cereal aphid density (Tulli et al., 2013).

The positive impact that plant diversity exhibits in ladybird reproductive response, is accounted for by the provision of prey in hibernation areas upon spring ladybird emergence, when aphid densities in crops are still low (Tulli et al., 2013). As food supply influences the fecundity (Dixon and Guo, 1993) and migration behaviour of ladybirds (Ferran and Dixon, 1993). Tulli et al. (2013) suggest that the availability of aphids within non-crop landscape elements is likely to impact the numbers and distribution of ladybirds within agro-ecosystems. Furthermore, **shelter habitats** that harbour prey populations in early spring can influence post-overwintering mortality, the fecundity of surviving of surviving ladybirds, and the phenology of dispersal into the crop (Griffiths et al., 2008). Bianchi and Werf (2004) established that when pest aphids infest wheat early in the season, prey availability alone is insufficient to allow *Coccinella septempunctata* Linnaeus (Coleoptera: Coccinellidae) optimal reproduction. Whereas, when infestation by aphids was delayed, *C. septempunctata* became increasingly dependent on non-crop habitats.

It is clear that foliar-foraging predators can be beneficial in reducing pest populations, but the extent to which epigeal predators play in pest suppression is not completely clear. Aphids can become dislodged from the crop, through both mechanical and behavioural means (Winder et al., 2013). The latter is due to a defence strategy of aphids is to **fall to the ground** as a response to natural enemies or alarm pheromones (Irwin et al., 2007). Either way, the fallen aphids rarely return to the same host plant (Winder et al., 2013). Despite the literature suggests that epigeal predators respond relatively slowly to aphid infestations, and are therefore potentially less efficient biological control agents than foliar-foraging natural enemies (Holland et al., 2012, 2008) Winder et al. (2013) demonstrated a strong spatial pattern for aphids falling to the ground. In this way, epigeal predators may exhibit some level of biological control. Minimal amounts of *M. dirhodum* were caught on climbing traps, suggesting that the trapping method used by Winder et al. (2013) was ineffective, or that *M. dirhodum* is poor at re-climbing the crop. If these aphids cannot return to the crop, damage will be reduced, and it is highly likely that they will not survive. Though depending on the hunting strategy of epigeal predators, mortality of fallen (or roaming) aphids may not necessarily be caused by direct predation.

In a study based on gut-content analysis of field-collected *Pardosa,* Kuusk and Ekbom (2010) found that alternative prey items may affect *Rhopalosiphum padi* in leys and spring cereals. There was a negative association between *R. padi* consumption by *Pardosa* and Collembola, which was assumed to be due to changed hunting strategy. The authors suggested that when Collembola were numerous, *Pardosa* changed from actively foraging to **"sit-and-wait"** ambush tactics, resulting in fewer interactions with relatively sedentary aphids. In a later study, Kuusk and Ekbom (2012) found that at sites that hosted considerably higher aphid **densities,** *R. padi* consumption was positively related to the availability (Kuusk and Ekbom, 2012). In total, 70% of analysed spiders, *R. padi* DNA, with predation rates that exceeded 50% at all sampling sites. Although this study disagrees with the previous findings, it is postulated that the later study, in which aphid densities were greater, aphids would tend to roam the soil surface when densities were too great on plants (Sopp et al., 1987). Kuusk and Ekbom (2010) observed no wayfaring aphids caught on ground-based sticky traps, whereas in Kuusk and Ekbom (2012) observed aphids on plants and on the ground surface. This strengthens the claim that if aphids were non-existent on the soil surface, *Pardosa* may have adopted a sit-and-wait strategy to consume Collembola in Kuusk and Ekbom (2010), rather than the actively foraging *Pardosa* in Kuusk and Ekbom (2012).

Pardosa tested positive for Collembola consumption regardless of Collembola availability, suggesting that some Collembola are important dietary items. Other work proposes that some invertebrate predators, including *Pardosa* will selectively hunt depending on **dietary requirements**, rather than random foraging at optimal capture rates (Mayntz et al., 2005). In this way, if the adopted hunting strategy allows for it, pests may be preferred prey items even at low pest densities, which may restrict virus transmission.

Despite the negative effect of alternative prey items at low aphid densities, **alternative prey** items, particularly Collembola which may provide vital dietary supplements (Kuusk and Ekbom, 2010) can increase the reproductive response of *Pardosa* spiders. Improved fitness and reproductive success may suppress pest populations when in greater abundance. Although *Pardosa* did not consume either aphid or Collembola in relation to their in-field abundance, Kuusk and Ekbom (2012) found that the presence of Collembola was positively related to aphid consumption. In this case, when pest populations are numerically greater, pest suppression may be facilitated. In review of *Pardosa*-prey research, soil and debris should be managed to enhance Collembolan communities to improve *Pardosa* reproductive numerical response, so that aphids and other pests can be controlled when in abundance.

In UK winter wheat, Harwood et al. (2004) found varying effects of **alternative Collembolan prey** on the spider family, Linyphiidae (money spiders). Rates of predation by Linyphiinae were related to aphid density, and not influenced by the availability of alternative Collembolan prey. Whereas, in Erigoninae, predation rates of aphid predation were significantly affected by Collembolan densities. Harwood et al. (2004) suggested that higher Collembola densities at the web sites of Erigoninae compared to non-web sites, allowed the web-dwelling Erigoninae to exploit Collembola rather than active hunters which would encounter aphids more often.

For more information on the use of artificial floral resources to enhance hoverfly egg laying in-field, please see Section 4.3.4.2.

1.1.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

All cereals are at risk from direct damage by *S. avenae* and *M. dirhodum*, although **winter barley** is less affected due to its earlier senescence. Crops that have also been injured by other pests and diseases are also more likely to suffer due to lower reserves of soluble stem carbohydrates. Dry and settled weather during grain filling can also enhance the chance for damage by *M. dirhodum*, particularly if the previous winter has been hard, and consequently the natural enemy survival is poor (HGCA, 2014).

Early sown winter cereals during warm autumns are most susceptible to *R. padi* attack, as aphids breed swiftly. It should be noted however, yield loss by *R. padi* is likely to be low in a crop suffering from a new BYDV infection after GS31, as BYDV is most harmful to less mature cereals. BYDV, which is most harmful to plants in early growth stages, is more likely to be transmitted when winged *S. avenae* can migrate later into autumn. Mild winters will cause migrations to continue into November, infecting later-sown cereals. Spring cereals are most susceptible to BYDV after mild winters, as the BYDV vectors, *R. padi* and *S. avenae* populations can proliferate. The effects of BYDV are exponentially worse when coupled with other stress factors, including weather, soil acidity, and other pests and diseases (HGCA, 2014). When winters are particularly cold, wheat may be able to elude attacks from aphids, as egg dormancy and hatching may be terminated (Brabec et al., 2014). Similarly, immigration of winged adults into cereals from overwintering grounds can also be delayed by low winter temperatures (Hansen, 2006). *S. avenae* is also a prominent vector of potato virus Y. Migration during late June and early July poses the most significant risk of high virus incidence within potato crops. In summer, *S. avenae* populations can be very large in potatoes, having migrated from desiccating and senescing cereal crops (HGCA, 2014).

At a landscape scale, Hawro et al. (2015) found that across five different European regions, there was no significant difference in the species composition of aphids, their parasitoids, or their respective parasitism rates. In spite of total aphid populations not being affected by landscape heterogeneity and agricultural intensification, there were some significant species-specific differences in regional abundance of aphids. *M. dirhodum* for example was affected by agricultural intensification, as was *S. avenae* to landscape structure (Hawro et al., 2015). In addition, *S. avenae* was significantly affected, reaching higher abundances in more structurally diverse landscapes, and was influenced negatively by the **proportion of arable land** in the landscape. The former finding aligns with Thies et al. (2005) who reported a positive influence of landscape heterogeneity on the dominant *S. avenae*. Indeed, this was explained by the preferred food resources that grassy habitats provide.

Complex landscapes are proposed to yield greater abundances of aphids than in more homogenous landscapes (Bianchi et al., 2006), which is supported in a French study by Hassan et al. (2013). **Complex landscapes** harbour more and better connected semi-natural habitats (Delattre et al., 2013) that not only provide stable refugia for aphids, but also more hibernation sites (Carter et al., 1982; Dixon, 1985). On a finer scale, Hassan et al. (2013) demonstrated that aphids (*S. avenae* and *M. dirhodum*) are more abundant in field centres than in the margins in both heterogeneous and homogenous landscapes. With respect to this, control can be focused on marginal field habitats.

1.1.5. Outlook

Table 1.1.5.1. A summarising table of management implications to control aphids in a sustainable manner.

Chemical control
• Use more resistant cultivars (e.g. 'Rapier'), to increase susceptibility of aphids to lower concentrations of insecticide (malathion*) (Clayson et al., 2014).
Biological control
• Encourage parasitoid wasps (Hawro et al., 2015). • Encourage lacewings, ladybirds (Brewer and Elliott, 2004), spiders (Kuusk and Ekbom, 2010), and to a lesser extent, carabids (Al Hassan et al., 2013). • Provide flowering borders (e.g. *Phacelia* spp.) around fields to increase hoverfly populations and thus efficiency of control of in-field aphids (Hickman and Wratten, 1996). • Increase non-crop structural complexity to increase ladybird abundance and reduce cereal aphid abundance (Tulli et al., 2013). • Encourage springtail populations, as they are likely to be important food sources to wolf spiders, and can increase aphid consumption (Kuusk and Ekbom, 2012).
Cultural control
• **Winter barley** is less susceptible to direct feeding damage by aphids (HGCA, 2014). • Avoid spring cereal cropping after mild winters, as BYDV is more likely to be transmitted by the BYDV vector aphids (HGCA, 2014). • Grain aphid (vector of both BYDV and PVY) benefits from heterogeneous landscapes (Hawro et al., 2015) with a large amount of grassy habitats (Thies et al., 2005).

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*Malathion is no longer approved

1.2. Wireworms (*Agriotes* spp.)

1.2.1. Introduction & life history

Wireworms are the larvae of click beetles of the genus, *Agriotes* spp. (Coleoptera: Elateridae) and are typically found in grassland, pastures and meadows (Kozina *et al*. 2015), and attack a wide array of crops. The larvae cause damage by burrowing into the roots of crops such as carrot, but are also known to damage vegetable seedlings (HGCA, 2014). *Agriotes* spp. adults will survive for about a year, and after overwintering below the soil surface between September and March, will lay eggs below the soil surface between May and June, which hatch in July and August. The larvae of *Agriotes* spp. are perennial developers (2-5 years) (Kozina *et al*., 2015), feeding year-round until mature enough for pupation, usually between July and August (HGCA, 2014). Upon emergence, the beetles do not migrate great distances (Sufyan et al., 2007) though the distance is now thought to be greater than previously estimated. Schallhart et al. (2009) for example found that *A. obscurus* (present in the UK), can disperse 80 m, and are therefore able to colonize new patches.

1.2.2. Damage/presence

Wireworm incidence has become more prevalent since the withdrawal of organochlorine insecticides (HGCA, 2014). Ragged holes are left at the base of cereal, sugar beet, and leek stems, moving along rows and exploiting new stems (HGCA, 2014). This damage may be enhanced in favourable conditions, as Čamprag (1997) observed a relationship between climatic factors and adult *Agriotes* spp. abundance, as adult form was greater when temperatures were high, and rainfall was minimal. Wireworms are damaging to all winter cereal, and winter cereal/grass lay rotations, causing damage up to 0.6 t/ha. Young sugar beet seedlings are also damaged, as small wounds caused by wireworm soon blacken on the stem and below the soil level, and enough to cause the seedling to wilt (HGCA, 2014). Total crop loss of leeks can also be caused (HGCA, 2014), whilst potato marketability can suffer, resulting in the difference between a crop worth >£100/tonne and one ploughed in at a significant loss (HGCA, 2014). Potato tuber damage is visible as small surface holes which lead to narrow internal tunnels, and similar symptoms are seen in carrots (HGCA, 2014).

1.2.3. Pest thresholds

In light of the extent of damage caused, wireworm control must be based upon the principles of integrated pest management (IPM) (e.g., EU Directive 2009/128/EC), and due to *Agriotes* spp. life cycle, suppression must be based upon population level forecasts (Kozina et al., 2015). Studies suggest that presence of captured adults can be correlated to larval presence, and thus damage potential, in soils for the three main species of southern Europe (*A. sordidus* Illiger, *A. brevis* Candèze, and *A. ustulatus* Schäller) (Furlan and Tóth, 2007; Furlan et al., 2001).

Pheromone traps have been deemed by some as reliable and cost effective (Furlan et al., 2001; Tóth et al., 2001) and are suitable for monitoring all of Europe's dominant *Agriotes* spp. (Furlan and Kreutzweiser, 2015). HGCA (2014) suggested the use of pheromone trapping to determine the presence or absence of *Agriotes* spp, but it does not relate to the potential abundance of the pest. Instead, **soil samples** (HGCA, 2014) can be taken to assess the prospective population size, as seen in Table 1.2.3.1.

A more integrated and refined method for ascertaining whether thresholds are exceeded has been compiled by Furlan and Kreutzweiser (2015). The authors describe two **main agronomic factors** which exacerbate wireworm damage. Soil organic matter content >5 % (Furlan, 2011, 2005) is the first, and continuous plant cover with meadow or double cropping (including barley and soybean, ryegrass and maize) in the previous two years (Furlan, 2005; Furlan et al., 2011) is the second. If neither factor is present, then no treatment will be necessary.

If pheromone traps have detected a high beetle population density, and/or the previously described agronomic risk factors are present, then localised wireworm population densities (Chabert and Blot, 1992; Parker, 1996) can be located using bait traps (Furlan and Kreutzweiser, 2015). As thresholds for pheromone trapping do not currently exist, perhaps then the presence or absence of trapped click beetle adults can be used to assess whether bait trapping is required. Certain *Agriotes* spp. cause greater damage than others (Furlan, 2014), but also respond to bait traps independently, and thus thresholds are required for each species (Furlan, 2011). Furlan (2014) demonstrates that there is a close correlation between the number of maize plants damaged by *Agriotes* spp. with both the larval number per square meter, and the average number of larvae per bait trap. Over this 19-year period, no yield reduction was observed in maize when the *Agriotes* spp despite varying climatic conditions and hybrid choices. **Bait traps** were used to develop the thresholds seen in Table 1.2.3.2 for maize. In this way, when thresholds are exceeded at local levels, more refined control can be exhibited, with agronomic and biological treatment first considered before chemical control (Furlan and Kreutzweiser, 2015).

Table 1.2.3.1. Thresholds for control of wireworms from soil core abundances, relating to their relative population size estimate (HGCA, 2014). Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Crop	**Soil core abundance requiring control**	**Estimated population size requiring control**
Cereals	> 12 wireworms/ 10 cm diameter soil core	>750,000 wireworms/ha*
Potatoes	1 wireworm/ 10 cm diameter soil core	60,000 wireworms/ha

*it should be noted that even if a seed treatment is used, damage can still occur if the pest pressure is high (1.25 million wireworms/ha)

Table 1.2.3.2. Interspecific thresholds for control within maize crops, when caught in bait traps (Furlan, 2004). Bait traps were used in accordance with (Chabert and Blot, 1992) and were deployed to estimate population densities between late February and mid-April. Research in UK conditions have found these traps and those similar to be efficient at catching wireworms (Parker, 1996). This guidance is given with hope that integrated pest management strategies are deployed, as seen in Section 2.6.4.

Crop	**Wireworm spp.**	**Threshold**
Maize	*A. brevis* (UK presence unknown)	>1 larva per trap
	A. ustulatus (UK presence unknown)	>5 larvae per trap
	A. sordidus (present in Britain)	>2 larvae per trap

1.2.4. Potential for control

1.2.4.1. Chemical control

For European maize farming, long-term studies suggest that insecticides are not neccessary at sowing to protect against wireworms (Ferro and Furlan, 2012; Furlan et al., 2011). High wireworm populations in Europe is actually quite low (e.g. below 5 %), as seen in results coming from the PURE (VII Framework) project. Insecticide application may therefore not be necessary (Goulson, 2013), and low pest populations can be monitored in field assessments for successful IPM implementation (Furlan and Kreutzweiser, 2015). No significant wireworm damage in French, Hungarian, Slovenian, German, and Italian experimental fields was detected over three years of monitoring (Furlan, unpublished data). There have also been **no significant differences** in yield and crop stand, between maize treated with neonicotinoids and untreated plots, due to crop compensation or low wireworm abundance (Ferro and Furlan, 2012; Furlan et al., 2011). Furlan (2014) reported that total maize damage (re-sowing, and yield loss due to delayed sowing or reduced stand), was often less than the total cost of prophylactic insecticide application, *and* this excludes the environmental side-effects (van der Sluijs et al., 2015).

Rather than applying prophylactic insecticides at low-risk levels, Furlan and Kreutzweiser (2015) propose that a **crop insurance programme** may be more sustainable. Growers would be able to purchase insurance to provide financial compensation when pests cause yield loss.

1.2.4.2. Biological control

- *Identify potential biological control agents*

HGCA (2014) describe parasitic wasps and fungi as the foremost natural enemies. Natural fungal infections of click beetle populations have been reported at high rates. Keller (1994) suggested that an epizootic of *Zoophthora elateridaiphaga* Turian (Zygomycetes: Entomophthorales) was an important mortality factor of click beetles.

Little is known about wireworm predation. HGCA (2014) confirm that carabids attack *Agriotes* spp. larvae, and that birds consume the adults. Larval stiletto flies (Diptera: Therevidae) are active predators of many immature coleopteran species, and have been known to attack wireworms (van Herk et al., 2015), particularly in loamy soil, where therevid larvae can move exceptionally quickly (Stubbs and Drake, 2001).

- *Evidence of biological control directly impacting the pest*

Novel observations in a North American study by van Herk et al. (2015) found that in laboratory conditions, therevid larvae predated wireworms. Though the study dealt with very few interactions, *Thereva nobilitata* Fabricius (UK present) was found to consume *A. obscurus* larvae, and therefore act as a biological control agent. Very little is known about the ecology and life history of British Therevidae, however, a report by (Hewitt and Parker, 2008) revealed that **therevid larvae** (*Cliorismia rustica* Panzer) were present in May and July, highlighting that the larval stage co-occurs when newly emerged *Agriotes* spp. larvae have hatched (HGCA, 2014). Therefore, they may be beneficial pest control agents during the most sensitive wireworm life stage, particularly as smaller therevid larvae appear to consume more prey before pupation (van Herk et al., 2015), The therevid of interest in van Herk et al. (2015) is known to inhabit wetland habitats, but knowledge of its larval stage may importantly be mirrored by other therevids. More research into therevid oviposition habitats might reveal whether therivids are likely to occur in-field, and therefore act as potential biological control agents.

Two entomopathogenic nematodes, namely *Heterorhabditis bacteriophora* Poinar and *Steinermema feltiae*, with the former being more pathogenic to *Agriotes lineatus* under laboratory conditions (Rahatkhah et al., 2015). *Heterorhabditis* spp. and *Steinermema feltiae* have both been recorded in wireworm species (Peters, 1996). Kovacs et al. (1980) even showed that *Heterorhabditis* spp. and *Steinermema* spp. reduced damage significantly in corn. In this way, there is potential to use subterranean pathogens to control wireworms. Though Rahatkhah et al. (2015) do reiterate that the soil is a hard environment to exert biological control on a pest.

- *Evidence that a certain habitat and/or management practice improves actual biological control*

In areas that have been found to be highly infested with wireworms, there are options for wireworm control besides synthetic chemical application. HGCA (2014) report that some strains of the **entomopathogenic fungus**, *Metarhizium anisopliae*, have shown encouraging results against wireworms under experimental conditions. Similarly, Kabaluk et al. (2005) reported that *Metarhizium brunneum* Petch (Hypocreales: Clavicipitaceae) conidia caused 100 % virulence in *A. obscurus* and *A. lineatus* in laboratory conditions using the LRC112 genotype. A later North American field study found that mortality in *A. obscurus* occurred due application and subsequent infection of *M. brunneum* LRC112. Notably higher mortalities were caused by conidia in spray rather than by dust application. The authors postulated that in an aqueous solution, the conidia could have been carried into crevices of the beetle bodies, adhered, and escaped the effects of rainfall. The dust treatment however was assumed to have washed off much more easily. Rainfall may be a crucial factor in wider application of the entomopathogenic fungus, as losses of conidia were attributed to heavy rainfall even after 35 hours post-application. This highlights that conidia application should be avoided if heavy rainfall is scheduled within two days of the application.

Direct contact was assumed to be a major route of infection, however, Kabaluk (2014) were uncertain of the extent of secondary contact in causing infection, for example, transmission from grass to beetle. As **conidia** was found to remain viable on the beetle bodies, the authors suggested that there may even be opportunity for horizontal transmission of infection (beetle-to-beetle).. In light of the mortality found by **spray-applied** conidia found by Kabaluk (2014) that entomopathogens can incur longer term infections to click beetles, and that horizontal infection transmission may occur, population growth may be reduced considerably by using entomopathogens. The authors finally advise that taking into account of the larval life stage within soil, applications would need to be administered over a course of 3-5 years.

1.2.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

According to Furlan (2005) crop rotation, food resources, climatic and agronomic conditions (organic matter content predominantly), and other soil characteristics are the most important variables that effect *Agriotes* spp. larval population densities. Any rotation with predominant winter cropping is at high risk, especially if the winter crops have a high degree of grass weeds (HGCA, 2014). Rotation and correct crop allocation may suffice to reduce economic crop damage without necessarily needing to use a specific control tool (Furlan et al., 2011). European data supports this, labelling that **crop rotation** is the most influential factor for affecting wireworm populations (Furlan et al., 2000). *Agriotes* spp. populations can overwinter as adults, and thus any modification of crop rotations may disrupt population dynamics. At present, pest populations may be benefit from meadows and the use of double cropping in the rotation cycle. Furlan and Toffanin (1996) generally advise that non- or low-sensitive crops (such as soybean) can be planted in infested fields (identified by methods from

Section 2.6.3). Oilseed rape and vegetable brassicas may also serve well in infested fields. Any remaining un-infested fields can then be sown with more sensitive crops (Furlan and Toffanin, 1996). Aspect and topographical factors may also be influential, as south-facing sloping fields, with heavy alluvial soils are of increased risk to wireworm damage (HGCA, 2014), and therefore, sowing wireworm-sensitive crops should be avoided in these areas.

Soil management can also be vital for wireworm control. Reduced- or zero-tillage may also increase wireworm damage in a susceptible crop (HGCA, 2014). Although there will be a trade-off with other key service provisions, soil tillage during the most critical stage of *Agriotes* spp. development (when eggs are laid and first-instar larvae are present in the soil), may also reduce wireworm populations (Furlan, 2004). For the present UK species (*A. lineatus* L., *A. obscurus* L., and *A. sputator* L.), this sensitive period would be between May and June (HGCA, 2014). This would require a very early harvest for many common crops. However, for crops such as potatoes, the HGCA (2014) advise that although potatoes should be avoided entirely if wireworm risk is great (alteration of rotation – see above), if potatoes *are* planted and damage is suspected, early lifting can reduce the degree of damage (HGCA, 2014). Therefore, first early-lifted potatoes, followed by ploughing in June could disrupt wireworm population dynamics. This tillage timing should be modulated to accommodate for the *Agriotes* spp. present (Furlan and Kreutzweiser, 2015). For example, irrigating after the period when the present *Agriotes* spp. are laying eggs, will help the upper soil horizons dry, which is detrimental to egg development (Furlan, 2004).

Kozina et al. (2015) investigated edaphic and climatic factors, alongside cropping history, and how these variables effected *Agriotes* spp. abundance within different Croatian geographic regions. The study highlighted the variation in population response of different *Agriotes* spp. to differing environmental conditions. The predicted population responses may be very different however on British soil. However, if a particular species is particularly abundant in a locality, predictors of wireworm abundance by Kozina et al. (2015) could be used as a loose guide, with **management tailored** to the most problematic *Agriotes* species. It is rather unlikely that resources and priorities will allow for wireworm identification to species level for most landowners. Due to this, Kozina et al. (2015) found that in general across all measured species, soil humus content and pH (measured in KCl) were the best predictors of click beetle abundance. The highest densities of certain species can be expected when soil humus content >3.3 %, and when soil pH (measured in KCl) is very acidic to moderately acidic. For more specific control methods, Kozina et al. (2015) predicted that the variables found in Table 1.2.4.3.1 would yield the lowest population densities of *Agriotes* spp, along with accompanying evidence.

Table 1.2.4.3.1. Important factors that are influential for *Agriotes* spp. population densities

Wireworm spp.	Variables that favour population growth	Variables that yield the lowest population densities
A. brevis L. (UK presence unknown)	More readily in wet soils that were rich in humus[1].	The *current* crop was sugar beet, barley or oats and the mean air temperature >11.45 °C (of study periods)[2].
A. lineatus L. (known presence in Britain)	A high soil humus content (>4.65 %)[2]. The *preceding* wheatcrop was found to be a predictor of abundance[2], as well as barley and lucerne which act as attractants for oviposition[3]. The *current* crop was wheat or sugar beet[2].	The *preceding* crop was corn, barley, soy, or oats and the mean air temperature <11.45 °C (of study periods)[2].
A. obscurus L. (known presence in Britain)	Preferred soils in which lucerne or white clover were grown[3].	The soil pH (measured in KCl) was <7.23 (neutral-acid)[2].
A. sputator L. (known presence in Britain)	Total rainfall <740 mm (during study periods)[2].	The *current* crop was white clover, lucerne, sugar beet, or barley, in combination with total rainfall >740 mm (during study periods), densities would be lower but nonetheless high[2,3,4].
A. ustulatus Schall. (UK presence unknown)	Soil pH <7.0 (neutral-acid) and soil humus content >3.3 %[2].	None strictly given

[1] Tóth (1984) [2] Kozina et al. (2015) [3] Štrbac (1983) [4] Čamprag (1997)

This aligns with guidance by the HGCA (2014) which state that crops that have been sown within two years of ploughing out permanent pasture is at the highest risk of damage (HGCA, 2014). It would be expected that newly converted land (that was once pasture) would be higher in organic matter, and thus, more susceptible to *A. lineatus* damage. *A. ustulatus* was also predicted to be greater in densities with humic matter >3.3 %.

There may be cases where avoidance of planting sensitive crops within infested fields is not feasible. If this is the case, there are alternatives options, such as the use of trap crops. Vernon et al. (2000) demonstrated that wheat acts as an effective **trap crop** within strawberry fields, when planted one week in advance to the strawberry crop. In contrast, Landl and Glauninger (2013) found that wheat and oilseed radish failed to attract wireworms away from the potato maincrop, but peas as trap crops were more attractive than the potato maincrop. As pea attractiveness diminished over time (Griffiths, 1974), Landl and Glauninger (2013) suggested that after initially being attracted to the pea plants, the larvae then returned back to the potato tubers, which would explain the higher density of wireworm found in the potato intercropped with peas at harvest, than with the other trap crops.

The authors proposed that re-sowing peas approximately two weeks prior to potato harvest would ensure pea attractiveness to wireworms, preventing migration of larvae back to the tubers, which will have stopped emitting CO_2. This is of importance as wireworms are attracted to CO_2 emitted by roots (Doane et al., 1975). In terms of row spacing, the potato rows 1.5 m away from the pea trap crop harboured 2.4 times less wireworms than those spaced 0.75 m from the peas (Landl and Glauninger, 2013). Besides the pest control benefit derived from using peas as potential trap crops, as a cover crop, they also offer a considerable amount of other soil benefits. As already explored, cover crops may not perturb wireworm population growth as well as fallow land or sowing with non-sensitive crops.

Staudacher et al. (2013) support literature that acknowledges trap cropping as an effective means of control against wireworms. Staudacher et al. (2013) displayed that increasing the non-crop plant diversity reduces damage in maincrop maize. Crucially, this can improve the maize yield. Compared to the monoculture treatment, the single and **mixed trap crop** improved the maize yield by 30% and 38% respectively. The mixture of associated trap crops provided season-wide protection and an enhanced 'attraction and retaining effect' than the single trap crop plant treatment (Staudacher et al., 2013), which agrees with the multiple trap cropping hypothesis (Shelton and Badenes-Perez, 2006). In the single trap crop treatment of Staudacher et al. (2013), the wheat withered by September, and no longer provided an adequate food source to the wireworms, thus resulting in a late season remigration and consumption of wheat. The plant mixture however provided an extended attraction effect. In August, buckwheat and wheat were preferred, and beans in September. Contrary to Vernon et al. (2000) (see above), Staudacher et al. (2013) demonstrated that trap cropping can also be practical, as their trap crop mixture could be planted at the same time as the maincrop maize. Akin to Schallhart et al. (2012), Staudacher et al. (2013) demonstrated that wireworms actively choose between plant species when several food item options were present within their foraging range. The results are support the trap crop hypothesis (Vandermeer, 1989) which predicts that the trap crop assemblage act as a pest attractant, but the possibility that the trap crops may also have masked (Tahvanainen and Root, 1972) or altered (Finch and Collier, 2000) the odour of the maize roots to the pest cannot be overlooked.

There is an air of concern relating to enhancement of plant diversity. Could the improved resource base for pests be a **detrimental management strategy?** Staudacher et al. (2013) rejected these concerns by suggesting that *Agriotes* spp. larvae are not usually limited by food in arable fields (Schallhart et al., 2011) and therefore the introduction of non-crop plants is unlikely to increase larval survival by increasing food supply. Similarly, as *Agriotes* spp. females prefer to oviposit in dense grass-clover vegetation, it was concluded that it was unlikely that their diversified treatment would also increase the egg load (Staudacher et al., 2013). Finally, as maize yields were increased in the diversified plant treatment compared to the maize monoculture (Staudacher et al., 2013), competition between plant species is not likely to reduce crop yield as found in other studies (Ratnadass et al., 2012). In any case, the attraction to the trap crop assemblage may allow for the sowing of sensitive crops in fields known to be infested with wireworms, if absolutely necessary.

Lethal trap-cropping was also suggested as a possibility by Staudacher et al. (2013), which is more sustainable than traditional insecticidal treatment methods as trap crops can be treated precisely in-field, to control any population outbreaks. At this point, the field could be left bare or sown with an unattractive crop, such as oilseed rape, to prevent further wireworm population growth.

If the planting of sensitive crops in an infested field cannot be avoided, there are other potential options, aside from chemical control. **Biocidal** plants and seed meals are the only practical options (Furlan et al., 2010) have been accurately assessed under controlled conditions (Furlan and Toffanin,

1996) and their control potential is comparable to that of neonicotinoids and additional insecticides (Ferro and Furlan, 2012) Biocidal compounds occur naturally as products of secondary plant metabolism (D'Addabbo et al., 2014). Their effect is best harnessed when attempting to interfere with sensitive pest life stages, rather than just application before or during sowing (Furlan et al., 2010).

Pheromone trapping is useful in monitoring adult and predicting larval *Agriotes* spp. outbreaks, however, few researchers have attempted to explore **mass trapping** as a control strategy. One such study by Sufyan et al. (2013) concluded that mass trapping did not reduce larval populations. Vernon et al. (2014) argue that the higher trap density mass trapping within non-farmed habitats may reduce wireworm populations more extensively. Vernon et al. (2014) deployed individual species (*A. obscurus* and *A. lineatus*) pheromone traps 3 m apart, along two parallel rows 3 m apart, and achieved ≥78 % recapture of marked male adults, 7-8 days after release (of marked adults). Indeed, the study demonstrates that pheromone trapping might be a useful strategy for removing males from the population, and that the traps can be spaced close together (2 m) without reducing the capture specificity of either. However, the effectiveness is in doubt as the removal rate of males was not 100 %, potentially allowing for male mating, especially if the male *Agriotes* spp. of interest are copulate more than once. Vernon et al. (2014) suggest that more research is needed to pinpoint the optimal trap spacing before this can be used as an effective method for wireworm control.

1.2.5. Outlook

Table 1.2.5.1. A summarising table of management implications to control wireworms in a sustainable manner.

Chemical control
• Many studies demonstrate that neonicotinoid treatment against wireworm yields no significant differences in crop stands that are untreated (Ferro and Furlan, 2012; Furlan et al., 2011), and are thus not necessary.
Biological control
• Encourage parasitoid wasps and larvae-predating birds (HGCA, 2014). • Encourage stiletto flies which have been shown to predate larvae in the soil (van Herk et al., 2015). • Spray-applied fungal spores to small-scale fields may provide feasible terrestrial control, but only when heavy rainfall is not forecast for two days after application (Kabaluk, 2014).
Cultural control
• Modify crop rotation: o Use non-sensitive crops such as soybean, OSR, and vegetable brassicas in infested fields (Furlan and Toffanin, 1996). o Use sensitive crops (all others) in non-infested fields (Furlan and Toffanin, 1996). o Use non-sensitive crops on south-facing slopes with heavy alluvial soils (HGCA, 2014). • Reduced-tillage may also increase wireworm damage in a susceptible crop (HGCA, 2014). • Entirely avoid **potatoes** if wireworm risk is high, and if damage is suspected, lift early (HGCA, 2014). If lifted, ploughing in June could disrupt pest populations drastically. • Avoid sensitive crops in fields that have high humus content, and are moderately to very acidic (Kozina et al., 2015). See Table 1.2.4.3.1 for greater detail on factors that influence specific wireworm species. • For maincrop **potatoes**, use peas as trap intercrops (1.5 m from potato rows), but re-sow the peas around two weeks before potato harvest, to prevent wireworm re-migration to potato rows (Landl and Glauninger, 2013). • Use a mixed trap crop to improve **maize** yield (and possibly of other sensitive crops), sown at the same time, including buckwheat, wheat, and beans ensure continuous attraction when one trap crop senesces (Staudacher et al., 2013). • Apply biocidal compounds and plant meals during sensitive life stages (May-Jun) (Furlan et al., 2010).

1.3. Orange wheat blossom midge (*Sitodiplosis mosellana*)

1.3.1. Introduction & life history

Larvae of the orange wheat blossom midge (OWBM), *Sitodiplosis mosellana* Gehin (Diptera: Cecidomyiidae), is a cause damage to developing seeds by feeding, resulting in small, shrivelled grains with poor germination rates. Damage to the pericarp (outer layer of the grain) provides access for water entry, and also facilitates the potential for secondary attack. Secondary fungal attack affects the grain quality and yield when harvested (HGCA, 2014). Larval OWBM can survive within the soil for a decade or more, after sheltering in constructed cocoons, though only pose a major threat for up to four years. Annually larvae will overwinter in this cocoon stage (Sep-Apr) before emergence, and migration towards the soil surface. If the soil is >13 °C and is moist, the larvae will pupate (May). Otherwise, they will return to their cocoon stage. Upon emergence from pupation, adults will rest at the base of the crop during the day, and lay eggs in the florets from dusk onwards (Jun). These eggs will hatch within 4-10 days, and the emerged larvae will feed on the developing grain for about two weeks, but those that have hatched after flowering cause little damage, and do not fully develop (Jun-Aug). When fully developed, larvae will drop to the soil surface, and burrow into the soil to overwinter (Jul-Aug) (HGCA, 2014).

1.3.2. Damage/presence

Any wheat fields that have been grown consecutively over a four year period are potentially at risk from OWBM damage. The larvae require warm and moist soil for pupation, and therefore, are often successful after heavy rainfall events. Adult midges will take to wing when temperatures >15 °C, though when temperatures are high accompanied with a lot of sunshine, flight will occur later in the evening (HGCA, 2014).

1.3.3. Pest thresholds

HGCA (2014) advise that crops should be monitored from the start of the ear emergence (GS53-59). Pheromone traps act as the earliest warning mechanism for OWBM activity, and so when set at crop height during GS45-GS61.Two pheromone traps in each field which has been subjected to damaging levels of OWBM in the previous two years, even if the current crop is not a cereal. Visual inspection by counting the midges around GS45 is best done in the mid-evening when the midges are more easily spread. Alternatively, yellow sticky traps can be hung at ear height around GS45, whilst spider webs act very similarly.

Table 1.3.3.1. Thresholds for control of OWBM via various monitoring techniques (HGCA, 2014). Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Trapping technique	Thresholds	Risk	Proposed action
Pheromone trap	>30 midges	General risk in the next week	Crops should be monitored for females
	>120 midges	Very high risk.	Treat wheat crops in surrounding fields at susceptible growth stages (GS53-59) as soon as possible
Visual inspection	1 midge per 3 ears for *feed crop*	>5 larvae per trap	na
	1 midge per 6 ears for *milling* and *seed crops*		
Sticky traps	10 midges per trap	Significant risk	na

1.3.4. Potential for control

1.3.4.1. Chemical control

If an insecticide treatment is required, when other options have failed, Chavalle et al. (2015) highlights the importance of careful application timing, in order to conserve the natural enemies of pests, as broad-spectrum insecticides also greatly effect parasitoid wasps (see Section 1.3.4.1). As *Macroglens* (syn. *Pirene*) *penetrans* Kirby (Hymenoptera: Platygastridae) emerges five days after *S mosellana* adults emerge, an early insecticide treatment will reduce the exposure of the parasitoid to the insecticide. This integrated technique will require careful monitoring of the pest. For more information on monitoring, please refer to (HGCA, 2014).

1.3.4.2. Biological control

Although the OWBM is attacked by various generalist predators, the most important natural enemy is suggested to be *M. penetrans* (Chavalle et al., 2015), a **parasitoid** that is able to achieve parasitism levels >80 %, and so is considered to be a highly useful biological control agent (HGCA, 2014). *M. macroglens* targets *S. mosellana* eggs and pupae (Doane et al., 1989), and has been recorded in the UK, and is believed to contribute to 31.5 % of *S. mosellana* in Saskatchewan, Canada (Olfert et al., 2009).

1.3.4.3. Cultural control

Reducing the frequency of the wheat crops in the rotation can also facilitate the reduction of midges (HGCA, 2014). It is known that growing resistant varieties is a very effective way of minimising damage risk from OWBM (HGCA, 2014). For more information on resistant varieties, please see the HGCA Recommended List. However, Smith et al. (2004) argued that a **resistant** crop would have a considerable impact on parasitoid (e.g. *M. penetrans*) populations, as their hosts will be greatly reduced. To combat this, Smith et al. (2004) suggested that the use of resistant wheat, which inhibits the larval development and oviposition of *S. mosellana*, combined with a 5 % susceptible refuge, provided effective control of damage, *and* provided for parasitoid populations. This is crucial for future bio-security, and the reduction of the chances of future pest outbreaks.

Soil cultivation may be important if *S. mosellana* was a problem in the previous season. In a Chinese study, Zhang et al. (2012) found that *S. mosellana* larvae benefited from reduced tillage practices, and therefore, soil cultivation may reduce pest emergence. However, the authors also found that in fields where rotary tillage was practiced, damage to cereals were more severe when flood irrigation had been practiced. Therefore, it is crucial to keep in mind that although tillage may reduce emergence, it may also benefit pest emergence if combined with very wet conditions.

1.3.5. Outlook

Table 1.3.5.1. A summarising table of management implications to control the orange wheat blossom midge in a sustainable manner.

Chemical control
• When insecticide treatment is required, early treatment would reduce the exposure of pesticides to parasitoid wasps, which emerge about 5 days later than pest adults (Chavalle et al., 2015).
Biological control
• Encourage parasitoid wasps.
Cultural control
• Interspersing resistant wheat with 5% of susceptible wheat will protect the resistant gene from becoming overcome by virulent pests, and will preserve parasitoid populations, for efficient control (Smith et al., 2004). • If pest has been a problem in the previous season, soil cultivation may be deleterious to overwintering larvae, if conditions are dry when cultivating (Zhang et al., 2012).

1.4. Wheat bulb fly (*Delia coarctata*)

1.4.1. Introduction & life history

The wheat bulb fly, *Delia coarctata* Fallén (Diptera: Anthomyiidae) is one of the most important yet sporadic pest within UK wheat production, though all cereals apart from oats are attacked. The wheat bulb fly overwinters as an egg (Sep-Dec) on bare soil such as fallows, set-aside, or early harvested crops such as vining peas, where cultivation occurs between mid-July and mid-August. The larvae will hatch and invade the roots of wheat, barley, and rye (Jan-Mar), and will later attack 3-5 further shoots (Mar-Apr), until pupation at the base of the cereal (May). The adult flies emerge over the summer (Jun-Aug) and feed on saprophytic fungi on the host plant, until eggs are laid on bare soil and between row crops (Aug). Eggs laying is not just restricted to cereal areas, as oviposition will occur between potatoes, sugar beet, and celery and onions (HGCA, 2014).

1.4.2. Damage/presence

Depending on the tiller density at the time of the attack, the yield loss can vary hugely. In February, crops at the single shoot stage are most susceptible, and damage can lead to complete crop failure. In comparison, in a well tillered crop, 100 larvae/m^2 can be tolerated by the crop, and have absolutely no impact on the crop yield. Spring wheat and barley are at risk if sown before March, but are rarely impacted if sown later (HGCA, 2014).

1.4.3. Pest thresholds

For more information regarding the monitoring of wheat bulb fly eggs, please refer to (HGCA, 2014) and www.hgca.com/pests, to see which regions and their important rotations that have reached threshold levels. Upon monitoring, the economic thresholds by HGCA (2014) (see below), may be of use for developing a sustainable management strategy.

Table 1.4.3.1. Thresholds for control of wheat bulb fly via egg monitoring of soil samples (HGCA, 2014). Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Threshold	Action
< 100 eggs/m^2	Seed treatment justified in spring-sown cereals.
100-249 eggs/m^2	Seed treatment justified in late-sown and spring-sown cereals.
250-500 eggs/m^2	Seed treatment justified in late-sown and spring-sown cereals and an egg-hatch spray may be justified.
> 500 eggs/m^2	Egg-hatch spray justified in early-sown cereals and a seed treatment and egg hatch spray justified in late-sown and spring-sown cereals.

1.4.4. Potential for control

1.4.4.1. Biological control

In a study in southern England, *D. coarctata* pupae were destroyed by both **predators and parasites** (Ryan, 1975). In the study, predators contributed to a greater proportion of mortality in a natural setting (27-34 % pupae destroyed), though this was considerably greater in microcosms. It is thought that *D. coarctata* is most vulnerable when in the egg and pupal stage, and the carabid, *Agonum* *dorsale* was shown to target both life stages. Larger carabids, such as *Pterostichus* spp. were not found to consume pest eggs (Ryan, 1973), but would target the pupae when presented, probably due to the larger size of the pupae (Ryan, 1975). The contribution of parasitoids, such as *Trichopria* sp. (Hymenoptera: Diapriidae), and the rove beetle, *Aleochara bipustulata* Linnaeus (Coleoptera: Staphylinidae) were small (0.5-5.8 % pupal mortality), but underlines the importance of parasitoids in the regulation of *D. coarctata* (Ryan, 1975). In a German study, Roloff and Wetzel (1989) found that *A. bipustulata* and *A. laevigata* contributed to parasitism of 9.6 and 18.2 % of *D. coarctata* pupae in wheat over two years, with a maximum level of parasitism of 48.5 %. Some predatory flies may also be important in the regulation of the wheat bulb fly (Bardner and Kenten, 1957).

Entomopathogenic fungi has also been regarded as a potentially important *D. coarctata* regulator. Jones et al. (1972) for example recorded that 40 % of *D. coarctata* caught in 1971 were infected with *Empusa* (syn. *Entomophthora*) *muscae*, although mortality was not caused in these flies. Wilding and Lauckner (1974) also concluded that despite fungal exposure, *D. coarctata* was still able to successfully breed and lay a considerable amount of eggs, and thus failed to prevent the population from increasing.

1.4.4.2. Cultural control

Bare soil is an important factor in the control of *D. coarctata*, as the pest will preferentially lay on soil with no cover (HGCA, 2014). To prevent egg laying in the summer on bare fallow, HGCA (2014) advise suggest ensuring that mustard is established by mid-July. High populations of *D. coarctata* were found in cultivated fields, likely due to the fact that the pest flies prefer to oviposit on freshly worked soil (Oakley and Uncles, 1977). In this way, it is important that soil is **not cultivated** between late July and early August, which is *D. coarctata* peak egg laying period, particularly in high risk areas, as *D. coarctata* rarely migrate more than 0.8 km (Oakley and Uncles, 1977). Additional cultural approaches approaches have also been postulated by HGCA (2014), suggesting that crops can compensate for the attacks by *D. coarctata* if they are sown early, and at an increased seed rate. Similarly, it has been suggested that for spring cereals, it is imperative to sow before March to reduce any potential damage from hatched larvae (HGCA, 2014).

1.4.5. Outlook

Table 1.4.5.1. A summarising table of management implications to control the wheat bulb fly in a sustainable manner.

Biological control
• Encourage fungal parasites, which have been regarded as important pest regulators (Wilding and Lauckner, 1974). • Encourage predatory flies (Bardner and Kenten, 1957). • Encourage carabids, which may provide useful regulation of pest eggs and pupae (Ryan, 1975) • Encourage rove beetles, which can achieve almost 50 % parasitism in some cases (Roloff and Wetzel, 1989).
Cultural control
• Egg laying (Aug) can be reduced by not cultivating from late July to early August, as egg laying is preferred on freshly cultivated fields (Oakley and Uncles, 1977). • On **bare fallow**, sowing with mustard cover by mid-July will reduce egg laying (HGCA, 2014). • Sow **spring cereals** before March to reduce damage from hatched larvae, with increased seed rate will allow the crop to compensate for attacks (HGCA, 2014).

1.5. Frit fly (*Oscinella frit*)

1.5.1. Introduction & life history

Three generations of frit fly, *Oscinella fit* Linnaeus (Diptera: Chloropidae), occur every year, with the first causing most damage to winter cereals, grasses, maize, and late-sown spring oats. The larvae cause direct damage, as they feed slowly in the shoots of cereals and grasses (Oct-Apr), and eventually the first generation of adults emerge, and lay eggs onto grasses and young cereals (May-Jun). During the same period (May-Jun), the larvae burrow into the central shoot of young cereals, and later (Jul), the second generation of adults emerge and lay eggs beneath oak husks and grasses. The larvae then hatch and consume the oat kernels (Jul-Aug). The third generation of adults then oviposit onto grasses in stubble and early winter cereals (Aug-Sep) (HGCA, 2014)

1.5.2. Damage/presence

Cereal damage susceptibility is greatest up to the four-leaf stage. Winter crops or spring crops that have been delayed are most at risk, or in crops immediately following a grass lay or in grassland-rich areas (HGCA, 2014).

1.5.3. Pest thresholds

To assess the risk before winter cereal sowing, HGCA (2014) recommend sampling the grass or stubble for frit fly eggs. Just as importantly, HGCA (2014) then recommend that plants should be examined after full emergence, and treatment would be required when 10% frit fly damage has been observed.

1.5.4. Potential for control

1.5.4.1. Chemical control

It has been suggested that because *O. frit* populations vary little between years, it can be assumed that the spring population sizes can be predicted from the populations of the previous autumn (Lindblad, 1999). As a result, appropriate control strategies can be designed to mitigate against any potential damage in high risk areas. If the later sowing of winter rye (before the middle of August) cannot be avoided (see Section 2.5.4.2.), some suggest that the crop should be secured with an insecticide (Huusela-Veistola et al., 2006).

1.5.4.2. Biological control

Lindblad (1999) explains that there are two predominant reasons for mortality in *O. frit*. The first of these factors are due to overwintering losses, probably a function of host plant death, colder conditions, and disease. The second factor is thought to be due to parasitism, as *O. frit* larvae are attacked by **parasitoid wasps** in the autumn (Nielsen, 1994; B. P. A. Umoru, 1993). Parasitism rates can be as high as 75 %. In Swedish samples, Lindblad (1999) found that parasitism did not vary much between the sampling years, although considerably more oscinellid flies were found to be parasitized in ryegrass plots (37 %) than in pastures (14 %). The predominant parasitoid found was *Rhoptromeris heptoma* Hartig (Hymenoptera: Figitidae) which has been recorded in the UK (Lindblad, 1999).

Nielsen (1994) made note of a particular association between *O. frit*, the grass known as red fescue (*Festuca rubra* Linnaeus), and a parasitoid, *Rhoptromeris heptoma* Hartig (Hymenoptera: Figitidae) in Danish farmland. The study summarised that as **grassy field borders** and other unploughed areas may harbour parasitoids such as *R. heptoma* and *Chasmodon apterus* Nees (Hymenoptera: Braconidae), then greater pest control could be exhibited, particularly if these bounderies contain red fescue (Nielsen, 1994). Aside from parasitoids, staphylinid beetles have also beenr regarded as useful biological control agents, as well as epigeal predators including spiders, carabid beetles, and predatory flies (HGCA, 2014).

1.5.4.3. Cultural control

Although HGCA (2014) advise that *O. frit* is most damaging to spring oats and late-sown cereals after grass, there is some evidence that suggests otherwise. In a Finnish study, Huusela-Veistola et al. (2006) found that the **postponement** of winter rye sowing, two weeks later than recommended (in late August), resulted in considerably less damage and allowed for the optimal establishment of crop stands, and was suggested as a useful cultural technique for other winter cereals (Fidler and Webley, 1960). For winter cereal crops in general, HGCA (2014) advise that it is best to avoid winter cereal cropping directly following grass leys, or in areas of dense grassland. If this cannot be avoided, any remaining grass should be **ploughed** in and left for four weeks before cereal sowing to allow the pests to die. This however conflicts with a suggestion by Umoru (1993), who found that double ploughing of grassland reduced populations of the parasitoid, *C. apterus* which is known to parasitize *O. frit*. Although this suggestion, echoed by Moore et al. (1986), relates more to grassland management, it could have important implaications for cereal rotations. Leaving more permanent grassland **undisturbed** should allow for stable parasitoid populations, whilst careful monitoring of *O. frit* in grass leys should indicate weather ploughing and a four week ‘starvation’ period (suggested by HGCA (2014), is necessary.

Later-sown spring crops however are much more likely to be delayed in their crop growth, and therefore more likely to be susceptible to attack by *O. frit*. Due to this, it is advised that spring oats are **sown early** to avoid damage (HGCA, 2014). Other techniques such as rolling, will enhance the establishment and growth of the cereal crop, and thereby reduce the susceptibility to *O. frit* (HGCA, 2014).

1.5.5. Outlook

Table 1.5.5.1. A summarising table of management implications to control the frit fly in a sustainable manner.

Chemical control

- If rye has to be sown early (before mid-Aug), secure with insecticide (Huusela-Veistola et al., 2006).

Biological control

- Promote wild grass margins, particularly with red fescue (Nielsen, 1994), to encourage parasitoid wasps, which can cause high mortality of overwintering pest generation (Lindblad, 1999).
- Encourage spiders, carabids, rove beetles, and predatory flies.

Cultural control

- Pest population size can be predicted based on estimates made in the previous autumn (Lindblad, 1999), and thus warrant cultural control strategies.
- Avoid winter cereals directly after grass leys, or in areas of dense grassland (HGCA, 2014).
- For winter cereals, plough any grass and leave for at least four weeks before sowing, to allow pests to die (HGCA, 2014).
- **Rye** sown two weeks after the recommended sowing date yields less pest damage (Huusela-Veistola et al., 2006) and for other cereals (Fidler and Webley, 1960).
- Sow **spring oats** early to avoid attacks (HGCA, 2014).
- Crop husbandry such as rolling, which enhances establishment and growth will minimise pest damage (HGCA, 2014).
- In **grassland**, reduced soil cultivation should be utilized to avoid parasitoid wasp mortalities (Umoru, 1993).

1.6. Leatherjackets (*Tipula* spp.)

1.6.1. Introduction & life history

Leatherjackets are the larvae of crane flies (or daddy long-legs), and are soil-inhabiting pests that mainly consume the roots and underground sections of the stem on a number of crops, including cereals, oilseeds, peas, field beans, and sugar beet (HGCA, 2014). Two main species are responsible for UK leatherjacket damage, and are *Tipula paludosa* Meigen and *T. oleracea* Linnaeus (both Diptera: Tipulidae). Leatherjackets feed as long as the soil exceeds 0.5 °C (late-Sep-Feb), until the main larval feeding period (Mar-May). Pupation then occurs near the soil surface (May), and the adult crane flies then emerge and lay eggs (Aug-Sep), with the larvae hatching in September (HGCA, 2014).

1.6.2. Damage/presence

Leatherjackets are at their most numerous after damp periods during late summer and early autumn, however, dry weather in September can be deleterious to the eggs and early-instar leatherjackets. Generally, damage occurs frequently after a grass rotation, and the larvae continue feeding on ploughed down turf until this rots away, and the leatherjackets then move onto the new crop. Of these new crops, winter cereals, particularly late-sown cereals, can be attacked in autumn and during mild winters (when soil temperatures > 0.5 °C), though are less vulnerable once they have tillered. Seedlings of spring sown crops are most vulnerable in April and May, when the leatherjackets are at their latest instar, and most voracious in their feeding habits (HGCA, 2014).

1.6.3. Pest thresholds

For information regarding the monitoring of leatherjackets, please refer to HGCA (2014), and see below for thresholds for control. Perhaps the easiest monitoring method by HGCA (2014), is to scratch either side of the crop row.

Table 1.6.3.1. Thresholds for control of leatherjackets from several monitoring methods for spring cereals and oilseeds (HGCA, 2014). Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Crop	**Thresholds per technique**		
	Soil cores	**Plastic pipes**	**Scratching**
Spring cereals	50 larvae/m^2	5 larvae per 12 pipes	5 per meter of row
Oilseeds	> 50 larvae/m^2	> 5 larvae per 12 pipes	> 5 per meter or row

1.6.4. Potential for control

1.6.4.1. Chemical control

Although the control of leatherjackets via chemical insecticides have been labelled as ‘easy’, there have also been cases in which winter pesticide applications have been inconsistent (Blackshaw and Coll, 1996).

1.6.4.2. Biological control

Carabid beetles have been suggested as useful biological control agents of leatherjackets, as *Pterostichus melanarius* (Coleoptera: Carabidae) has been found to reduce soil-dwelling *Tipula* spp. larvae in a laboratory setting (Chapman, 1994). It was found that the main activity period for *P. melanarius* was August, most of the beetles would have already emerged and fed in the spring

(May), towards the latter end of the *Tipula* spp. larval main feeding period (Mar-May) (Chapman, 1994). As *P. melanarius* peak feeding period coincided with the time at which *Tipula* spp. larvae approach pupation and become inactive, it is thought that much of the feeding damage would already have occurred (Chapman, 1994).

A parasitoid wasp, namely, *Anaphes* sp. (Hymenoptera: Mymaridae), has also attacked *Tipula* spp. eggs at a rate of 44% (Blackshaw unpublished data), and therefore may also offer considerable control. Birds (Barbash et al., 1991) and mammals including shrews, hedgehogs, and moles (Blackshaw and Coll, 1996) may also have a significant role to play in the reduction of leatherjackets. Although other forms of biological control have shown control potential, such as the use of predatory nematodes (Peters and Ehlers, 1994), the application costs have been shown as unsustainable at a large field scale compared to conventional control methods (Blackshaw and Coll, 1996).

1.6.4.3. Cultural control

Anecdotal evidence highlights the vulnerability of spring cereals to damage when sown into ploughed grassland (Blackshaw and Coll, 1999). To combat this damage, Blackshaw (1988) found that leatherjacket populations within spring barley rarely exceeded the economic threshold when there had been multiple **seedbed preparations** since grass was last sown. It has also been suggested that following grass, ploughing in early July and August before the main egg laying period will reduce the risk of future attack (HGCA, 2014). **Rotation modification** must also be an important consideration, particularly for winter cereals following OSR. As powerful dispersers, *Tipula* spp. adults can usually migrate well, dispersing from loocalised populations, however, under certain crops like OSR, the canopy can cause high populations under the OSR crop. This can lead to high populations in drilled cereal fields following OSR (Blackshaw and Coll, 1996), and therefore, monitoring of adults under rape canopies will be important to determining whether rotation modification is necessary.

Rolling the soil may also limit the amount of larval movement in conjunction with encouraging plant growth, and hence, reducing cereal damage (Blackshaw and Coll, 1996). It has also been suggested that rolling the soil in the summer, may restrict the emergence of *Tipula* spp. adults for four weeks by trapping the pupae under a soil cap, and thus reducing egg laying (Kell and Blackshaw, 1988). HGCA (2014) are in support of this technique, as they suggest thorough consolidation and a good tilth will allow the crop to grow away, if ploughing occurred later.

For other crops, such as vegetable brassicas, it is important to ensure that they are well established by mid-June, which is the major leatherjacket feeding period, to prevent any seedling damage (HGCA, 2014).

1.6.5. Outlook

Table 1.6.5.1. A summarising table of management implications to control leatherjackets in a sustainable manner.

Biological control
• Encourage carabid beetles, though most damage would have occurred before the main activity period for carabids (May) (Chapman, 1994). • Encourage parasitoid wasps that target leatherjacket eggs (Blackshaw unpublished data). • Encourage farmland bird populations (Barbash et al., 1991).
Cultural control
• Following grass in the rotation, minimise attacks by ploughing in July to early August, burying herbage, before the main egg laying period (HGCA, 2014). • Thorough consolidation and a good tilth will enable the crop to grow away if ploughing occurs later (HGCA, 2014). • The larvae of the main pest (*Tipula paludosa*) stop feeding by mid-June, so establishing crops later than this (e.g. vegetable brassicas) can prevent seedling damage (HGCA, 2014). • In **spring cereals**, two or more seedbed preparations after grass growth should prevent populations reaching the economic damage threshold (Blackshaw, 1988). • Consider rotation modification, as high populations can occur in drilled **winter cereals** as the OSR canopy prevents adult dispersal from OSR (Blackshaw and Coll, 1996). • Producing a soil cap by rolling may reduce pest emergence and egg laying (Kell and Blackshaw, 1988).

1.7. Minor pests within cereals

1.7.1. Gout fly (*Chlorops pumilionis*)

Chlorops pumilionis Bjerkander (Diptera: Chloropidae) is an occasional pest of UK cereal crops, including wheat, barley, and triticale, and can cause total crop failure in extreme circumstances (HGCA, 2014). With two generations of *C. pumilionis* per year (May-June and August-September), shoots damaged by the spring generation can cause a loss of 30 % grain yield, compared to 50 % in late-sown spring crops. HGCA (2014) advise that sowing winter wheat and barley after September will reduce any damage risk, if the fields are sheltered and in close proximity to woodland, which harbour the pest. To further minimise risk, HGCA (2014) also advise that spring crops should be sown as early as possible in high risk areas.

Two parasitoid species are associated with *C. pumilionis*, namely *Stenomalina micans* and *Coelinus niger*, but unfortunately, a report by Bryson et al. (2005) found that although *C. pumilionis* is now widespread throughout England, the parasitoid populations are relatively low. Therefore, at the time of the study, the parasitoids did not have a marked effect on *C. pumilionis* populations (Bryson et al., 2005). This does however highlight that *C. pumilionis* control by parasitoid communities does exist, and may be enhanced with better land management.

SECTION 2. Oilseed rape and other brassicas: biological control strategies

2.1. Slugs

2.1.1. Introduction & life history

In the UK, *Derocerus reticulatum* Müller (Mullusca: Limacidae) (grey field slug) has frequently been regarded as the principle slug pest of cereal crops (HGCA, 2014). Other species are also prominent, including *Arion intermedius* Normand (Bohan et al., 2000), *Arion hortensis* Férussac (southern garden slug), *Arion distinctus* Mabille (common garden slug) (AHDB, 2013), as well as other *Arion* species, and *Milax, Tandonia, and Boettgerilla* species (keeled slugs). Slugs can be active year-round if local conditions are suitable, and particularly when wet (HGCA, 2014). The grey field slug is one such slug that has been known to feed at temperatures as low as 0 °C (Mellanby, 1961) and therefore could pose a significant risk in lowland southern UK to agricultural and horticultural crops.

Although some slug species are self-fertile, all are hermaphrodite, and most mate before laying 10 to 50 eggs in sheltered cavities, plant bases, and around soil aggregates. Within several weeks, up to 500 eggs could be laid, which will develop slowly during the cooler winter months, but as spring temperatures rise, the majority will hatch producing many juveniles (AHDB, 2013). Slug reproduction and survival is hugely dependent on moisture and temperature (Carrick, 1942). Slug behaviour can vary between species, as some are more likely to be more mobile on the surface, whilst others below ground. If dehydrated, slugs will alter their behaviour by huddling or searching for shelter (cracks in soil, stones, leafy foliage) (Cook, 1981; Prior, 1989), and fundamentally crop damage will be alleviated (Shirley et al., 2001). Slug life cycles vary depending on the species, and particularly for events such as breeding and egg laying, this can be central for biological control measures, as highlighted by the life cycles of three separate pest species in Table 2.1.1.1 below.

Table 2.1.1.1. Life cycles of a few important pest species in the UK. It should be noted, the timing of life events may vary locally, as slugs are highly sensitive to climatic and food abundance variations.

Species	Hatching	Breeding
A. hortensis (**southern garden slug**)	Jan-Feb[1] and late spring[2]	Jul[1]-Aug[3]
D. heterocerus (syn. *Agrioclimax reticulatus*) (**grey field slug**)	All year - colder autumns increase egg mortality[1]	All year[1], but with peaks in Apr-May[3] and Aug[1]-Oct[3]. Food abundance encourages egg production[4], damp conditions encourage ovisosition[5]
Milax budapestensis Hazay (**Budapest slug**)	Autumn[1]	Autumn, with egg laying throughout Autumn and Winter[1]

[1](Bett, 1960), [2](AHDB, 2013), [3](HGCA, 2014), [4](Coe, 1944), [5](Carrick, 1939)

2.1.2. Damage/presence

Damage to plants can occur both above and below ground, and can result in a thin crop stand or more devastatingly, complete germination failure due to grain hollowing (Port and Port, 1986). Oilseed rape and cereal crops among others are vulnerable as seeds and seedlings.

Slugs are particularly damaging to **oilseed rape** (*Brassica napus* Linnaeus) (hereafter OSR) **seedlings**, perhaps more so than in cereals as the growing point of a germinating oilseed rape seed is above ground (AHDB, 2013), and therefore more accessible to slug attack. 'Double low' cultivars are generally most vulnerable to attack (than 'single low' cultivars) (Glen et al., 1990), as well as OSR plants before the fourth true leaf stage (AHDB, 2013). With respect to **cereals**, seeds can be attacked directly, when most of the damage occurs at or below the soil surface, where a single slug can potentially kill up to 50 seeds within a week of sowing (AHDB, 2013), by 'hollowing' the grain. Defoliation is also important with cereals, which are most vulnerable up to GS14 (four leaves unfolded), but can be vulnerable even at GS21 (one main shoot and one tiller) (AHDB, 2013).

Potatoes also suffer from slug damage, particularly during the early stage of tuber bulking. Small holes in the tuber's skin are exploited by the slug, which then enter and cause irregular-shaped cavities leading from the surface towards the tuber centre (AHDB, 2013). Some maincrop potato cultivars are more at risk than others, such as Maris Piper and King Edward (Gould, 1965; Winfield et al., 1967). For **higher value crops**, quality is also reduced close to harvest, and although the yield loss is minimal, the feeding damage can often render the crop as unmarketable or of insignificant value, such as in the case of strawberries or asparagus (Glen, 2002).

Although some terrestrial slug species pose no risk to agricultural production, and actively contribute to nutrient cycling and biological diversity (Theenhaus and Scheu, 1996), those species capable of considerable damage to arable and horticultural crops (Howlett, 2012) are thought to be a **growing problem**. Glen (2002) suggests that these agriculturally damaging species have been becoming ever more prominent, in relation to an expanding area of oilseed rape (provides abundant slug food and shelter), and a shift towards reduced- (or zero-) tillage systems (avoids soil disturbance). Some have reported that UK slugs cause £10 million damage (Garthwaite and Thomas, 1996), with an overall cost to the growing industry at £30 million (Redbond, 2003). In review of the damage to the UK **economy**, it is crucial to understand slug dynamics, and their relationship with their natural enemies and food plants so that biological control potential can be explored and fully exploited.

2.1.3. Pest thresholds

To ascertain whether a crop may potentially be infested with slugs in the future, HGCA (2014) describe measures to monitor slug activity. If the thresholds are exceeded, and if the management strategies discussed later in this section apply, then sustainable slug control strategies should be chosen. For more information on the monitoring of slugs, refer to HGCA (2014). The following thresholds represent a potential risk of crop damage when slug activity is favoured by soil and weather conditions.

Table 2.1.3.1. HGCA (2014) threshold table for treatment. Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Crop	**Control threshold**
OSR	Four slugs per trap in cereal crops (before harvest), or one slug per trap in cereal stubble.
Winter cereals	Four slugs per trap
Vegetables	No recommended thresholds
Other crops	One slug per trap

2.1.4. Potential for control

2.1.4.1. Chemical control

If chemical control is deemed necessary as a means to save a crop, then this should be done with a sound knowledge of the growing conditions. (Glen et al., 2006) found that although slug abundance was significantly reduced by conventional ploughing before drilling compared to zero-tillage with drilling, surviving slugs were likely to re-emerge at the soil surface between 10 days and 4 weeks. To test the variation in effective control using pellets, Glen et al. (2006) applied **molluscicide** before drilling (to stubble) and after, in winter wheat and oilseed rape. They therefore highlighted that if sufficient slugs survived ploughing, then they could potentially avoid contact with slug pellets, and damage emerging crops after pellets have ceased in their effective control. They therefore concluded that pellets applied to stubble before drilling in dry weather were more effective at crop protection than in wet conditions.

An individual-based simulation model developed by (Shirley et al., 2001) found that molluscicide applied in the summer months before harvest (when juvenile slugs are most abundant), did not give adequate control, presumably as environmental conditions induced sheltering behaviour. Slugs would therefore not come into contact with surface applied pellets. In comparison, control of slug populations was greater in September, following harvest, where conditions were suitable for slug activity. Crucially, egg production was restricted in the autumn population, removing the '**egg bank**', and therefore reducing slug hatching in the following spring. January application was negligible, as slugs were inactive and therefore unaffected by pellet application. Thus, the study highlights that if required, the application of slug pellets should only be post-harvest (for arable), when conditions favour slug activity.

Although it is advised to only apply pellets during the post-harvest **'window of opportunity'**, when conditions are suitable, it is imperative not to apply metaldehyde slug pellets when heavy rain is forecast. There is even evidence indicating that chemical control is **not especially effective**. Glen (2002) found that metaldehyde pellet application at drilling had a similar effect on slug populations as the untreated plot did. As metaldehyde is often found above the drinking water standard in raw water despite the Water Framework Directive (WFD), action will be taken resulting in regulatory restrictions or complete withdrawal (AHDB, 2013). In consideration of ineffective chemical control and environmental protection, sustainable stewardship options should be chosen (see below).

The use of **iron phosphate** (EDTA)-based molluscicide pellets are permissible for UK organic growers (when exceptional permission has been granted) (Soil Association, 2010) as it has a very low toxicity to mammals, and occurs naturally in strengite and metastrengite (Speiser and Kistler, 2002). Vitally, iron phosphate control has shown promising levels of control within a range of crops (Speiser and Kistler, 2002). Iron phosphate formulations have been seen as possessing a better pellet integrity (particularly in wet conditions), and has the potential for reduced repellent effects compared to other molluscicides (Wedgwood and Bailey, 1986). Recently, Capinera and Rodrigues (2015) highlighted that although iron phosphate baits allow continued slug survival, foliage consumption was immediately reduced, indicating that slug mortality should not be used as an assessment of efficiency. Rather, the reduction in crop damage should be used.

However, control by iron phosphate may have **deleterious** impacts on non-target fauna, such as those found by Langan and Shaw (2006). In this study, iron phosphate (Sluggo®) pellets reduced the survival and growth of the earthworm, *Lumbricus terrestris* Linnaeus, compared to the same exposure of metaldehyde pellets. Langan and Shaw (2006) applied the iron phosphate pellets at eight times the recommended field application rate, to ensure that earthworm contact occurred in the artificial arena. Edwards et al. (2009) reported a similar effect on earthworm populations (*Eisenia fetida* Savigny) in artificial conditions, where doses were five times the recommended rate. These observations are a cause for concern, as earthworms are integral for soil formation and functioning (Edwards, 2004). Gavin et al. (2012) provide one potential answer to this detrimental effect, as they found that earthworms showed little behavioural interest in granulated or liquid formulations compared to the rapid removal of pelleted baits.

2.1.4.2. Biological control

- *Identify potential biological control agents*

Perhaps the most studied potential natural enemy of slugs are families of Coleoptera, namely the **carabid family** (Coleoptera: Carabidae). Most carabids are polyphagous predators (will consume unrelated prey items), and are therefore generalist predators, but also opportunist (Bohan et al., 2000). In not restricting themselves on one or a few closely related prey species, they also consume non-molluscan prey, which is beneficial with regard to biological control, as predator abundance can be maintained even when slug populations are low. In this way, as polyphagous predator populations are sustained by alternative prey, when pest populations recover, there are sufficient predator numbers to control the dynamic pest populations (Murdoch et al., 1985).

Carabids are known to be heterogeneously present within agricultural fields (Bohan et al., 2000) although the root causes are not entirely understood. Carabids will **overwinter** in field margins (Coombes and Sotherton, 1986; Thomas et al., 2000) or in-field (Holland et al., 2007), and will migrate after appropriate environmental cues, in search of food supplies (Holland et al., 2009). As adult carabids are active throughout the summer (June-September), they are seen as particularly valuable commodities for protection of conventionally autumn-sown crops such as winter wheat and oilseed rape.

- *Evidence of biological control directly impacting the pest*

Upon migration from the overwintering habitat, predatory carabids will encounter potential prey items, including slugs, as control of slugs by carabids has been reported (Bohan et al., 2000; Oberholzer and Frank, 2003; Symondson et al., 2006). Though very little literature has explored the actual impact that carabids can have on slugs in-field, Oberholzer & Frank (2003) found that some carabid beetles do predate slugs in laboratory conditions. *Pterostichus melanarius* Linnaeus

(Coleoptera: Carabidae) was found to **kill freshly hatched slugs**, as well as **destroy slug eggs** and appeared to have a greater biological potential than *Poecilus cupreus* Linnaeus (Coleoptera: Carabidae), mostly due to the larger body size and greater consumption. *P. melanarius* has been shown in other studies to consume slugs, as McKemey et al. (2001) found that slugs up to 50 mg would be killed, but smaller slugs were preferred, probably as they are easier to overcome. In the field also, Burn (1988) found that slugs were found in higher numbers in plots where predators were excluded, indicating that predators, particularly carabids, do have a role in slug control.

- *Evidence that a certain habitat and/or management practice improves actual biological control*

Certain studies have found that the diversity of predatory arthropod is greater in close proximity to **grassy field boundaries** (Dennis and Fry, 1992), whilst undisturbed boundaries such as hedges and beetle banks also act as a semi-natural arsenal of carabids adjacent to arable fields (Sotherton 1984; 1985).

Hof & Bright (2010) found that carabids and earthworms were most abundant on wheat fields that were bordered by **grassy margins** (alongside a hedgerow). Unlike the carabids, the earthworms were more numerous near the edge of the field, whereas carabids abundance was not significantly different at 0-10-20 m from the edge. In contrast, gastropods were less abundant on fields with grassy margins than those without, and more abundant near to the edges, potentially due to the presence of the carabids. Hof & Bright (2010) found a total of 18 species of carabid, of which 72% were predacious, dominated by *Pterostichus madidus* Fabricius (Coleoptera: Carabidae) (89%), which have been known to predate slugs (Asteraki, 1993; Oberholzer and Frank, 2003). In the presence of alternative prey items such as earthworms (Mair and Port, 2001; Symondson et al., 2006), slug control by carabids may be curbed (Hof and Bright, 2010). Despite this, the presence of alternative prey items may be resourceful for carabid populations during periods of low slug populations.

Symondson & Liddell (1993) found that molluscs (including commonly occurring pest slugs) were the preferred prey items for *Abex parallelepipedus* Piller & Mitterpacher (Coleoptera: Carabidae), even when natural alternative prey items were available within woodland edge sites. These alternative items included the likes of earthworms and dipteran larvae which are proven prey items. Of the *A. parallelepipedus* population, 89.5% had recently consumed mollusc remains, which were assumed to be live prey items. This is proof that some carabid species, although polyphagous, prefer to consume slugs, and for those that are less pernickety, their populations may well be sustained by **alternative prey**, for suppression of pests when pest populations begin to rise again (Symondson & Liddell 1993). The management implications that can be taken from Hof & Bright (2010) and Symondson & Liddell (1993) is that a **grass margin combined with a hedgerow**, appears more beneficial for slug control than a lone hedge does.

A more recent study by Symondson et al. (2006) has challenged Symondson & Liddell (1993), by finding that the presence of alternative prey items may negate the control of reproducing slug pests (*D. reticulatum*) by the carabid *Pterostichus melanarius* Illiger (Coleoptera: Carabidae). In artificially controlled mesocosms (mimicking wheat stubble field conditions), slugs were predated less often in treatments that contained carabids *and* alternative prey items (including various earthworms and dipteran larvae) than in carabid and slug-only mesocosms. In the alternative prey treatments, carabids were fitter (enhanced biomass and egg load), and controlled slugs populations the least of all prey items. Reservedly, the study was conducted in artificial conditions, limiting integration and movement of species, and used alternative prey items that are not commonly found in arable fields. Despite this, (Symondson et al., 2006) highlight that *P. melanarius* may not select *D. reticulatum* as its **primary prey choice**. It is important to remember that carabid and slug communities are dynamic and heterogeneous, and therefore, these interactions may not be representative of all carabid species under natural conditions.

As habitat enhancement has bolstered 'beneficial' invertebrate communities it may also potentially harbour **more diverse pest species**. Damage has been observed on above and below ground parts of young oilseed rape bordering field margins and semi-natural habitats. In Switzerland for example, field and laboratory experiments estimated that above ground feeding in four study fields caused 72-89% damage to an oilseed rape crop stand 1 m from sown wildflower strips. *A. lusitanicus* caused 54-69% of above ground damage, while to a lesser extent, *D. reticulatum*'s estimated damage was thought to be 3-26% (Frank, 1998a). Although other pests may have been liable to have caused this damage, their contribution was assumed to have been negligible. Elsewhere, complete crop loss 1 m from wildflower strips has been caused by slugs when in the absence of chemical control (Frank, 1998b). Similarly, van Alebeek et al. (2006) reported greater slug damage in **Brussels sprouts** with field margins compared to those without. The authors of the study, which was conducted in the Netherlands, stipulated that the margins improved slug survival by providing favourable microclimate conditions. Brussels sprouts are sown when slug predators that are enhanced by field margins (like carabids), are overwintering and therefore unable to control slug damage. In this way, for field vegetables sown when slug predators are inactive, a combination of cultural and biological control will be needed. This is even more important as *D. reticulatum* will be active year round (Mellanby, 1961), and has been found in Brussels sprouts alongside *A. intermedius* in November (ADAS, 1990), just after the key time for sprout button damage.

2.1.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

Although ploughing fields has been used as a control method, slugs are able to survive in moist gaps between soil aggregates (Glen, 2002), though much of the soil structure is disrupted, and often kills large numbers of slugs (Glen and Symondson, 2002). **Reduced- and zero-tillage** has been increasingly used (Glen, 2002), nullifying the deleterious effect on slugs in the field. If ploughing is necessary, cultivation under dry conditions are likely to have a greater deleterious effect on slug numbers than in wet conditions, which are generally favoured by slugs (Glen, 2002). Irrespective of the cultivation method used, a fine, firm seedbed is produced, to reduce any large macropores that slugs use as refugia (Glen, 2002).

In a three year study on sites with *D. reticulatum* and *A. intermedius*, (Glen et al., 2005) reported 90% slug damage within direct-drilled oilseed rape into the previous cereal crop's stubble in England. In comparison, around 40% plant loss was observed in noninversion tillage, and only slight damage on conventionally **ploughed plots**. This damage was positively related to slug biomass within the upper 10 cm of the soil at the time of establishment. Similarly, Voss et al. (1998) monitored slug activity in response to different cultivation strategies alongside metaldehyde (3 kg ha^{-1}) applications. They found that reduced and particularly zero tillage increased slug activity and abundance of the four commonly found species (*Deroceras agreste* L., *D. reticulatum*, *A. distinctus,* and *Arion fasciatus* Nilsson) to a variable extent across three autumns, when compared to conventional tillage. Although they found no long-term effect of the applied molluscicide, they were able to observe a 2 to 3 week spell of reduced slug activity in four out of six treated plots.

With direct drilling, the slugs have been shown to use the drill slits as 'motorways', providing direct access to the seeds in the relative absence of predators at the surface. Under lower tillage regimes, slugs benefit further from any retaining stubble or crop residue, as well as any overwintering green crops (Glen, 2002). If adopting a reduced tillage regime, Glen (2002) suggests attempting **cultivation twice**, once immediately after harvest (if dry) so as to incorporate the crop residues into the upper soil horizons, and then a second time at the sowing time. Glen et al. (2005) found that slug densities were greatly reduced in plots cultivated three times compared to uncultivated or those cultivated just once. This of course depends on the soil type, and sometimes the preparation of a fine, consolidated seedbed is not possible, and if this is the case, wheat seeds can be drilled a little deeper than normal, perhaps to 44 mm (Glen, 2002), or even to 50 mm (AHDB, 2013), to reduce slug access in cloddy soil. By the time the shoot reaches the soil surface, the plant is more robust than it would have been.

2.1.5. Outlook

Table 2.1.5.1. A summarising table of management implications to control slugs in a sustainable manner.

Chemical control
• Control of slug populations by metaldehyde pellet application was greatest in September, following harvest, where conditions were suitable for slug activity (Shirley et al., 2001). • Iron phosphate pellets appears to be safe, and is able to achieve adequate control of slugs (Capinera and Rodrigues, 2015). However, it can have adverse effects on earthworm populations, compared to metaldehyde (e.g. Langan and Shaw, 2006).
Biological control
• Encourage carabid beetles, which have been shown to predate slugs in laboratory and field conditions (e.g. Bohan et al., 2000). • Promote grassy field margins of **cereal fields** (and possibly other crops), which benefit carabids and reduced the presence of slugs in field (Hof and Bright, 2010). • Grass margins combined with a hedgerow, appears more beneficial for slug control than a lone hedge does (Hof and Bright, 2010; Symondson and Liddell, 1993). • Increasing biodiversity of invertebrate food items as alternative prey items may serve to increase (Symondson and Liddell, 1993) or decrease (Symondson et al., 2006) slug control by carabids. • For **field vegetables** sown when slug predators are inactive (e.g. Brussels sprouts) and slugs are active, a combination of cultural and biological control will be needed.
Cultural control
• Slug populations can be reduced by multiple cultivations, particularly in dry conditions, producing a fine, firm seedbed is produced, to reduce any large macropores that slugs use as refugia (Glen, 2002). • In cloddy soil where it is not possible to produce a firm seedbed, **wheat** seeds can be drilled a little deeper than normal, perhaps to 44 mm (Glen, 2002), or even to 50 mm (AHDB, 2013), to reduce slug access. • Investigate drill coulter for a less broad slot to prevent slug ‘highways’ (Glen, 2002). • Under lower tillage regimes, remove stubble and debris which are favourable habitats for slugs (Glen, 2002).

2.2. Flea beetles (Alticini spp.)

2.2.1. Introduction & life history

There are several damaging flea beetle (Coleoptera: Chrysomelidea) species in the UK, which have varying life cycles. The cabbage stem flea beetle (hereafter CSFB) *Psylliodes chrysocephala*, is an exclusive pest to WOSR, while SOSR crops can be ravaged by other flea beetles of the genus, *Phyllotreta*. The CSFB (see Table 2.2.1.1) is probably most problematic, where a combination of larval and adult feeding can ensure year-round damage (HGCA, 2014). However, the Wessex flea beetle (*Psylliodes luteola*) – increasingly important in southern England after an initial outbreak in Wiltshire. Attacking crops in the autumn, the Wessex flea beetle is most likely to damage earlier sown crops, especially if slow to grow away in September (HGCA, 2003). Damage by *Phyllotreta* spp. larvae (otherwise known as turnip flea beetles), including the large striped flea beetle (*Phyllotreta nemorum*) is usually not considered economically important (Ekbom, 2010).

Table 2.2.1.1. The life histories of some of the most agriculturally damaging flea beetles present within the UK.

Flea beetle	Autumn	Winter	Spring	Summer
Psylliodes chrysocephala **(Cabbage stem flea beetle)**	Adults move to newly sown WOSR crops just after crop emergence (Sep), chewing holes in cotyledons and the earlier true leaves. In WOSR, adults feed on newly emerged crops for around a week, and by October if the weather is mild enough, adults will lay eggs at the base of the newly emerged plant[1], in soil surface cracks[2], or on the lower parts of the plants themselves[3].	Upon hatching (November-December), the larvae bore into the rapeseed petioles and feed under the surface (Nov-Feb)[1]. This tunnelling causes the majority of the plant damage[4].	The larvae will feed within the main stem after the growing point (Mar-Apr). It should be noted that a mild autumn may stimulate earlier egg hatching, which would coincide with more vulnerable plants, exacerbating the damage over winter[1]. The larvae will pupate within the soil (May), and the adults will emerge, and again feed on the foliage in a ragged manner.	In August, the adults will seek refugia in moist, sheltered places, before locating a new crop[5].
Phyllotreta spp. – otherwise known as **turnip flea beetles**, including the **large striped flea beetle** (*Phyllotreta nemorum*).		*Phyllotreta* adults will overwinter in habitats away from their original field, and depending on the temperature, will leave their overwintering sites (March-May), locating newly emerging SOSR crops[6].	Later sown SOSR crops are most vulnerable *Phyllotreta* species, particularly if growth is stunted by sunny, dry weather[5], which will feed on cotyledons and stems, even if the seedling has not yet emerged from the soil[6].	A maximum of 28 eggs can be laid at any one time, and once hatched, the larvae feed on the fine roots of the crop, for four weeks, until they emerge as adults in the late summer[6].

[1](HGCA, 2014), [2](Sáringer, 1984), [3](Bonnemaison and Jourdheuil, 1954), [4](Nilsson, 1990), [5](HGCA, 2003), [6](Ekbom, 2010)

2.2.2. Damage/presence

As CSFB migrate into oilseed rape fields during crop emergence, they attack the crop in its most vulnerable stage, and cause 'shot-holing' symptoms which can result in stunting and reduced plant vigour. A snapshot survey of CSFB damage was conducted in AHDB (2015) to assess **beetle damage** levels at the end of September 2014. It was found that 6% of GB crops (40,000 ha) were damaged (by CSFBs) to a level that exceeded thresholds, and alongside this, 2.7% of winter oilseed rape (18,000 ha) had to be replanted due to CSFB damage. These losses coincided with a period of neonicotinoid seed treatment ban by the EU as of December 2013 (AHDB, 2015). (Veromann *et al.*, 2006) found that in Estonia, *Phyllotreta armoraciae* Koch (horseradish flea beetle) and *Phyllotreta nemorum* (large striped flea beetle) were found in winter OSR in very low numbers, but were much more abundant on spring OSR.

Damage and numbers within both winter and spring OSR of this sort by flea beetles has been shown to be crippling to entire crops (HGCA, 2015). With the future of EU legislation surrounding the use of neonicotinoids within oilseed rape uncertain, it is important to investigate more sustainable methods that may control flea beetles.

2.2.3. Pest thresholds

HGCA (2014) advise that for CSFB, a quick glance in the grain tillers will give a good indication of the number of beetles available to invade the crops. Pest pressure can also be assessed by monitoring volunteer OSR plants. The amount of leaf area eaten will indicate whether control is necessary, as soon as the crops emerge. Water traps and plant dissections will also provide useful information for the potential of infestation. More information can be found in detail in HGCA (2014), but if the thresholds below are exceeded, control (as covered below) may be necessary:

Table 2.2.3.1. HGCA (2014) threshold table for treatment. Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Pest life stage	**Control threshold**
Assessing the need to spray adults in OSR:	>25% leaf area eaten at cotyledon-2 leaf stage >50% leaf area eaten at the 3-4 leaf stage Crop is growing more slowly than the consumption rate
Assessing the need to spray larvae in OSR:	>35% beetles per yellow water trap caught in total over the monitoring period >2% larvae per plant, when dissected >50% of petioles damaged

2.2.4. Potential for control

2.2.4.1. Chemical control

The future of CSFB control by chemical means is uncertain due to a two-year restriction of the use of **neonicotinoids** in flowering crops (December 2013 – December 2015). Pyrethroid insecticides have been relied upon to control the CSFB over the last 30 years, however, there have been increased reports of reduced performance of pyrethroid insecticides against CSFB in Germany, Denmark (IRAC, 2015). Additionally, **pyrethroid resistance** (knockdown resistance, or kdr) has been fully confirmed in the UK (HGCA, 2015). Barari et al. (2005) found that an autumn and spring application of pyrethroid insecticide to *B. rapa* (turnip rape) trap crop borders had no effect on the infestation of CSFB into the main OSR crop, though it did reduce the surviving population in the trap crop. The authors concluded that there was no direct benefit from treating the turnip rape with insecticide, other than reducing the surviving population within the trap crop. Authors of similar studies have also come to the same outcome, where fields sown with an admixture of 90% OSR with seed dressing and 10% turnip rape with seed or without seed dressing, were not significantly different from each other, with respect to larval infestation (Buechi, 1995). Buechi (1995) suggested that undressed turnip rape trap crops around OSR perimeters would decelerate the likelihood of insecticide resistance.

2.2.4.2. Biological control

- *Identify potential biological control agents*

CSFB is **parasitized** in in its larval and adult stages by *Tersilochus tripartitus* Brischke, *T. microgaster* Szepligeti, *Aneuclis melanarius* Holmgren (all Hymenoptera: Ichneuomonidae), *Diospilus morosus* Reinhardt (Hymenoptera: Braconidae). All are larval parasitoids of CSFB and present in the UK, the only exception being *T. tripartitus* (UK presence unclear). Both *A. melanarius* and *D. morosus* are facultative multivoltine parasitoids of several coleopteran species, while the latter is the most common parasitoid of *P. nemorum* (large striped flea beetle) (Ulber and Williams, 2003). Several *T. tripartitus* individuals were caught within Estonian spring OSR, which are known univoltine endoparasitoids of CSFB, and thus provides an evidence of CSFB potential parasitism (Veromann *et al*., 2006) though further evidence is few and far between.

Aside from confirmed parasitoids of flea beetles, **generalist predators** have been observed to consume flea beetles, though their contribution to control is unexplored. Apart from *Pyllotreta nemorum* larvae which mines in leaves, most flea beetle larvae of the genus, *Phyllotreta,* live within the Brassica rhizosphere, and are thus unavailable to above-ground generalist predators (Dodsall and Mason, 2010; Ekbom, 2010). However, the adults are often found in high numbers on the ground, and in the foliage, and could therefore be viable prey items for above-ground predators (Ekbom *et al*., 2014).

Though little experimental data exists for predator control of flea beetles, there have been **incidental observations** of flea beetle predation within various crops. (Renkema et al., 2014) found that Canadian carabid beetles consumed blueberry flea beetles (*Altica sylvia* Malloch), and that the probability of detecting pest DNA was positively related to pest density. Blueberry flea beetles have similar but not identical life cycles to flea beetles such as *Phyllotreta* spp. in the UK. Likewise, Burgess (1980), reported *Chrysoperla* (syn. *Chrysopa*) *carnea* Stephens (common green lacewing) larvae attacking adult *Phyllotreta cruciferae* Goeze in 1972 on two occasions, both having just been swept from oilseed rape, highlighting that larval lacewing predation of flea beetles occurs in-field, as well as in artificial conditions. During a study within mustard crops, Burgess (1982) observed *Nabis alternatus* Parshley (western damsel bug) predating *P. cruciferae* adults. Culliney (1986) on three occasions found two predatory Heteroptera consuming adult *Phyllotreta*; *Podisus maculiventris* Say (spined soldier bug) and *Navicula americolimbata* Carayon. (Burgess and Hinks, 1987) reported that all four field-collected adult *Gryllus pennsylvanicus* Burmeister (northern fall field cricket) consumed live *P. cruciferae*, as well as fifteen out of sixteen late-instar *G. pennsylvanicus* nymphs, in laboratory conditions. Although these are North American observations, the predatory groups are representative of UK fauna, and therefore, similar interactions might be expected on UK soil, particularly as some of the observations were those of real-life situations.

- *Evidence of biological control directly impacting the pest*

In response to numerous *Phyllotreta* samples found within predatory spider guts in OSR (Öberg et al., 2011), a novel Swedish study by (Ekbom et al., 2014) investigated **polyphagous spider predation** of *Phyllotreta* flea beetles using molecular analysis. In this study, five *Phyllotreta* beetles (*P. atra* (Fabricius), *P. undulata* (Kutschera), *P. striolata* (Fabricius), *P. tetrastigma* (Comolli), and *P. vittula* (Redtenbacher)) were collected to develop primers for DNA analysis of spider gut-contents, from *Pardosa* spp. Koch (Araneae: Lycosidae) (wolf spiders), and *Phylloneta impressa* Koch (Araneae: Theridiidae) (tangle-web spiders). In total, 19.4% of the 674 hand-collected *Pardosa* specimens, and 10% of the 509 hand-collected *P. impressa* tested positive for flea beetle DNA. Clearly, the two spiders consume flea beetles, but importantly, complemented each other in both space (web versus ground dwelling) and time. *Pardosa* spp. predated flea beetles between the start and the end of the flowering period, whilst *Phylloneta* spp. predated flea beetles between the end of flowering until the beginning of pod ripening, highlighting the minimal overlap between the two spider niches. In this way, it is expected that there is little spider competition for flea beetle consumption, and thus suppression could be maintained throughout parts of the spring and summer OSR season. *Pardosa* appeared to readily predate flea beetles in the laboratory and in-field, in no relation to flea beetle densities, as was the case in previous studies exploring aphid predation by *Pardosa* (Kuusk & Ekbom 2010, 2012).

Öberg et al. (2011) reported that within OSR fields, **predator communities** were dominated by *Pardosa* spp. (63%) and carabids (22%) from pitfall traps, while sweep net species were predominantly *Theridion* spp. (86%). Aside from pollen beetles, the alternative ground-dwelling and foliage-dwelling prey items were *Phyllotreta* spp. (72% and 71% respectively). These predator-prey communities described by Öberg et al. (2011) and Ekbom et al. (2014) should be seen as highly significant for integrated pest management. This is particularly important for flea beetles, as Ekbom et al. (2014) observed that flea beetles were much more prevalent on the ground compared with the foliage. Ekbom et al. (2014) explained this by suggesting that flea beetles were more abundant on the ground, and as a result, were not as accessible to the foliage-dwelling *P. impressa*, but more available to *Pardosa.* It is possible that other generalist ground-dwelling predators, other than polyphagous spider predators, have a considerable role to play in the suppression of flea beetles. However, the contribution that other ground-dwelling generalist predators can make to flea beetle control is unknown due to a lack of research.

Evidence of CSFB **egg predation** is also apparent. Warner et al. (2003) aimed to identify any potential CSFB egg-consuming carabids, as over 90% of CSFB eggs are laid during the autumn (Bonnemaison and Jourdheuil, 1954) (when carabids may be present), particularly in mid-October when female CSFB adults were in the crop at their maximum (Warner et al., 2003). Of the three studied carabids (*Trechus quadristriatus* Schrank, *Pterostichus madidus* Fabricius, and *Nebria brevicollis* Fabricius (all Coleoptera: Carabidae) which were active during the study period, Warner et al. (2003) found that *T. quadristriatus* and *P. madidus* was spatially and temporally associated with *Psylliodes chrysocephala* in October when adult *P. chrysocephala* females were egg laying. In the laboratory, only *T. quadristriatus* consumed the flea beetle eggs, with an average of six eggs in 24 hours. Owing to Finch (1996) and (Burn, 1982) suggesting that the ease in which carabids seize prey in their mandibles is the most important factor in carabid predation, the smaller *T. quadristriatus* (3.5-4.0 mm) may be more equipped to predate CSFB egg compared to the larger carabids studied (*P. madidus* and *N. brevicollis*). If *T. quadristriatus* is as effective in-field as it is in laboratory conditions, then it would be an ideal candidate for control, as *T. quadristriatus* is able to continue its activity even at low temperatures, even during the short period within mid to late autumn when CSFBs can oviposit (Warner et al., 2003). In times when pest populations are low, it is vital that *T. quadristriatus* individuals are supplemented, to ensure future generations of control. Warner et al. (2003) found that the three carabid species were spatially associated with Collembola during mid-September, suggesting that Collembola are an important food source, particularly as they are one of the most abundantly active invertebrates on cultivated soil (Joosse, 1981).

Other small carabids may also offer egg predation services akin to *T. quadristriatus*, such as small carabids of the genus, *Bembidion* Letreille which do not exceed 7.5 mm (Lindroth, 1974). (Wallin et al., 1992) found that the common arable carabid, *Bembidion lampros* Herbst was roughly 5 mm in length, and therefore a size similar to *T. quadristriatus*, and therefore may also provide CSFB egg consumption. Mitchell (1963) found that in laboratory conditions, *Bembidion lampros* consumed 48 of 50 damaged cabbage root-fly eggs within 60 minutes, more frequently than undamaged eggs, and also greatly exceeding the egg removal by *T. quadristriatus* in the same experiment. The fact that **damaged eggs** were eaten more often than undamaged eggs, suggests that chemical stimuli, or perhaps removed integument is important for these carabids to consume eggs. Although the larger species of carabid that (Warner et al., 2003) did not directly consume the CSFB eggs, a small amount were damaged, which may lead to easier location or handling time by smaller carabids. (Mitchell, 1963) also suggested that the larger beetles may yet play a part in assisting smaller carabid beetle's feeding. Warner et al. (2003) postulate that the larger carabids (*P. madidus* and *N. brevicollis*) may still be able to consume fully grown larvae that are exiting the plant and ready to pupate, though this is unstudied.

- *Evidence that a certain habitat and/or management practice improves actual biological control*

Cultivation is also vital for natural enemies, particularly those which spend a substantial amount of their time in-field. For carabid beetles, the timing of soil tillage should ideally be focused on periods in which carabid larvae and adults are vacant from the cultivated area (Warner et al., 2003). Dosdall et al. (1999) found that reduced and zero-tillage in Alberta, Canada, reduced *Phyllotreta* spp. damage to levels experienced in insecticidal treatments. **Zero-tillage** systems are characterised by higher soil moisture and organic matter contents (Holland, 2004) and generally less favourable microclimate for flea beetles. Valantin-Morison et al. (2007) proposed that zero-tillage yields reduced flea beetle damage because the previous crop's stubble may render the field a **less favourable habitat** (reduced egg oviposition sites, and a reproductive barrier). As teneral *Trechus quadristriatus* adults will be emerging during August and early September (around harvest) (Mitchell, 1963), minimal tillage is generally recommended. Damage and numbers of flea beetles are quite often less in reduced- and zero-tillage (Soroka and Elliott, 2011). (Ulber and Schierbaum-Schickler, 2003) similarly reported that zero tillage systems decrease the level of larval infestation. The effect of reduced- and zero-tillage were mirrored by Valantin-Morison et al. (2007), where **shallow tillage** regimes significantly limited larval CSFB infestations when compared to ploughing regimes, as *T. quadristriatus* pupate below (15 cm below the soil surface) the typical depth of disturbance by minimal tillage (Warner et al., 2003). Baguette & Hance (1997) likewise found reduced carabid presence after deep ploughing.

Mitchell (1963) found that first- and second-instar larvae of *T. quadristriatus* were found in September, and third-instar larvae (mainly) in May, indicating that larvae will **overwinter in the field**. Furthermore, female carabids were dissected and the number of mature eggs were collected, and found that copulation of *Bembidion lampros* (see Section 2.7.4.2 and 4.2.4.3 for more information on *B. lampros* stewardship) occurred between late April to late July, whilst in *T. quadristriatus*, copulation occurred between August and the following spring. In this way, intrusive tillage in preparation of OSR could potentially damage *T. quadristriatus* **eggs** and larvae, and thus remove predation of CSFB larvae year-round. As carabids have been shown to consume, and be spatio-temporally associated with flea beetles, deep ploughing could diminish the biological control of flea beetles by carabids, and spiders alike.

2.2.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

Cultivation can have an impact on flea beetle populations within brassica crops including *B. rapa* (Milbrath et al., 1995) though the extent of flea beetle damage depends on the cultivar used.

Establishment, timing, and sowing methods can also greatly impact the effect of flea beetles. For example, *Phyllotreta* spp. flea beetle damage is more probable in a spring *B. rapa* (turnip rape) crop (Dosdall and Stevenson, 2005). And in winter OSR, **early sowing** reduced the level of attack by CSFB, the latter due to the larval consumption and tunnelling of leaves and petioles destined to fall before winter, whilst high **plant density** is thought to be less attractive to flea beetles due to an altered microclimate and crop structure (Valantin-Morison et al., 2007). Dosdall et al. (1999) also found that **seeding rates** of 10 kg/ha received less damage to individual plants than seeding rates at 5.0 or 7.5 kg/ha, thought to be due to a dilution effect of the plants. However, higher density stands will incur a greater capital cost, and could increase chances of lodging and disease susceptibility (Soroka and Elliott, 2011). Flea beetle damage to OSR and *Brassica rapa* L. (field mustard) was somewhat lower with 30 cm **spaced rows**, compared to 10 or 20 cm spaced rows. Higher plant densities associated with wide row spacing may reduce flea beetle numbers and/or damage to individual plants (Soroka and Elliott, 2011). Burgess (1977) found variation in the intensity of the attacks in nearby brassica fields, meaning that **crop rotation** may not be effective as a means of flea beetle control, and similarly, diversifying fields via intercropping has also been regarded as insufficient control (Soroka and Elliott, 2011).

In a French study by Valantin-Morison et al. (2007), the broader scale spatio-temporal variation between sites appeared to cause much more variation in the occurrence of insects than changing cropping practices did. Particularly high levels were experienced in the south of France (73% plants with at least one larva), compared to the eastern and western Parisian Basin (19% and 7% respectively) in 2001-2002. In contrast, in 2003-2004, 92% and 97% of plants were infested with at least one larva in the eastern and western Parisian Basin respectively, highlighting the **temporal and spatial variability** of infestation. At a landscape scale, lower CSFB attacks in **region**s with a high proportion of land cropped with winter OSR, possibly due to landscape-scale insecticide application within oilseed rape that would be deleterious to the pest (Valantin-Morison et al., 2007). Whilst on a smaller scale, the immediate **surrounding environment** (of the focal field), which constitute to overwintering sites for CSFB (Warner et al., 2003), had no effect on CSFB variation in regions with a large proportion of winter OSR cropped. Burgess (1977) found that although flea beetle distribution is generally continuous across brassica-crop **landscapes**, there can be hotspot areas where flea beetle populations can be very high, ranging from 10 to 20 km across, and even 60 km.

An alternative to chemical control of flea beetles was found by Barari et al. (2005), who showed that turnip rape (*Brassica rapa* Linnaeus) grown in crop borders as a trap crop, can reduce infestations of *Ceutorhynchus quadridens* Panzer syn. *pallidactylus* Marsham (cabbage stem weevil), also trapping the parasitoids associated with the pest. **Trap cropping** strategies are adopted to reduce pest colonization in the main crop, by planting strips of more attractive trap crops in close proximity to the main crop (Hokkanen, 1991). Very few studies have explored the effectiveness of trap crops to avoid flea beetle damage to UK OSR. In one such study, Barari et al. (2005) found that by using a trap border of *B. rapa* (turnip rape), infestation of CSFB in the main OSR crop was reduced, and with this, insecticide application (pyrethroid treatment in early October and mid-April) of the trap crop had no significant effect on the CSFB or its parasitoid *Tersiolochus microgaster.* The parasitoid, *T. microgaster* (see Section 2.2.4.2), was caught in very low numbers and solely in April, and therefore parasitoid arrival date, and whether this coincided with pest infestation (March), was not certain. Akin to other studies, CSFB appeared to favour turnip rape (Buechi, 1995; Lambdon et al., 1998) as OSR main crops had lower CSFB infestation rates when bordered with turnip rape than with OSR borders, and turnip rape borders harboured greater CSFB larvae than in OSR borders. This demonstrates that turnip rape is an efficient trap crop for CSFB (Barari et al., 2005). Low levels of parasitism of CSFB larvae were found in the turnip rape border (7.7%) not sprayed with pesticide, whilst no CSFB larvae were parasitized in the OSR field centres. Although Barari et al. (2005) did not find that turnip rape trap crops affected the percentage parasitism of CSFB, this may be due to stochastic perturbations.

2.2.5. Outlook

Table 2.2.5.1. A summarising table of management implications to control flea beetles in a sustainable manner.

Chemical control
• Pyrethroid resistance (knockdown resistance, or kdr) has been fully confirmed in the UK (HGCA, 2015).
Biological control
• Increase natural enemy diversity, as flea beetles are known to be parasitized by a number of larval parasitoids (e.g. Veromann et al., 2006). • Encourage ground-dwelling generalist predators, including wolf spiders and carabids, the latter of which act as flea beetle egg predators (Warner et al., 2003).
Cultural control
• Zero- and reduced-tillage systems reduce damage by improving soil moisture and organic matter content, which is not favoured by flea beetles (Valantin-Morison et al., 2007). • Shallow tillage regimes have less of a deleterious effect on natural enemies of flea beetles (spiders and immature carabids) than with deep ploughing. This is particularly important around the time of preparation for OSR (Warner et al., 2003). • Early sowing of OSR is unfavourable to flea beetles (Valantin-Morison et al., 2007). • Higher plant densities receive less damage by flea beetles, and can be achieved by enhanced seeding rates (e.g. 10 kg/ha rather than 5.0 or 7.5 kg/ha), or larger row spacing (30cm rather than 20 or 10 cm) (Dosdall et al., 1999). • Intercropping may not be sufficient for control (Soroka and Elliott, 2011). • Trap cropping using turnip rape borders can reduce damage to the OSR maincrop, as cabbage stem flea beetle will preferentially attack turnip rape (Barari et al., 2005).

2.3. Pollen beetles (*Meligethes* spp.)

2.3.1. Introduction & life history

The widespread *Meligethes aeneus* Fabricius (Coleoptera: Nitidulidae) (CABI, 2009) overwinters in uncultivated sites as adults, and emerge during the spring, in synchrony with the host plant green bud stage (Singh and Singh, 2005). At 12-15°C, they consume pollen from numerous resources (polylectic), before locating their breeding hosts. Using upwind-anemotaxis (Williams et al., 2007) and being capable of flying 200-300 m within a couple of hours (Taimr et al., 1967), pollen beetles are effective searchers of their host plants of the brassica family. Eggs are oviposited into green flower buds, where after hatching, the larvae then feed on the pollen within the buds (Cook et al., 2004), and thus bud destruction is not induced (HGCA, 2014). The adults will move to the open flowers of OSR, becoming pollinators as opposed to pests (HGCA, 2014). Completing two larval instars in 9-13 days (Osborne, 1960), the pollen beetle will then pupate in the soil after dropping off of the flower buds. Once pupated, the adult pollen beetles will return to the oilseed rape flowers (Free and Williams, 1979) and a variety of other plants, including vegetable brassicas (HGCA, 2014) to feed before overwintering.

2.3.2. Damage/presence

The pollen beetle, *Meligethes aeneus* exploits the genera, *Brassica* and *Sinapis* (both Brassicales: Brassicaceae) as hosts for breeding sites in Europe (Free and Williams, 1978). *M. aeneus* is a key pest to OSR (Alford *et al.,* 2003a), and occasionally, pollen beetle adults will feed on vegetable brassicas including cauliflower curds and broccoli florets in mid-summer after the new generation of adults have emerged from OSR fields, and moved further afield (AHDB, 2014). Ahuja *et al.* (2010) found that OSR can be subject to **yield damage** exceeding 80%, most of which occurring at the green bud stage (Free and Williams, 1978), causing podless stalks (Free and Williams, 1979). For effective crop management, it is vital to remember that pollen beetle damage is extremely difficult to predict, as attack depends on timing, crop growth stage (Nilsson, 1994), and compensation potential by the crop (Podlaska et al., 1996). Therefore, in certain localities affected by a cocktail of factors, *x*-amount of pollen beetles may cause lasting damage in one scenario, whilst in other a scenarios, *x*-amount of pollen beetles will cause little damage.

2.3.3. Pest thresholds

To establish whether a pollen beetle threshold (see Table 2.3.3.1) has been met, the crop density should be estimated, by counting the number of plants per m^2. More guidance can be found in HGCA (2014), but pollen beetles should be counted in the green bud stage, as this is when the crop is susceptible to damage. When in flower, OSR is no longer at risk.

Table 2.3.3.1. HGCA (2014) threshold table for treatment. Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Crop density	Pollen beetle threshold
<30 plants m^2	25 beetles per plant
30-50 plants m^2	18 beetles per plant
50-70 plants m^2	11 beetles per plant
70 plants m^2	7 beetles per plant

2.3.4. Potential for control

2.3.4.1. Chemical control

It has been suggested that decreasing the use of chemical control on crops will increase parasitoids of pollen beetles, such as *Phradis interstitialis* Thomson (Hymenoptera: Ichneumonidae) parasitization. *P. interstitialis* mortality will be reduced from declining use of pre-flowering insecticides, as it is usually the first **parasitoid** to enter winter *B. napus* fields (Nilsson, 2003). Hokkanen et al. (1988) argue that if a proportion of the *Meligethes* spp. populations could be decreased, without causing harm to their parasitoids, there would be a more favourable host-parasite ratio, which will enhance parasitism throughout the year. The only way to enhance *P. intersitialis* parasitism *and* use a form of chemical control would be to spray during the early bud growth stage as later pesticide applications will harm all parasitoids (Hokkanen et al., 1988). Where spring and winter OSR fields are grown in close proximity to each other, parasitoids are likely to migrate to spring rape before anthesis, and are therefore prone to insecticides, which means at present, it is less advantageous to have both spring and winter *B. napus* crops grown in the close proximity, even if it does aid parasitoid migration (see Section 2.3.4.3). Veromann *et al.* (2006) found that significantly more *M. aeneus* larvae were found at the field edges than in the centre of both winter- and spring-OSR, and that *M. aeneus* parasitoids are more sensitive to insecticide application than their hosts.

HGCA (2014) highlight control thresholds on winter and spring OSR before commencing chemical control, as pollen beetles are pollenivorous, and thus important pollinators at low densities. With *Meligethes* spp. resistance to pyrethroid is now widespread in the UK (HGCA, 2014) and other parts of Europe (Zamojska et al., 2014).

2.3.4.2. Biological control

- *Identify potential biological control agents*

The multivoltine parasitoids of greatest importance in the UK are *Brachyserphus parvulus* Nees (Hymenoptera: Proctotrupidae) and the better studied, *Diospilus capito* Nees (Hymenoptera: Braconidae) (Nilsson, 2003). *M. aeneus* is most vulnerable to **parasitism** by endoparasitic koinobiont Hymenoptera (Osborne, 1960) when eggs are oviposited into green flower buds and the larvae develop (Cook et al., 2004) between April and June (HGCA, 2014). *D. capito* females oviposit into different host larval sizes, including through the bud wall using a relatively long ovipositor. In comparison, *B. parvulus* prefers second-instar host larvae (Osborne, 1960). After, *Meligethes* spp. larvae drop to the floor to pupate and the parasitoid will continue to feed until the pollen beetle moult into the final larval instars, when the parasitoids emerge from and consume the host. Using the cavity in the soil prepared by the pollen beetle, *D. capito* then spins a cocoon and undergoes pupation, with the earliest bred *D. capito* emerging during July when *Meligethes* spp. are still numerous (Osborne, 1960). Jourdheuil (1960) found that low autumn temperatures induced a poorly surviving overwintering quiescence of *D. capito* within *Meligethes* spp. larvae, rather than same-season emergence. This could have an impact on further control by the next generation of *D. capito*.

Parasitoids of the genera *Phradis* and *Tersilochus* (both Hymenoptera: Ichneumonidae) have also been identified (Billqvist and Ekbom, 2001; Osborne, 1960) as univoltine parasitoids of *M. aeneus* in the UK (Osborne, 1960). However, some **nomenclature confusion** has arisen from the papers; the unidentified *Tersilochus* sp. that had been identified as a key parasitoid of *M. aeneus* by Osborne (1960) and Winfield (1963), is certainly *Phradis interstitialis*. Additional key univoltine parasitoids of *M. aeneus* in the UK have been identified as *Tersilochus heterocerus* and *Phradis morionellus* (Osborne, 1960).

Both *Phradis* species will only hatch when the host larvae is fully fed and about to enter the soil for pupation. Most of the parasitoid growth takes place in the host pupal chamber, and after pupation, the adult will remain in **diapause** in the cocoon until the following spring or summer (Nilsson, 2003). The univoltine parasitoids will emerge in synchrony with the period in which their host pollen beetle completed their larval development (Nilsson, 2003). On **emergence**, female parasitoids are sexually mature and can immediately begin ovipositing on suitable hosts by searching buds and flowers (Nilsson, 2003). Female *P. morionellus* and *T. heterocerus* appear on the crop during early flowering, or sometimes earlier (Nilsson, 1985) and prefer ovispositing into large second-instar larvae, searching where hosts are numerous (Winfield, 1963) such as open flowers (Nilsson and Andreasson, 1987). Contrastingly, Ferguson et al. (2003) observed *T. heterocerus* adults emerging in early May when *M. aeneus* larvae were dropping from the rape canopies to pupate in the soil. Rather than ovipositing on second-instar larvae closer to pupation, the spatially associated *P. intersitialis*, with long, slender ovipositors (Osborne, 1960), can perforate the bud wall into first-instar larvae and eggs of pollen beetles.

Veromann *et al.*, (2006) found a single parasitoid specimen (*P. morionellus*) of *M. aeneus,* which was caught on winter OSR (water traps in May 2002) when 10-20% of the flowers on the main raceme were open. In comparison many more *M. aeneus* parasitoids (predominantly *Phradis* spp.) were caught in water traps in spring OSR during May 2003, when host larvae were abundant in the flowers (Veromann *et al.*, 2006). It may be that **parasitoid abundance varied** so much between seasons due to stochastic factors, such as poor weather. Generally, as winter OSR is less vulnerable to pollen beetle attack than spring OSR, due in-part to earlier flowering and a longer growing season to compensate for attacks (Tarang et al., 2004), then perhaps parasitoid prevalence is likely to be lower too, as was seen by Veromann *et al.*, (2006).

Aside from the most widely studied *M. aeneus* parasitoids, there are several **others** that are known to attack pollen beetles; *Blacus nigricornis* Haselbarth, *Eubazus sigalphoides* Marshall, (Hymenoptera: Braconidae), *Aneuclis incidens* Thomson (Hymenoptera: Ichneumonidae), *Cerchysiella planiscutellum* Merect (Hymenoptera: Encyrtidae), and *Brachyserphus parvalus* Nees (Hymenoptera: Proctotrupidae) (Nilsson and Andreasson, 1987; Nilsson, 2003). *B. nigricornis* and *B. parvalus* have both been recorded in the UK, whilst it is unclear as to whether the other three are present in the UK. None of the listed parasitoids are considered to be as effective as *P. morionellus* and *D. capito* in their control of pollen beetles.

Mortality of the univoltine parasitoids mostly arises from **competition** for host larvae, especially between *T. heterocerus* and *P. morionellus*, which both compete for fully fed second-instar host larvae (Winfield, 1963). However, even in the absence of a competing parasitoid, some cases of non-hatching eggs and larval death of *T. heterocerus* occurred. Some adult *Meligethes* spp. adults were found with 1-3 black egg-shells embedded in the body, indicating possible resistance of pollen beetles to *T. heterocerus*. It has been suggested that *T. heterocerus* is a facultative parasitoid of *Meligethes* spp. for this reason (Osborne, 1960). Likewise, *Phradis* spp. eggs and first-instar parasitoid larvae have been encapsulated four days after oviposition (Nilsson, 2003), and therefore, the multivoltine parasitoids may **not be particularly effective** at pollen beetle control.

D. capito on the other hand, is a **fierce competitor**, prevailing in interspecific competition scenarios by causing larval competitor death within the same host body (Jourdheuil, 1960). Although spring *D. capito* emergence is usually poor (Osborne, 1960), parasitism of *M. aeneus* later in the season may actually be enhanced due to the parasitism of the alternative host, CSFB earlier in the season.

Intraspecific competition seems to limit *D. capito* parasitism, especially when *Meligethes* spp. abundance is much lower than in the previous year, as the host-parasitoid ratio is lowered (Nilsson, 2003). Female *D. capito* adults are inefficient egg layers as they do not discriminate between parasitized and non-parasitized hosts (Nilsson and Andreasson, 1987), only laying one random egg at a time. Jourdheuil (1960) found that it can take 460 eggs to parasitize 99 host larvae, an **inefficiency** which can be much more pronounced at total parasitzation levels of 50-60%.

Regardless of the inefficiency, multi-parasitism can reduce **host vigour**, increasing survival chances of one of the immature parasitoids (Jourdheuil, 1960). Parasitoid egg wastage seems almost advantageous as encapsulation suppression from multi-parasitism occurs; to a certain extent, the more eggs laid within a host may increase survival chances of *one* individual parasitoid offspring. In the same way, interspecific competition between *Phradis* spp. is actually beneficial to parasitoid larvae survival, if, at intermediate host-parasitoid ratios, both parasitoids oviposit in the same host (Nilsson, 2003). *D. capito* out-competes *Phradis* spp. and *T. heterocerus* when sharing a host as it was more adept at killing its competitors, **supressing encapsulation**, and invoking Ichneumon encapsulation (Jourdheuil, 1960). What may appear as egg laying inefficiency by *D. capito* in particular (Jourdheuil, 1960), may actually be an adaptation to *M. aeneus* encapsulation, as the more eggs oviposited into the host larvae will increase the survival chances of at least one *D. capito* egg, and hence, multi-parasitsm may in fact be advantageous.

Furthermore, parasitoids may negatively impact *M. aeneus* through **non-consumptive mechanisms** by inducing costly defensive behaviours in *M. aeneus* to avoid being parasitized (Price *et al.*, 2011). A defensive 'dropping' behaviour will reduce *M. aeneus* fitness as it may stimulate greater epigaeic predatation, reduce herbivory opportunities, or simply reduce fitness so much that the larvae don't survive pupation within the soil. *M. aeneus* can also drop to the floor via bud abortion in years of very large *Meligethes* spp. populations, which can cause considerable immature parasitoid mortality (Nilsson, 1988), particularly to the early emerging *P. interstitialis*, as successful parasitoid development is dependent on host survival. As carabid predators are epigaeic, there is a clear resource partitioning between carabids and parasitoids of *Meligethes* spp., which oviposit on buds and flowers. More likely to feed on *M. aeneus* when dropping to pupate, carabids are probably unintentional intraguild predators of parasitoid larvae within *M. aeneus* and therefore the effect of parasitoids and predators are not likely to be additive. This of course is antagonistic, but *M. aeneus* control is still occurring, and should therefore be encouraged. Some **epigaeic predators** have been reported within scientific literature. Öberg et al. (2011) reported that the spider genera, *Pardosa* (Araneae: Lycosidae) and *Theridion* (Araneae: Theridiidae) are known predators of pollen beetles, while a DEFRA (2004) report identified five carabid species in the UK which are potential biological control agents. Similarly, in choice tests, *Tachyporus hypnorum* Fabricius (Coleoptera: Staphylinidae) was observed to preferentially predate upon *M. aeneus* larvae significantly more than the larvae of *D. brassicae* and other food items (Schlein and Büchs, 2004).

In review of the literature regarding potential natural enemies of pollen beetles, it appears that if managed correctly, **pollen beetles can be controlled**. Direct parasitism by *D. capito*, a reduction of host vigour due to multi-parasitism, or the forced expression of defensive behaviours (for epigaeic control) in pollen beetles will all render pollen beetles more susceptible to death, and thus control.

- *Evidence of biological control directly impacting the pest*

Ferguson et al. (2003) found that 23.7% of dissected UK *M. aeneus* larvae were **parasitized**, predominantly from *T. heterocerus*, and to a lesser extent, *P. interstatialis*. Parasitoid larval survival was considerably lower (1.5% and 1.0% respectively) compared to *M. aeneus* survival (26.0%). The effect of density dependence of host *Meligethes* spp. was highlighted by Billqvist and Ekbom (2001), whereby increasing densities of *Meligethes* spp. larvae dropping to the soil resulted in a lower proportion of parasitism by *P. morionellus* on OSR. Billqvist and Ekbom (2001) found that *P. morionellus* parasitism varied between 25% and 53%, but when combined with *D. capito*, parasitism rates increased to between 31% and 66%. As *D. capito* oviposits into different host larval sizes (Osborne, 1960), and *P. morionellus* prefer ovipositing into large second-instar larvae (Winfield, 1963) in the flowering season, there is likely to be level of antagonistic competition between the two, and perhaps successful parasitism is not quite as high than it might be if these two parasitoids did not overlap. In another study however, *Phradis* spp. were caught in periods when host larvae were abundant in the flowers, whilst *D. capito* appeared in catches during the middle of August (Veromann *et al*., 2006), and therefore may not overlap as much as first thought.

Due to **multi-parasitism**, randomly egg laying univoltine parasitoids can reach parasitizaiton levels of more than 50%, as more than one egg (Nilsson and Andreasson, 1987) can be found within a larva. Parasitism efficiency is thus low, and is also limited by the short female parasitoid life-span, and under-utilized fecundity. Fritzsche (1957) reported that although having a presence of 200 ovarioles, *T. heterocerus* and *P.interstitialis* only laid 40 and 24 eggs respectively. Osborne (1960), and Nitzsche and Ulber (1998) found that *P. interstitialias* out-competed *T. heterocerus* in host larvae. The latter study suggested that this was likely due to earlier hatching, resulting in relatively more *P. interstitialis*, however, this could also be related to better *P. interstitialis* resistance to host defences (Osborne, 1960). Although the parasitoids aren't hyperparasitic, there is clearly an antagonising, negative effect by intraguild parasitoids.

When pollen beetles drop to the ground as a last-instar larva, they are susceptible to **foliage-dwelling** and **epigaeic predators** (Öberg et al., 2011). In a winter oilseed rape study in Sweden, Öberg et al. (2011) found that both genera *Pardosa* and *Theridion* spiders consume pollen beetles, particularly when pollen beetle larvae were available, using DNA-based molecular analysis. 13.5% of 673 hand-collected *Pardosa* spp. spiders, compared to 51.7% of 509 *Theridion impressum* contained pollen beetle DNA. The two spider guilds were thought to complement each other in space, as *Pardosa* spp. are actively searching epigaeic predators, whilst *Theridion* spp. construct webs near to the OSR flowers and pods (Öberg et al., 2011). Contrary to Denno et al. (2004) the spider genera are also complementary of each other in time (akin to flea beetle control in Section 2.2.4.3), as *Pardosa* spp. consume pollen beetles earlier in the growing year, whilst *Theridion* spp. feed later, much like the temporal partition seen with the two genera and *Phyllotreta* flea beetles by Ekbom et al. (2014). It is important to remember that the total proportion of pollen beetle DNA found within the gut analysis cannot be taken that *Theridion* spp. are higher ranking control agents, as the prey detectability half-life is not known for *Theridion* (Greenstone et al., 2010). 100% of pollen beetle DNA could be detected in *Pardosa* spp. guts over 24 hours, however, fell considerably to 11% within 48 hours (Cassel-Lundhagen et al., 2009). If the prey detectability half-life for *Theridion* spp. is longer than in *Pardosa*, and *Pardosa* are known to have a wider diet breadth than the sit-and-wait strategy of *Theridion* spp. (Nyffeler, 1999), then *Pardosa* may actually be more effective at pollen beetle control. With *Pardosa,* Öberg et al. (2011) found that the density of alternative prey negatively affected the number of *Pardosa* individuals that tested positive for pollen beetle consumption, indicating that alternative prey may draw *Pardosa* spiders away from primary pest species. In this way, it is impossible to create a one-size fits-all strategy to increasing biological control of crop pests as food webs are sensitive to additional interactions.

Other natural enemies of *M. aeneus* cannot be over-looked in their regulation potential, although these epigaeic predators are probably facultative polyphagous predators. An IPM plan by DEFRA

(2004) identified five UK carabid species that were **temporally associated** with *B. napus* pest larvae when *Meligethes* spp. dropped from the canopy to undergo pupation. *Nebria brevicollis* Fabricius was seen as the most important Carabid predator, alongside *Asaphidion flavipes* Linnaeus, and *Amara similata* Gyllenhal (all Coleoptera: Carabidae), which were all spatially associated with *Meligethes* spp., and were supported by Collembola when *Meligethes* spp. were limited. Warner et al. (2008) found that *N. brevicollis, A. similata*, and *Asaphidion* spp., were **spatially associated** with *M. aeneus* larvae in May, though the latter is unlikely to predate pollen beetles due to its size. *N. brevicollis* has an unorthodox life-cycle as an autumn breeding carabid, as it emerges between April and May (Penney, 1969) ubiquitously within the crop (Warner et al., 2008), and is known to consume pollen beetle larvae during this period in winter OSR (Piper and Williams, 2004), and therefore is a potentially beneficial biological control agent. Caught in greater abundance by Warner et al. (2008) and others in OSR (Luka et al., 1998), was *A. similata*, which has been known to consume pollen beetles in the laboratory (Schlein and Büchs, 2004). Their extent as epigeal predators remains in doubt however as they were mostly caught in water traps (Warner et al., 2008). *N. brevicollis* was spatially associated with collembolan prey, may have allowed the carabid to remain coincident with pollen beetle larvae at the same time (Warner et al., 2008). In times when pest populations are low, it is vital that natural generalist natural enemies are supplemented, to ensure future generations of control. It is not clear however whether collembolan prey aid or inhibit pest control within arable fields (Warner et al., 2008).

- *Evidence that a certain habitat and/or management practice improves actual biological control*

Field margins greatly influence levels of parasitism rates, which decline towards the centres of fields (Hausammann, 1996). As other brassica crops have been shown to yield greater parasitism rates, namely when *Sinapis alba* Linnaeus (Brassicales: Brassicaceae) (white mustard) is a host-plant (Billqvist and Ekbom, 2001), greater diversity of brassicas in the landscape may enhance parasitoid populations. Old fallow and unploughed strips with natural vegetation enhance parasitoid populations, allowing population increases and dispersal into neighbouring fields. The presence of flowering margins on emergence are insignificant for univoltine parasitoids (Thies and Tscharntke, 1999), whereas, for multivoltine species such as *D. capito*, feeding from pollen and nectar is mandatory, highlighting the vital importance for bio-diverse flowering margins (Nilsson, 2003) or nectar and pollen strips (Rusch et al., 2011). In field semi-natural habitats are crucial too. Predators will overwinter in field-boundaries (Sotherton, 1984), and disperse slowly into the field (Coombes and Sotherton, 1986), assisted by the presence of 'beetle banks' which reduce the field size, allowing more rapid colonisation by predators (Sotherton, 1995). As beetle banks have been shown to support polyphagous predators, it is important to incorporate them into farming landscapes, particularly larger OSR fields.

Nielsen and Philipsen (2005) found that pollen beetles are susceptible to **entomopathogenic nematodes** during pupation within soil, in laboratory conditions. Though it was difficult for the authors to differentiate between mortality due to parasitism by wasps and by nematodes, it was concluded that nematodes had the potential to reduce *Meligethes* spp. emergence. This study was mirrored by Menzler-Hokkanen and Hokkanen (2005), which found that *Steinernema feltiae* Steiner (Rhabditida Steinernematidae) was able to reduce pollen beetle emergence by 93.8% under field conditions, when one million infective juveniles were applied per square meter. However, at such a scale as would be necessary for control within UK OSR, it remains unknown as to whether this would ever be feasible.

2.3.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

B. napus is sown in a different field each autumn or spring, as it is usually a break crop (Williams and Cook, 2010), so it is of vital importance that pollen beetles are efficient searchers of their host plants after spring emergence (Fritzsche, 1957).

Land management practices will greatly influence the natural enemy survival of *M. aeneus* (Nilsson, 1985), as the parasitoids complete their pupation within the pollen beetle chamber in the soil. A reduction of parasitoid populations of 50-75% has been recorded in Finnish, Swedish, and German experiments when **ploughing or tillage** has occurred (Nilsson, 1985). Alternatively, direct drilling of the new crop following rape harvest, and soil loosening (Nitzsche and Ulber, 1998) has less of an effect on parasitoid emergence in the following spring. To aid parasitoid migration from their overwintering sites, new crops should be drilled relatively close to the former *B. napus* crop field, as reproductive strategies supress long-migratory ability (Nilsson, 2003). Valantin-Morison et al. (2007) found that **soil nitrogen** content at sowing had a significant effect on the proportion of flowers potentially destroyed by pollen beetles. It may be that soil nitrogen improves plant vigour, which may compensate for the pollen beetle damage on new racemes (Podlaska et al., 1996).

Crop establishment may also be important for pollen beetle control. (Valantin-Morison et al., 2007) went on to show that high OSR plant density was associated with a lower level of damage by pollen beetles, and that pollen beetles favoured taller plants, as did (Ferguson et al., 2003) as plant height is related to the growth stage of the main raceme. Crop management however, though suffering less attacks by pests, supposedly would not reduce pest incidence sufficiently in regions of high pest incidence (Valantin-Morison et al., 2007). While the growth of winter and spring oilseed and turnip rape in the same area should be avoided due to brassica pod midge (*Dasineura brassicae*) and cabbage aphid (*Brevicoryne brassicae*), multivoltine parasitoids like *D. capito* in the UK are favoured by the presence of both spring and winter rape crops in the **same area**, particularly if there their phenologies differ (Jourdheuil, 1960). Using a border trap crop at a different phenological stage has also been shown to be effective, as flowering *B. napus* on field margins successfully prevents migration further in-field, to the vulnerable crop at green bud stage (DEFRA, 2004). Various studies have found trap crops to have controlled pollen beetles (Cook et al., 2006; Hokkanen, 1989; Hokkanen et al., 1986).

In an Estonian study by (Veromann et al., 2006), pollen beetles (namely *M. aeneus*) were considered the key pest in winter and spring oilseed rape, particularly early June when 10-20% of pods had reached their final size. There was a distinct difference in *M. aeneus* abundance on the **seasonality** of crops, as double the *M. aeneus* were found on spring OSR compared to winter OSR (Veromann et al., 2006), and similar results were found by (Šedivý and Vašák, 2002). Veromann et al. (2006) also found that *Meligethes viridescens* Fabricius (Coleoptera: Nitidulidae) (bronze or rape blossom beetle) in winter OSR was found to be relatively abundant on winter-, but not spring-OSR.

It is unclear whether **crop complexity** hinders or aids parasitism by pollen beetle parasitoids, as a Swedish study showed no significant difference in parasitism between *S. alba* (white mustard) and OSR as host plants (Ferguson et al., 2003). Hokkanen (1989) found that more intensive and homogeneous OSR cropping yielded the lowest levels of parasitism by *D. capito* and *P. morionellus*, whilst the highest rates were in patchier landscapes. Some studies have explored the resistance potential of different crop cultivars to pollen beetles (Bartlet et al., 1999; Ekbom and Ferdinand, 2003). **Landscape complexity** is also highlighted as an important factor in pollen beetle damage, as Valantin-Morison et al. (2007) found that the proportion of plants attacked by pollen beetles was positively correlated with the proportion of land under winter OSR cropping in the region. In regions with more than 1.2% of land under winter OSR cropping, the most severe attacks occurred in fields bordered by trees, hedges, and bushes. Valantin-Morison et al. (2007) found that the surrounding environment, was highly significant effect on pollen beetle related crop damage (48%). Despite this, it is vital to remember that field margins can increase pest control in the field (see Section 1.3.4.2).

Parasitoid host selection mechanisms have not been duly studied, but it is thought that volatiles from either *Meligethes* spp., OSR flowers or stamen and bud herbivory aid parasitoid searching (Nilsson, 2003). Jourdheuil (1960) noted that more multivoltine parasitoids were found in areas of more **intensive flowering**, irrespective of host population density, indicating that synomones (beneficial to both emitter (plant) and receiver (parasitoid)) may be the dominating stimuli for host selection. Glucosinolates (mustard oils), or more specifically allyglucosinolate of Brassicaceae, attract pest herbivores to the plant host (Price, 1981), and in the same way, may also attract their natural enemies. At present, synomones, or herbivore-induce plant volatiles (HIPVs), appears to be the dominant pathway for parasitoid attraction. The use of plant varieties that emit more HIPVs, the release of synthetic HIPVs, or genetic manipulation to optimise HIPV release may successfully attract more parasitoids (Peñaflor and Bento, 2013). Apart from Husberg and Hokkanen (2001) who studied the effects of the entomopathogenic fungus, *Metarhizium anisopliae* on pollen beetles, natural insecticides are relatively unexplored.

2.3.5. Outlook

Table 2.3.5.1. A summarising table of management implications to control pollen beetles in a sustainable manner.

Chemical control
• Pollen beetle resistance to pyrethroid is now widespread in the UK (HGCA, 2014). • Pest parasitoids are more sensitive to insecticide application than their hosts (Veromann et al., 2006). • To enhance parasitism *and* use a form of chemical control would be to spray during the early bud growth stage as later pesticide applications will harm all parasitoids (Hokkanen et al., 1988).
Biological control
• Parasitoids should be encouraged using intensively flowering (Jourdheuil, 1960) field margins which enhance the levels of parasitism (Hausammann, 1996). • Spider populations should also be encouraged, including wolf and tangle-web spiders, though alternative prey items may reduce wolf spider control of pollen beetles (Öberg et al., 2011). • Carabids should also be encouraged, as they appear to be associated with pollen beetles that drop to the soil surface (DEFRA, 2004). • Greater diversity of brassica plants in landscape may enhance parasitism levels (Billqvist and Ekbom, 2001).
Cultural control
• Avoid ploughing which can reduce parasitoid populations by 50-75% (Nilsson, 1985). • Trap cropping using flowering OSR successfully prevents pollen beetle migration further in-field, to the vulnerable maincrop crop at green bud stage (DEFRA, 2004). • Higher soil nitrogen content at sowing may reduce the proportion of flowers destroyed pollen beetles (Valantin-Morison et al., 2007) due to improved plant vigour (Podlaska et al., 1996). • Higher OSR plant density has been associated with reduced pollen beetle damage (Ferguson et al., 2003). • The use of plant varieties that emit more HIPVs (herbivore-induce plant volatiles), the release of synthetic HIPVs, or genetic manipulation to optimise HIPV release may successfully attract more parasitoids (Peñaflor and Bento, 2013). • Use of spring OSR due to crop failure, near to winter rape crops can be beneficial for parasitoids (which are poor migrators), particularly if the crop phenologies differ. It should be noted that this aids brassica pod midge and cabbage aphid colonization (Jourdheuil, 1960).

2.4. Aphids (Aphididae spp.)

2.4.1. Introduction & life history

There are two serious aphid pests of OSR; *Brevicoryne brassicae* Linnaeus (cabbage aphid) and *Myzus persicae* Sulzer (peach-potato aphid) (both Hemiptera: Aphididae), which share similar life histories, as can be seen in Table 2.4.1.1.

Table 2.4.1.1. Life histories of the two pest aphid species of OSR (HGCA, 2014).

Aphid species	Autumn	Winter	Spring	Summer
Brevicoryne brassicae (**cabbage aphid**)	Winged adults allow for migration to new brassica crops, multiplying in hot, dry conditions (**Mar-Oct**).	Most overwinter as active stages on brassica crops and wild hosts. Some overwinter as eggs (**Nov-Feb**).	Winged adults allow migration to new brassica crops, multiplying in hot, dry conditions (**Mar-Oct**).	Winged adults allow migration to new brassica crops, multiplying in hot, dry conditions (**Mar-Oct**).
Myzus persicae (**peach-potato aphid**)	Adults infest OSR and vegetable brassicas during mild autumns and transfer viruses (**Sep-Dec**).	Asexual females overwinter in brassica and herbaceous crops and weeds (small proportion of eggs overwinter on peach and nectarine trees). Cold weather reduces survival. (**Nov-Feb**).	Adults migrate into a variety of summer crops, multiply quickly (**Mar-Aug**).	Populations peak (**Jul**) Another small peak (**Aug-Sep**).

2.4.2. Damage/presence

Mild winters can accentuate aphid infestations within winter OSR to damaging levels, as overwintering survival is improved. Spring OSR can also be severely infested after mild winters. Similarly, hot and dry summers will also cause populations to soar (HGCA, 2014).

The **cabbage aphid** is an important pest of OSR and vegetable brassicas, including broccoli, cauliflower, and mustard (Blackman and Eastop, 2000). Cabbage aphid infestations can lead to foliage distortion and contamination of produce by wax, cast skins, honeydew, and the aphids themselves. The growth of a young plant can be stunted (Bonnemaison, 1965), and later indirectly killed in unfavourable weather. Infestations can cause leaf distortions, mid-rib twisting, and chlorotic patches (HGCA, 2014). Cabbage aphids also act as vectors of several viruses within vegetable brassicas, including **turnip mosaic virus** (TuMV) and **cauliflower mosaic virus** (CaMV), which causes leaf mottling, vein clearing, stunting, and black mottling and streaking on stems (HGCA, 2014).

The **peach-potato aphid** has a broader diet than the cabbage aphid, consuming OSR, vegetable brassicas, potatoes, sugar beet, and lettuce. Only when infestations reach very high levels will significant feeding damage occur, however, even low densities allow for the transmission of viruses, which do cause serious economic damage. Like the cabbage aphid, the peach-potato aphid also transmits the **turnip yellow virus** (TuYV) and **cauliflower mosaic virus** (CaMV), the former resulting in a yield loss averaging 15% in OSR, but rising to 30% in some cases. Peach-potato aphids also transmit several other viruses, including the potato leaf roll virus (PLRV), potato virus A (PVA), potato virus Y (PVY), beet yellow virus (BYV), beet chlorosis virus (BChV), and beet mild yellowing virus (BMYV) (HGCA, 2014). In UK OSR, virus transmission is heightened in **early-sown autumn** crops during mild autumns, whilst **late-sown spring** crops are more susceptible after mild winters (HGCA, 2014).

2.4.3. Pest thresholds

Monitoring of aphids on their associated host brassicas should be executed to assess whether control is necessary. AHDB Aphid News provides information on aphid migration (HGCA, 2014). There is unfortunately no threshold available for peach-potato aphids within OSR. This is not the case for the cabbage aphid however, where HGCA (2014) advise that OSR should be monitored for infestation, as seen in Table 2.4.3.1.

Table 2.4.3.1. HGCA (2014) threshold table for treatment. Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Crop	Threshold
Winter OSR	>13% plants infested with *Brevicoryne brassicae* before petal fall
Spring OSR	>4% plants infested with *Brevicoryne brassicae* before petal fall

2.4.4. Potential for control

2.4.4.1. Biological control

- *Identify potential biological control agents*

Natural enemies of the cabbage aphid include parasitic wasps, ladybirds, hoverflies, lacewings, predatory flies, spiders, and insect-pathogenic fungi. Providing diverse habitats that can harbour predator and parasitoid communities, may help to control the cabbage aphid. These predator-prey assemblages may not be effective in preventing virus transmission however, as relatively low aphid densities can even result in TuMV and CaMV transmission (HGCA, 2014).

For more information on the use of artificial floral resources to enhance hoverfly egg laying in-field, please see Section 4.3.4.2.

The **endoparasitoid**, *Diaretiella rape* MacIntosh (Hymenoptera: Braconidae), is a primary parasitoid of over 60 aphid species across the world, including important UK aphid species including the peach-potato aphid (Pike et al., 1999), and is regarded as a specialist on Brassicaceae host plants, with the cabbage aphid as its main host (Blande et al., 2004; Pike et al., 1999).

Mobility is thought to be a vital feature that determines the effectiveness of the natural enemies such as syrphids (Chaplin-Kramer et al., 2013), as exclusion experiments have demonstrated that pest populations are better supressed by flying rather than ground-dwelling natural enemies (Holland et al., 2012, 2008; Schmidt et al., 2003). As hoverflies are not usually monophagous, the diet variation (of multiple aphid species) may buffer against stochasticity and fluctuations of prey densities (Chaplin-Kramer et al., 2013). **Hunting strategy** is also crucial, particularly for generalist predators. Depending on the availability of prey items, some *Pardosa* individuals adopt a "sit-and-wait" predators and ambush their prey (Edgar, 1969), whilst others rely on active hunting to encounter more sedentary prey. Samu et al. (2003)described *Pardosa agrestis* as a "sit-and-move forager", as it moves from spot to spot waiting in ambush. Kuusk and Ekbom (2010) postulated that *Pardosa* change their hunting style depending on sedentary-mobile prey ratios (see aphid control in cereals in Section 1.1.4.2). The authors proposed that when springtails (Collembola) were numerous, "sit-and-wait" strategies were adopted by *Pardosa*. This has important implications, as *Pardosa* were more inclined to actively forage when collembolans were less numerous, allowing for encounters with (and predation of) sedentary aphids.

Entomopathogenic fungi have also been identified as potential biological control agents, as genera such as *Beauveria* spp. are known to kill Lepidoptera (Soetopo, 2004), Coleoptera (Lord, 2001; Wraight and Ramos, 2002), and Homoptera (Wraight et al., 1998). Although Akbari et al. (2013) found that concentrations (1 x 10^7 conidia ml^{-1}) caused significantly greater mortality in *B. brassicae* than other fungi isolates in laboratory conditions, it is unclear whether this would be economically feasible at field scale. In the same way, the entomopathogenic extent of these fungi is also uncertain. It may be that they have a similarly deleterious effect on non-target insects to pesticides.

- *Evidence of biological control directly impacting the pest*

Moayeri et al. (2013) found that in laboratory conditions, *Diaretiella rapae* was able to **parasitize** the cabbage aphid (*B. brassicae*) exhibiting a type II functional response. Fathipour and Hosseini (2006) also found the same response between both individuals, whilst Yu et al. (1993) found the same response between *D. rapae* and the potato-peach aphid (*Myzus persicae*). Larger host aphid species, like the cabbage aphid) are thought to require a greater handling time by parasitoids compared to the smaller Russian wheat aphid (*Diuraphis noxia* Mordvilko for example (Hofsvang and Hågvar, 1986). Moayeri et al. (2013) found that lower temperatures required significantly longer handling times of host aphids. The authors conclude that in light of present research, *D. rapae* can be an effective biological control agent at temperatures between 17 and 30 °C. Particularly, with climate change forecasts, and the fact that *D. rapae* performs best at 25 °C, more *D. rapae* parasitism may occur in the UK.

Suenaga and Hamamura (2014) investigated the suppression of pest populations within small enclosed plots by the wolf spider, ***Pardosa** astrigera* L. Koch, in Japan. Peach-potato aphid (*M. persicae*) densities were reduced in the autumn experiments by *P. astrigera*. Their results indidcate that *P. astigera* should suppress the pest population if the pest species is abundant early in the crop season, with populations that remain stable. It was suggested by the authors that the lack of pest suppression during the season in which the pest populations are low is owed to **prey switching**. Fundamentally however, this suppression did not increase the cabbage yield. Indeed, no marked effect of pest suppression was experienced in the cabbage yield, which is the primary driver for biological control. Ekbom et al. (2014) found that *Phylloneta* spp. (tangle-web spiders) predated pest beetles in OSR later in the season to *Pardosa* spp., indicating that both predatory genera can be complimentary in time. As *Phylloneta* spp. occupy a niche within the foliage, they may be more likely to consume aphids that share the tangle-web habitat.

In Sweden, Kuusk et al. (2008) demonstrated that *Pardosa*, or wolf-spiders feed on the bird cherry-oat aphid (*Rhopalosiphum padi* L.) within spring-sown cereal fields at low pest densities. In a study based on gut-content anaylsis of field-collected *Pardosa,* Kuusk and Ekbom (2010) found that even at **low aphid densities**, *Pardosa* spiders were able to suppress aphid populations to below an economic threshold (Chiverton, 1986; Östman et al., 2001a). Evidently, aphids will serve as prey items for *Pardosa* spp., however, the cabbage aphid and peach-potato aphid is likely less to be encountered by *Pardosa* spiders than the bird-cherry oat aphid, which will infest the lower leaves and stems before higher parts of the plants. In this sense, *Pardosa* spp. may only suppress aphid pests in near-epigaeic circumstances. Please refer to Section 1.1.4.2 for more information regarding these cereal aphid pests, and how improving springtail abundance may cause predator assemblages in-field.

- *Evidence that a certain habitat and/or management practice improves actual biological control*

Chaplin-Kramer et al. (2013) investigated the natural enemy service provisions by natural habitats, and how this affected cabbage aphid (*B. brassicae*) populations within organic broccoli (*Brassica oleracea,* var. *italic* cv. Gypsy) fields in North America. By analysing weekly insect samples over the course of three years, the authors found that lower cabbage aphid population growth was associated with **syrphid** abundance found on farms in more natural landscapes, in spite of considerable inter-annual aphid density variations. Syrphid diversity was positively correlated with **natural habitat** at all spatial scales (0.5-3 km at 0.5km increments), but was stronger and only significant at smaller scales. As all of the sites were of organic status, Chaplin-Kramer et al. (2013) were confident that the positive response of syrphid populations was to natural habitat abundance, as opposed to pesticide intensity, which has been considered as a stronger driving force of natural enemy abundance by some (Hendrickx et al., 2007; Jonsson et al., 2012).

Hoverflies which have aphidophagous life stages (Diptera: Syrphidae: Syrphinae) are probably extremely dependent upon floral resources during their adult life stage (Van Rijn et al., 2013). Protein-rich **pollen** resources have been shown as necessary for reaching sexual maturity (Haslett, 1989; Laubertie et al., 2012). Sugar-rich **nectar** is on the other hand, a vital energy resource, of which are diminished by demanding activities including flight (Gilbert, 1985; Haslett, 1989). The sugar-rich product of aphids known as honeydew, secreted by aphid's corniclula, has been reported to have been used by hoverflies (Hogervorst et al., 2007; Ssymank and Gilbert, 1993). It has also been shown to act as a searching cue and an oviposition stimulus for adult aphidophagous hoverflies (Budenberg and Powell, 1992; Haubruge et al., 2009). In a caged cabbage study, Van Rijn et al. (2013) found that honeydew consumption by hoverflies enhances adult hoverfly survival in the presence *and* absence of abundant floral resources. On the contrary, parasitoids often perform significantly worse when utilizing aphid honeydew (including honeydew from *B. brassicae*) (Wäckers et al., 2008). Hoverflies still however require pollen for floral resources for their reproduction, which is often much more broadly accessible than extrafloral nectaries in contemporary agricultural landscapes (Van Rijn and Wäckers, 2010). Van Rijn et al. (2013) confirm that hoverflies are only able to reproduce when pollen-providing flowers are present and available. Hindayana et al. (2001) found that hoverfly fecundity is highly variable depending on dietary host plants.

Prasad and Kabaluk (2009) suggested that for effective biological control of aphids, hoverflies should oviposit their predatory offspring in the crop when aphid numbers are low. Within caged conditions, one fertile female hoverfly produced offspring that were capable of supressing the growth of a cabbage aphid colony, originally consisting of 30 individuals (Van Rijn et al., 2013). Van Rijn et al. (2013) confirm that predatory hoverflies can control aphid numbers efficiently, even the cabbage aphid despite their defensive system (Kos et al., 2012), but only when sufficient **floral resources** are available. *Fagopyrum esculentum* Moench (buckwheat) was selected for its suitability to aphidophagous hoverflies and other natural enemies (Bowie et al., 1995), though other studies show that many species provide floral resources that are not suitable (Laubertie et al., 2012; Van Rijn and Wäckers, 2010).

In small cabbage (*Brassica oleracea* L. var. *capitata* 'Kinkei 201') plots, Suenaga and Hamamura (2015) proposed that increased spider activity density in the spider-addition plots can be ascribed to the application of **straw mulch** which may have provided refugia for the spiders. From their observations, once the straw mulch was added before weeds provided cover, the spiders dispersed reducing spider-spider interaction rates. This could be very important, as the spiders are known to have cannibalistic tendencies, and therefore, refugia provision may reduce cannibalistic interactions (Halaj et al., 2000; Langellotto and Denno, 2006; Rickers and Scheu, 2005). Although straw mulch may not be a feasible option within large-scale UK agriculture, it does demonstrate that by diversifying the system, intraguild predation can be reduced, allowing for stable predator populations. Suenaga and Hamamura (2015) implied that weed cover may also act as a refuge, and perhaps in areas where weeds are not too problematic, conservation headlands could be adopted, to improve predator refuge in field perimeters. Indeed, **enhanced structural complexity** may also serve as a refuge for pest populations, particularly those such as edge-distributed brassica pod midge (Warner et al., 2008).

Please refer to Section 1.5.4.2 for more information regarding how the enhancement of alternative prey populations may increase predator (*Pardosa* spp.) abundance within cereal crops.

2.4.4.2. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

Jahan et al. (2013) found that the selection of cauliflower (*Brassica oleracea* var. *botrytis*) **cultivar** had a significant effect on the development, reproduction, and longevity of the cabbage aphid (*B. brassicae*) in laboratory conditions. Although the study did not focus on OSR, it did show that cultivar selection of other Brassicaceae crops can influence potential biological control. Munthali and Tshegofatso (2014) firstly advise that high chlorophyll and water content reduces aphid abundance on leaves, as a high chlorophyll-diet will yield reduced reproduction within aphids, whilst higher water contents will dilute the nutrient-poor phloem sap. Secondly, they also advise that thin leaves with a low protein content will reduce honeydew damage which can render the goods as unmarketable. Although these studies were conducted in environments very different from those in the UK, the implications regarding selective breeding, and cultivar selection are far-reaching, and should be adopted to alleviate aphid damage.

Simon et al. (2014) showed that in Mediterranean France, a permanent **mesh net covering** a cabbage crop (*Brassica oleracea* var. *capitata*) significantly reduced *B. brassicae* populations, but had no effects on *M. persicae* and *Lipaphus erysimi* Kaltenbach (mustard/turnip aphid), which is probably explained by the more globular and larger size (>3 mm) of *B. brassicae* compared to the other two which are <1.5 mm in length. The netting also improved the microclimate and thus crop yields, though the netting size (0.73 mm and 1.6 mm) did not cause significant variations. In areas where *B. brassicae* is a major pest, netting over OSR could be adopted, however, considerable labour would be involved. Additionally, no research has explored the potential exclusion of smaller aphids using finer nets, and whether these would affect the microclimate. More research is needed to explore other potential effects of netting, such as whether netting would act as a trap for emerging soil pests post-pupation.

2.4.5. Outlook

Table 2.4.5.1. A summarising table of management implications to control aphids in a sustainable manner.

Biological control
• Parasitoids and generalist predators including spiders, carabids, ladybirds, lacewings, and predatory flies should be encouraged. • Predatory hoverfly larvae can control aphid populations effectively (Van Rijn et al., 2013) and populations can be improved by increasing the area of semi-natural habitat (Chaplin-Kramer et al., 2013), within organic **broccoli** fields. • Flowering habitats are important for the production of predatory larvae (Laubertie et al., 2012). • The use of straw mulch in small-scale **vegetable** fields may prevent spiders from cannibalistic tendencies, focusing on aphid control, by providing refuge from other spiders (Suenaga and Hamamura, 2015).
Cultural control
• Selecting **vegetable** brassicas with high chlorophyll and water content reduces cabbage aphid abundance, while thin leaves with a low protein content will reduce honeydew damage to prevent unmarketable vegetables (Munthali and Tshegofatso, 2014). • A fine mesh net cover over cabbage and other **vegetables** significantly reduces cabbage aphid (> 3mm in length) damage.

2.5. Weevils (*Ceutorhynchus* spp.)

2.5.1. Introduction & life history

Three weevil species of the genus, *Ceutorhynchus* (Coleoptera: Curculionidae) are known pests of brassicas, to varying extents. All three species are univoltine and complete three larval instars before reaching maturity by feeding inside the leaves and stems of plants (Alford et al., 2003; Cox, 1998; Graham and Gould, 1980). **Cabbage seed weevils** (*Ceutorhynchus assimilis* Paykull) lay their eggs in OSR pods which have previously not been oviposited into (Ferguson et al., 1999), and the larvae feed on the developing seed (HGCA, 2014). Much of the time, yield losses are greater due to the bored exit holes in the pods which allow brassica pod midge, *Dasineura brassicae* Winnertz (Diptera: Cecidomyiidae), to gain entry. OSR crops in the north of the UK are most at risk (HGCA, 2014).

The occasional pest, **rape winter stem weevil** (*Ceutorhynchus pictarsis* Gyllenhal), causes harm in its larval life stage, by feeding within the stems. Attacks originated around Lincolnshire and Cambridgeshire, but has since spread further afield, often to a greater extent in wooded landscapes (HGCA, 2014).

The **cabbage stem weevil**, *Ceutorhynchus quadridens* Panzer (syn. *C. pallidactylus* Marsham) is known to infest vegetable brassicas as well as OSR, and can be particularly damaging to high value crops such as cauliflower. Adults and larvae can cause damage, which is more prevalent in the southern counties within spring crops (HGCA, 2014).

Table 2.5.1.1. Life histories of three UK OSR *Ceutorhynchus* spp. pests.

Weevil species	**Autumn**	**Winter**	**Spring**	**Summer**
Ceutorhynchus assimilis (syn. *obstrictus*) (**Cabbage seed weevil**)	**Sep-Dec**: Adults will continue to feed on other brassica crops if present, until hibernation in wooded areas [1] under leaf litter [2].	**Jan-Mar**: Adults continue to overwinter [1].	**Apr-Jun**: Adults migrate from overwintering sites into crop, feeding on brassica buds and flowers before oviposition [2]. Eggs are laid in pod [1] punctures as single eggs [3].	**Jun-Aug**: Larvae feed within the pod [1], and complete three instars consuming 3-6 seeds each [3]. Mature larvae bore out of pod and pupate in soil for 9-30 days[2]. **Aug**: New generation of adults emerge [1] and are capable of dispersing several km for food [4].
Ceutorhynchus pictarsis (**Rape winter stem weevil**)	**Sep-Oct**: Adults invade autumn-sown OSR, feeding on leaves[1].	**Oct-Mar**: eggs laid in punctures and crevices in the leaf stalk and plant crown. Larvae hatch and then tunnel into stem to feed [1].	**Mar-Apr**: Mature larvae drop to the soil to pupate [1].	**May-Aug**: Adults emerge from the soil find refuge in woods and hedges [1].
Ceutorhynchus quadridens (syn. *pallidactylus*) (**Cabbage stem weevil**)	**Sep-Mar**: Adults overwinter in sheltered locations [1].	**Sep-Mar**: Adults overwinter in sheltered locations [1].	**Apr-May**: Adults migrate from overwintering sites into crop. Eggs are laid under the leaf surface [1], in small groups [5].	**May-Jul**: First and second instar larvae tunnel inside the leaf petioles and midribs, before boring into the stem. Mature larvae bore out of stem[6] and pupate in the soil [1]. **Aug**: Adults emerge and feed for a short time [1].

[1](HGCA, 2014), [2](Dmoch, 1965), [3](Carcamo et al., 2001), [4](Doucette, 1947), [5](Alford et al., 2003), [6](Barari *et al*. 2005)

2.5.2. Damage/presence

Yield losses from *C. assimilis* damage are potentially not particularly high. They do however pave the way for the brassica pod midge to cause damage. The *C. assimilis*, upon exit as a larva, will bore through exit holes, and fall to the soil for pupation (HGCA, 2014). This **pod damage** can reduce OSR crop yields by approximately 18% (Alford et al., 2003). *C. quadridens* can at times be particularly damaging to high value vegetable brassicas, whilst *C. pictarsis* is regarded as an occasional pest (HGCA, 2014).

Veromann et al. (2006) found that *C. assimilis* were relatively abundant in **winter OSR** in comparison to other OSR pests, whilst in spring OSR, they were much less abundant. Kevväi et al. (2006) found similar abundances and synchrony of the *C. assimilis* in winter OSR in Estonian farms. Although some studies have found that pod damage in winter OSR was only 9.9%, compared to 1.2% in spring OSR, HGCA (2014) regard spring OSR in the UK as a higher risk crop, particularly in the southern counties. Veromann et al. (2006) found higher numbers in winter OSR, it is likely that the OSR plants can compensate for the damage due in-part to earlier flowering and a longer growing season (Tarang et al., 2004) than in spring OSR. In an Estonian study, Kevväi et al. (2006) found that **colonisation** occurred during OSR flowering at GS 63-66, whilst the peak *C. assimilis* abundance was at growth stage 78-80, when most pods were fully sized. In another study, *C. assimilis* abundance was greatest in early June (10-20% of pods had reached final size), but despite their abundance, no larval damage to the pods was observed, suggesting that the pest infestation was not synchronised with the crop growth stage Veromann et al. (2006). Veromann et al. (2006) suggested this is because the pests were sexually immature or the crop growth stage was inappropriate for egg laying. In this way, although *C. assimilis* abundance may be high, the extent of larval damage dictates whether they can be considered a pest. In a UK study, *C. quadridens* were caught in greatest abundance in early April when green buds were starting to extend, until the end of June, when the flowering senesced and seeds were brown within pods (Barari et al., 2005).

In review of a whole-system approach, the *C. assimilis* was found in greater numbers in Estonian **integrated systems** (non-inversion tillage and no insecticide use) than in standard cropping farming systems, though this difference was not significantly different (Kevväi et al., 2006).

2.5.3. Pest thresholds

HGCA (2014) have no published thresholds for direct *Ceutorhynchus* spp. control, however, it is advised that crops are checked in early summer for adults emerging from overwintering sites. The use of water traps for catching adults may indicate when females are egg-laying, which could lead on larval, adult, and brassica pod midge damage.

For the control of *Dasineura brassicae* (brassica pod midge), which relies upon the bore holes created by *C. assimilis*, HGCA (2014) suggest that 0.5 weevils per plant or 1.0 weevils per plant in the north of the UK and elsewhere respectively, represents the threshold for control. This control should alleviate *D. brassicae* damage. It has been suggested that damage caused by *C. assimilis* exceeding 26% (of pods damaged per plant) is considered to be the infestation rate at which yield loss will occur (Buntin, 1999; Free and Williams, 1978; Lerin, 1984). **Adequate control of *C. assimilis* will also control *D. brassicae*, the latter of which causes yield-loss.**

2.5.4. Potential for control

2.5.4.1. Chemical control

After seed treatments and autumn sprays for winter OSR pests, further insecticide is used to control spring pests including the *C. assimilis*. Kevväi et al. (2006) found that insecticide treatment of winter OSR was synchronised with *C. assimilis* parasitoid peak abundance, and therefore, around half of the parasitoids are likely to have been killed (Alford et al., 1995; Murchie et al., 1997). Within spring OSR, although insecticide treatment was assumed to have no detrimental on host parasitoids as the treatment occurred during the flowering stage, it may have had a detrimental effect on **non-target** beneficial insects which are active during crop flowering (Walters and Young, 2003), such as predatory beetles and spiders.

A recent Polish study by Zamojska et al. (2014) found that *C. assimilis* was **resistant to neonicotinoids** to some extent, highlighting the need for control strategies that do not rely upon chemical inputs.

2.5.4.2. Biological control

- *Identify potential biological control agents*

C. assimilis is attacked by various parasitoids at every life-stage (HGCA, 2014), however *C. assimilis* larvae are most frequently targeted (Murchie et al., 1998). Over 20 known parasitoids of the *C.*

assimilis have been reported by some (Alford et al., 2003; Williams, 2003), whilst other reports suggest the pest is host to 34 species of parasitoid (Alford et al., 1995). Most commonly cited are the **ectoparasitoids of the larval stage**; *Trichomalus perfectus* Walker, *Mesopolobus morys* Walker, and *Stenomalina muscarum* Linnaeus (Hymenoptera: Pteromalidae). *T. perfectus* is regarded as the most abundant and important parasitoid known to attack the *C. assimilis* (Williams, 2003) and capable of controlling *C. assimilis* populations in excess of 70% (Alford et al., 1995). New generations are said to mate upon emergence and subsequently leave the crop before harvest, while the females overwinter (Williams, 2003). *S. muscarum* has been reported in the UK, though it is unclear whether the former two parasitoids are resident in the UK. Veromann et al. (2006) caught minimal amounts of *T. perfectus*, *M. morys*, and *Stenomalina gracilis* Walker (Hymenoptera: Pteromalidae) (within winter- and spring-OSR during May in two separate years. Likewise, Kevväi et al. (2006) also reported low abundances of these parasitoids, peaking 2-4 weeks after host arrival.

European reports of **endoparasitoid** attacks of *C. pallidactylus* by *Tersilochus tripartitus* Brischk (Jourdheuil, 1960), *T. exilis* Holmgren, and *T. obscurator* Aubert (Jourdheuil, 1960; Ulber, 2000) (all Hymenoptera: Ichneumonidae), though it is unclear as to whether these species are present in the UK (Barari et al., 2005). In a UK study**,** *T. obscurator* was caught in increasing numbers between mid-April to mid-June, but none thereafter (Barari et al., 2005).

Parasitoids of the family **Myrmaridae,** which are known to attack the *C. assimilis*, have been considered negligible in their control of the pest weevil (Williams, 2003). Interestingly, in an Estonian study, (Kovács et al., 2013) found that 15% of the emerging parasitoids of *C. assimilis* larvae were Mymarid, of which two species had never before been recorded as parasitoids of cabbage seed weevils; *A. tarsalis* Mathot and *A. arenbergi* Debauche (both Hymenoptera: Mymaridae). In light of their abundance, Mymarids may be more influential than previously thought.

- *Evidence of biological control directly impacting the pest*

Parasitism rates of the *C. assimilis* can be as high as 50% in Estonia (Veromann et al., 2013, 2010), and greater than 50% within Europe (Germany (Nissen, 1997), Switzerland (Buechi, 1993), and the UK (Murchie, 1996)). Herrström and Rosen (1964) found that in one location, *C. assimilis* larvae were fully parasitized (100%), predominantly by *M. morys*. Lower parasitism rates of 22.2% within integrated cropping systems were recorded in Kevväi et al. (2006) by *T. perfectus, S. gracilis,* and *M. morys*. *T. perfectus* dominated in spring and winter OSR in Estonia, accounting for 64.8% of emerged parasitoids from *C. assimilis* larvae, whilst *M. morys* and *S. gracilis* were proportionately less (28.6% and 6.6% respectively).

In a UK study, 99% of emerged parasitoids were *T. perfectus* from winter OSR, whilst in spring OSR, *M. morys* contributed to half of the actively parasitizing individuals (Williams, 2003). In this way, it is clear that *T. perfectus* and *M. morys* are the parasitoids achieve parasitism of *C. assimilis* and these two ectoparasitoids should be the focus for weevil biological control, particularly *C. assimilis*.

Epigaeic predators may also be important biological control agents, as *Anchomenus dorsalis* Pontoppidan was found to be **spatially associated** with *Ceutorhynchus* spp. larvae in June winter OSR fields (Warner et al., 2008). Vitally, the spring breeding *A. dorsalis* has been known to **consume** *Ceutorhynchus* spp. larvae in laboratory conditions (Warner, 2001). Although *A. dorsalis* is regarded as edge-distributed, as associated with the edge-distributed brassica pod midge (Warner et al., 2008), it may be capable of consuming *C. assimilis* larvae that are edge-distributed *and* centrally-distributed in the field, as it is capable of rapid migration into crops along the ground (Thomas et al., 2002).

- *Evidence that a certain habitat and/or management practice improves actual biological control*

In replicated small plots, Kovács et al. (2013) explored the **attractiveness** of members of the brassica family to *C. assimilis*, and whether the host plant would affect the oviposition preference of the pest's parasitoids. Over two years, they found that OSR was more attractive than *Brassica juncea* Linnaeus (Chinese mustard) and *B. rapa* (turnip mustard) to *C. assimilis*. Additionally, the parasitism rate on *B. juncea* and *B. rapa* was significantly higher than on OSR. The implications of this study could be far-reaching, as it suggests that more *B. juncea* and *B. rapa* within diversified landscapes would be unlikely to increase pest abundance, whilst *increasing* parasitism.

Effective control of *C. assimilis* require **parasitism** rates that exceed 32% (Hawkins and Cornell, 1994). Kovács et al. (2013) found that OSR was the only brassica crop which did not experience effective control (29.8% larvae were parasitized). Parasitism was dominated by *M. morys* and *T. perfectus* in Estonia, with the former comprising of 59.5% of the parasitoids (Kovács et al., 2013). In growing *B. rapa* and *B. juncea*, which appear to enhance parasitoid numbers and parasitism rates, interspecific competition may be reduced (Kovács et al., 2013), and enhance overall biological control within OSR.

2.5.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

To explain low levels of *C. assimilis* caught in spring OSR, Veromann et al. (2006) suggested that adult beetles may have already laid eggs in alternative brassicas, which were at a more suitable growth stage. By ensuring there are alternative brassica plants at a more advanced growth stage, egg-laying in OSR may be avoided. HGCA (2014) however, suggest that **early drilling** can reduce any potential *C. assimilis* risk, as more mature plants are able to tolerate feeding in late summer.

The basic presence of *C. assimilis* does not necessarily indicate that damage exhibited by *D. brassicae* will occur as a consequence, as was found in an Estonian study within **winter OSR.** Despite reporting *C. assimilis* presence, Veromann et al. (2006) reported no caught *D. brassicae*, and there was no sign of damage caused by *D. brassicae*. Even if *D. brassicae* were abundant, damage by *D. brassicae* is unlikely to have occurred in this study. Although *C. assimilis* were caught in abundance in traps, there was no evidence of larval pod damage, thought to be due to poor synchrony of *C. assimilis* with the crop growth stage. Due to the lack of *C. assimilis* induced bore holes, adult *D. brassicae* would be lacking in oviposition sites. In consideration of the findings by Veromann et al. (2006), selection of OSR crops that are asynchronous with *C. assimilis* life cycles could prevent *D. brassicae* damage. Veromann et al. (2006) suggests that winter OSR may be past its **optimal growth stage** for ovispositon by *C. assimilis* when it eventually arrives in the crop. By selecting winter OSR cropping as opposed to spring OSR cultivars in areas that have previously been subjected to *D. brassicae* and *C. assimilis* damage, damage may be avoided.

Dechert and Ulber (2004) observed that the rape stem weevil, *Ceutorhynchus napi* Gyllenhal, showed a significant preference for plants with larger stem diameters. Valantin-Morison et al. (2007) suggest that due to this selection inclination, **soil nitrogen** content and **sowing date** are likely to affect female egg-laying, as it will affect the stem diameter. Similar oviposition preference of UK *Ceutorhynchus* spp. may also occur.

Very few studies have focused on stem-mining weevil response to using **trap crops** (Buechi, 1995, 1990) where the use of turnip rape was preferred for feeding and oviposition, but did not prevent oviposition into OSR (Buechi, 1990). In a North American study by Carcamo et al. (2001) found that by using an earlier flowering Polish cultivar of turnip rape alongside (1-2 weeks earlier) and a later flowering Argentine cultivar of turnip rape, found that *C. assimilis* were concentrated within the trap strips. The authors suggested that in trapping the pests within the turnip rape, growers may be able to prevent damage to the maincrop by spraying the trap crop before the *C. assimilis* disperses, and thereby use insecticides more responsibly and to reduce non-target insect fatalities. However, in another North American study, Buntin (1998) found that the use of a spring OSR cultivar trap crop, planted at the same time around the periphery of the maincrop winter OSR, did trap *C. assimilis*, but later control with pyrethroid did not prevent yield loss of the unsprayed maincrop. Only Barari et al. (2005) have investigated trap crop efficiency within the UK (see flea beetle control in Section 2.2.4.3) who showed that turnip rape can reduce infestations of *C. quadridens* as a trap crop. A later North American study by Cárcamo et al. (2007) found that a trap crop of *B. rapa* which flowered one week prior to the maincrop OSR sufficiently trapped *C. assimilis*, which were controlled with pyrethroid spraying in large square fields (256 ha). The control efficiency was not however mirrored in smaller and narrower fields, which are more likely in UK landscapes, and this method also relies upon insecticide treatment, which is fundamentally avoided within the scope of this review.

There are several other relatively unexplored routes in which *Ceutorhynchus* spp. damage could be reduced. **Hybridisation** between OSR and white mustard (*S. alba*), were produced in a North American study to produce OSR hybrids that are more resistant to *C. assimilis* attack (Brown et al., 1997), as *S. alba* is known to be resistant to *C. assimilis* attack (Doucette, 1947). Though the hybrids did succumb to *C. assimilis* attack, fewer larvae developed fully when compared to the OSR parent (McCaffrey et al., 1999) which was thought to be due to higher glucosinolates (inherited from the white mustard parent). Carcamo et al. (2001) postulated that developing hybridised OSR-white mustard cultivars, capable of high quality oil products, would be an alternative to current OSR cultivars which are ravaged by pests.

The *C. assimilis* is thought to respond to **oviposition-deterring pheromones** (ODP) deposited by female *C. assimilis*, which reduces intraspecific competition of developing larvae (Ferguson and Williams, 1991). It has been suggested that the identification of the ODP chemical, produced and marked by female *C. assimilis* (by brushing the eighth abdominal tergite) (Ferguson and Williams, 1991), has been proposed as a future control mechanism for the *C. assimilis* without resorting to chemical control. However, little work on the identification or the agricultural feasibility of this method has arisen.

2.5.5. Outlook

Table 2.5.5.1. A summarising table of management implications to control weevils in a sustainable manner.

Chemical control
• Kevväi et al. (2006) found that insecticide treatment of winter OSR was synchronised with *C. assimilis* parasitoid peak abundance, killing around half of the parasitoids (Alford et al., 1995; Murchie et al., 1997). • A recent Polish study by Zamojska et al. (2014) found that *C. assimilis* was resistant to neonicotinoids to some extent.
Biological control
• 50 % of cabbage seed weevil larvae can be parasitized (Veromann et al., 2013), so encouragement of parasitoid wasp populations is important. • Carabids are also known to consume weevil (Warner, 2001), so should be encouraged. • Diversifying brassicas in the landscape, particularly using Chinese mustard and turnip rape is likely to increase biological control within OSR (Kovács et al., 2013).
Cultural control
• Early drilling can reduce damage risk, as more mature plants are able to tolerate feeding in late summer (HGCA 2014). • Use winter OSR in areas that have previously been subjected to *D. brassicae* and *C. assimilis* damage, as Veromann et al. (2006) suggests that winter OSR may be past its optimal growth stage for ovisposition upon *C. assimilis* arrival. • Trap cropping with turnip rape can reduce weevil infestations (Barari et al., 2005), with a pyrethroid spray (Cárcamo et al., 2007), but other studies have found this to be ineffective.

2.6. Brassica pod midge (*Dasineura brassicae*)

2.6.1. Introduction & life history

The brassica pod midge, *Dasineura brassicae* Winnertz (Diptera: Cecidomyiidae), larvae overwinter in the soil between July and February, pupate, and emerge as adults between March and April. The adults mate and fly towards oilseed rape between May and July, where numerous eggs are laid in the bored exit holes left by *C. assimilis*, and other damaged areas of the plant. The larvae grow within the developing pod as they feed, and cause the pod to swell and eventually burst between June and July. Having reached their final larval instar, the larvae will drop to the soil to overwinter, but some will develop to produce second and third generation adults (HGCA, 2014).

2.6.2. Damage/presence

Damage is greatest on the headlands, and can cause significant yield loss in spring OSR, though often the damage is overrated due to the conspicuous damage (HGCA, 2014). Infested pods will yellow and split open prematurely. They become distorted and swollen, and are often described as 'bladder pods', resulting in complete seed loss within that particular pod (HGCA, 2014).

2.6.3. Pest thresholds

HGCA (2014) advise that adequate control of the brassica pod midge depends upon the control of *C. assimilis* damage, and therefore, avoidance of weevil damage is likely to prevent damage by the secondary pest, the brassica pod midge. See Section 2.5.3 for more information regarding thresholds for *C. assimilis* and thus *D. brassicae*.

2.6.4. Potential for control

2.6.4.1. Chemical control

Nitrophenolates are a category of **biostimulant** that trigger natural plant vitality, stress tolerance, and defense mechanisms (Gawrońska et al., 2008; Kazda et al., 2015; Przybysz et al., 2008) and have been seen by some as an alternative to conventional insecticides. There is currently no evidence to suggest that the application of nitrophenolates are toxic to flora and fauna Djanaguiraman et al., (2004) and EFSA (2008) report that soil and water are relatively residue-free shortly after application. A study based upon in-field plots in Czech-Polish locations by Kazda et al. (2015) explored the effectiveness of nitrophenolates in their effectiveness at increasing OSR yields and resistance to *D. brassicae*. The study found that nitrophenolate application enhanced protection against stressors and by stimulated vital processes under near-optimal conditions. Pod damage by *D. brassicae* in plots treated with nitrophenolates was lower, and as a result, yields were improved. The reduction in pod damage coincided with an increase in pod lignin level in young pods, which were similar to that in older and larger pods, potentially preventing oviposition by *D. brassicae*, which preferentially oviposit into young pods. Another reason for enhanced *D. brassicae* resistance was postulated to be due to a repellent effect, whereby *D. brassicae* females may have deemed the pod unsuitable for larval development (Kazda et al., 2015). One reason not suggested or observed by the authors, was that it may have deterred *C. assimilis* damage, which would render the pods completely inaccessible for *D. brassicae*. In any case, the application of nitrophenolates to small OSR plots in this study appears to deter *D. brassicae* damage.

There was however a high degree of variation depending on the location and the year, which could be accounted for by stochastic events. Aside from spatio-temporal variations, it is also generally thought that the positive effect of nitrophenolates is much more evident when the plants are grown under stressful conditions (Gawrońska et al., 2008; Przybysz et al., 2008) and when grown at near-optimal conditions, the positive effects of nitrophenolates may not be observed at all (Gawrońska et al., 2008; Krawiec, 2008). Kazda et al. (2015) reiterate that this is a novel study within OSR, and so requires **further research.**

2.6.4.2. Biological control

- *Identify potential biological control agents*

Of 28 species of **parasitoids** known to attack *D. brassicae*, the most observed and widespread parasitoids within Europe belong to the genus, *Platygaster* spp. (Hymenoptera: Platygastridae) (Williams et al., 2003). Another commonly reported larval endoparasitoid of *D. brassicae* is *Omphale clypealis* Thomson (Hymenoptera: Eulophidae) (Williams et al., 2003). Together, *O. clypealis* and *Platygaster subuliformis* can kill up to 75% of *D. brassicae* larvae (HGCA, 2014).

In a **no-choice laboratory-based test** (one prey species available), Schlein and Buchs (2004) explored the predation of *D. brassicae* by five carabid species (*Amara similata*, *Anchomenus dorsalis*, *Harpalus rufipes* (syn. *Pseudoophonus rufipes*) Degeer, and *Pterostichus melanarius*). The authors found that in laboratory conditions, the key carabid species varied significantly in their mean daily consumption rate of *D. brassicae* larvae, which is not necessarily related to the body size of the predator. The mean daily consumption rate of *A. similata* was as high of that of *P. cupreus*, despite the former being reported mostly as a granivorous or phytophagous species (Buchs, 2003; Jorgensen and Toft, 1997). This study highlights the importance of epigaeic predators in the control of crop pests in their vulnerable late-larval instar stage, or pupation stage. Even predators previously speculated to be granivorous or phytophagous may be of value as occasional predators of pest larvae. In the instance of Schlein and Buchs (2004), if *D. brassicae* larval predation occurs in field as well as in the microcosm experiments, then it should be assumed that crop damage has already occurred as larvae are ready to pupate. However, epigael predation will reduce the survival of adults, and consequently reduce the availability and abundance of adults in the following year.

Despite being an effective control method for some pest species, the use of **entomopathogenic nematodes** as a control measure for *D. brassicae* was deemed negligible by Nielsen and Philipsen (2005). In laboratory conditions, the authors found that pupating *D. brassicae* were almost completely unaffected by the tested nematodes, which is in agreement with previous work by Nielsen and Philipsen (2004). In any case, control of pupating *D. brassicae* would not negate the yield damage that had already occurred, and thus, efforts must be aimed at controlling *C. assimilis* damage, earlier in the season (see Section 2.5.4).

- *Evidence of biological control directly impacting the pest*

There is evidence that carabid beetles, aside from predating *C. assimilis* which provide the gateway for *D. brassicae* damage (see Section 2.5.4.2), will directly predate upon *D. brassicae* larvae. In laboratory feeding studies and gut dissections of **field-collected carabids**, the remains of *M. aeneus*, *Ceutorhynchus* spp., and *D. brassicae* have been found (Piper and Williams, 2004; Schlein and Buchs, 2004; Schlein et al., 2006; Warner, 2001). More generally, Buchs and Nuss (2000) found that small epigeal predator exclusion plots resulted in increased survival of soil-pupating pests as adults, and that when predators are present, *D. brassicae* emergence was reduced by 58%. In parallel to this, *C. assimilis* emergence was reduced by 82%, highlighting that if damage has occurred already, the next generation of pests can be reduced. Although the estimates of contribution to complete mortality made by these predators was low (10% *D. brassicae* and 52% *C. assimilis*), this may be sufficient to avert outbreaks (Buchs, 2003).

For more information on biological control via indirect mechanisms (control of *C. assimilis*), refer to Section 2.5.4.2.

- *Evidence that a certain habitat and/or management practice improves actual biological control*

For more information on biological control via indirect mechanisms (control of *C. assimilis*), refer to Section 2.5.4.2.

2.6.4.3. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

Please refer to Section 2.5.4.3 for cultural control of *C. assimilis,* and hence indirect control of *D. brassicae*.

2.6.5. Outlook

Table 2.6.5.1. A summarising table of management implications to control the brassica pod midge in a sustainable manner.

Chemical control
• Nitrophenolate (biostimulant) application may improve yields due to suspected pod lignin increase or as a repellent effect (Kazda et al., 2015), and there is no evidence that these are toxic to flora and fauna.
Biological control
• Encourage parasitoids which can provide 75 % of control (HGCA, 2014). • Encourage carabids (Buchs and Nuss, 2000), which can control future generations (after pod damage) by reducing pod midge and cabbage seed weevil emergence (Buchs, 2003). • Refer to biological control of cabbage seed weevils in Table 2.5.5.1.
Cultural control
• Refer to cultural control of cabbage seed weevils in Table 2.5.5.1.

2.7. Cabbage root fly (*Delia radicum*)

2.7.1. Introduction & life history

Present throughout the UK, and of particular importance on vegetable brassicas, *Delia radicum* Linnaeus (Diptera: Anthomyiinae) is a minor pest of OSR, and relies upon semi-natural habitats for reproduction and resources (Hawkes, 1972). *D. radicum* often have three generations within a single year, and the life cycle is variable depending on the temperature. Between November and March, *D. radicum* overwinter in the soil, and adults emerge, feed and mate on flowers within hedges and field-banks (Josso et al., 2013) in April, and lay the first generation of eggs on the ground, aggregated around host plant stems (McDonald and Sears, 1992) in May. Newly emerging adults of the first generation then lay the second generation of eggs between July and August, and the newly emerging second generation adults will lay the third generation of eggs between August and September. The larval feeding stage can span between May and October, whilst the pupal stage within the soil can occur between June and October, as a mixture of generations. In the south, there is generally two to three generations of *D. redicum* and just two in the north of the UK.

2.7.2. Damage/presence

Plants with a low degree of root damage usually survive, particularly if conditions are wet. For vegetable brassicas, total crop loss can occur if left uncontrolled, and many can be left unmarketable due to cosmetic damage. Early emerging OSR plants before the end of August are at the greatest risk (HGCA, 2014).

2.7.3. Pest thresholds

For more information regarding the monitoring of *D. radicum*, please refer to HGCA (2014). It is important to note that there are no validated thresholds for control of *D. radicum* (HGCA, 2014).

2.7.4. Potential for control

2.7.4.1. Biological control

- *Identify potential biological control agents*

In terms of biological control, it is reported that *D. radicum* are controlled by areal agents such as parasitoids and muscid flies (Diptera: Muscidae) and epigael predators, including carabids, staphylinids, and spiders (HGCA, 2014). There is a frequent and specialist larval parasitoid, *Trybliographa rapae* (Hymenoptera: Figitidae), and two pupal parasitoids, *Aleochara bilineata* and *A. bipustulata* (both Coleoptera: Staphylinidae) which also act as egg and larval predators of *D. radicum* (Josso et al., 2013). *A. bilineata* is a specialist of *Delia* pupae, whilst *A. bipustulata* is considered a generalist of other Diptera (Maus et al., 2008).

- *Evidence that a certain habitat and/or management practice improves actual biological control*

Like other studies which found that semi-natural habitats supported both crop colonization by pests *and* natural enemy activity, thus having a negligible effect on crop protection (Thies et al., 2005), a French study be Josso et al. (2013) found that **semi-natural habitats** supported colonizing *D. radicum* and its natural enemies.

Hedgerows provide the floral resources for *D. radicum* egg maturation, and enhancement of fecundity, reproductive success and longevity (Havukkala and Virtanen, 1984; Košťál, 1993). It has also been suggested that hedgerows may provide favourable microclimatic conditions for *D. reticulatum* adults (Estorgues and Cochard, 2004). Despite these characteristics, (Josso et al., 2013) found that hedgerows decreased *D. radicum* colonization within the crop, and thus acts as a physical barrier, possibly due to adult low flying height (<90 cm from the soil surface) (Vernon and Mackenzie, 2012). Valantin-Morison et al. (2007) found that hedgerows enhanced OSR pest infestations in regions where OSR is abundantly cropped. Josso et al. (2013) on the other hand, found that hedgerows decreased field colonization of *D. radicum*, and although providing floral resources, could prospectively represent a significant physical barrier to the low flying *D. radicum*. In unison, it may be that hedgerows also limit walking insect dispersion too, as was seen in Josso et al. (2013) for the pupal parasitoid *A. bilineata*, the larval parasitoid staphylinid beetle. The same physical barrier may be exhibited by built up areas, such as buildings and fences, and thus restrict *D. radicum* dispersion (Josso et al., 2013).

Josso et al. (2013) found that other parameters affected *D. radicum* and its natural enemies. **Field banks** (assumed to be uncultivated margins between fields in the absence of a hedgerow) appeared to provide pest resources and shelter, and thus increased field colonization by *D. radicum*. *D. radicum* emergence from the soil was reduced when surrounded by high-densities of **woodland** (Josso et al., 2013), which are associated with high abundances of natural enemies, and thus pest control (Attwood et al., 2008), for example both *Aleochara* spp. were positively affected by woody habitats in the case of Josso et al. (2013). A high **proportion of *Brassica* crops** within the landscape enhanced parasitism rates by the specialist staphylinid, *A. bilineata*, but not for the generalist, as is expected with specialization degree of the natural enemies. Though responding similarly to woody habitats and field banks, *A. bilineata* exhibited greater parasitism rates nearby to **meadows**, whilst *A. bipustulata* parasitism was increased by a greater density of **hedgerows**, with both habitats likely to provide shelter and resources when pest hosts are limiting.

For the pupal parasitoids (*Aleochara* spp.), control at this stage is beyond the initial damage period (excluding the next generation of damage). As with other brassica pests, namely *Dasineura brassicae* (please refer to Section 2.6 for more information), control around the mature larvae or pupal stage will only protect against future generations of pest damage, as damage has already occurred by the developing larvae. However, in the French study by Josso et al. (2013) **early biological control** through consumption of eggs or larvae did not appear enough to reduce crop damage.

2.7.4.2. Cultural control

- *Evidence that cultural techniques can reduce pest populations*

For crop protection at a small scale, a fine mesh netting has been used successfully on susceptible crops such as swede, as it impedes female egg laying. Oviposition can still occur, but incidence is minimal. Other cultural approaches, including the use of companion planting, trap crops, and vertical fences have appeared to be ineffective (HGCA, 2014).

Josso et al. (2013) found that ridged fields that have been subjected to **finger weeders** influenced *D. radicum* and its natural enemies in different ways. *D. radicum* prepupal mortality was increased, resulting in reduced pest emergence from ridged fields. Staphylinid abundances were reduced, however the carabid, *Bembidion* (syn. *Metallina*) spp. and the specific larval endoparasitoid, *T. rapae* populations benefited from the mechanical soil treatment probably as the treatment allowed for access to the root, and hence the pest prey/host respectively. For *Bembidion* spp. and *T. rapae*, it appeared that the effect of the **preceding crop** had little precedent over colonization the following year, which was suggested to be due to their ability to disperse from overwintering sites. Although (Dalthorp and Dreves, 2008) found that spring *Brassica* near to a field recently damaged by *D. radicum* was more likely to be recolonized by *D. radicum* the following year, Josso et al. (2013) argued that as *D. radicum*, akin to *T. rapae* and *Bembidion* spp. are proficient dispersers from their overwintering sites (previous year’s *Brassica*) (Finch and Skinner, 1975). Similarly, the relative abundance of **host crops within a landscape** has been shown to have no effect, or even a negative effect on the pest abundance within landscapes (Thies et al., 2003; Zaller et al., 2008) and with regard to brassica cropping within the landscape, Josso et al. (2013) found a negative effect on *D. radicum*.

2.7.5. Outlook

Table 2.7.5.1. A summarising table of management implications to control the cabbage root fly in a sustainable manner.

Biological control

• Encourage carabid beetles (HGCA, 2014).
• Encourage parasitoid wasps (targeting pest larvae and pupae) and muscid flies (HGCA, 2014).
• Encourage rove beetles that act as parasitoids and predators (Balog et al., 2008).
• In **OSR** areas previously damaged by cabbage root fly:
  o Use fields surrounded by high density hedgerows and woodland, which act as physical barrier, and harbours natural enemies respectively, preventing field colonization (Josso et al., 2013).
  o Avoid fields surrounded by field banks which provide resources and shelter, and thus field colonization by pest (Josso et al., 2013).

Cultural control
• A fine mesh netting will reduce pest incidence on **vegetables** (HGCA, 2014). • Use finger weeders to reduce pest emergence from soil, and increase carabid and parasitoid wasp access to pest (Josso et al., 2013). • Avoid spring brassicas near to a field that was recently damaged by the pest (Dalthorp and Dreves, 2008).

2.8. Minor pests within oilseed rape

2.8.1. Turnip sawfly (*Athalia rosae*)

There have been sporadic outbreaks of *Athalia rosae* Linnaeus (Hymenoptera: Symphyta) since the 1940s, and a major outbreak in 2006 caused significant crop damage in southern England. Adult activity, and thus mating and oviposition, is increased in warm conditions, as adults only fly at temperatures exceeding 18 °C. Immigration from mainland Europe can aid mass immigration in the southern English counties (HGCA, 2014). Pupae overwinter between October and April, and after, the first generation adults lay up to 300 eggs (HGCA, 2014) inside fresh young brassica leaves (Lee *et al*., 1998) between May and June. The eggs hatch reportedly after 6-8 days and the larvae feed inside and externally on the underside of the leaves (May-June), and once mature, the larvae drop to the soil to undergo pupation (May-July). The second generation of adults emerge between July and August, and lay eggs, allowing for the emergence of a third generation of adults emerging between August and September if the summer is hot enough, and adult arrival coincides with the early stage of crop emergence (HGCA, 2014). For more information relating to the monitoring and thresholds for control of *A. rosae*, please refer to (HGCA, 2014).

A. rosea larvae when feeding in loose assemblages, will sequester **glucosinolates**, which are secondary metabolites of brassicas (Gols et al., 2008; Hopkins et al., 2009). The larvae are well known for their 'easy bleeding' defence strategy, whereby attackers are deterred by *A. rosea* voluntarily rupturing its haemolymph (Boevé and Schaffner, 2003). A laboratory based study by Van Geem et al. (2014) found that the naïve predator, *Podisus maculiventris* (Hemiptera: Pentatomidae), was only lightly affected by allelochemicals sequestered by larval *A. dorsae*. For this reason, the authors suggested that *P. maculiventris* may bypass the feeding deterrant by feeding selectively on less toxic tissues. Although HGCA (2014) report that *A. dorsae* are host to parasitic wasps and flies, Van Geem et al. (2014) suggest that no parasitoids are known to attack *A. dorsae* in the field, and given that sawflies are often attacked by many parasitoids (Price, 1972), sequestration of glucosinolates may serve as a useful deterrent to endoparasitoids and less selective predators. In this way, biological control of *A. dorsae* may not be as reliable as other control methods.

Both chemical defences and mechanical defences are inducible by herbivory. Glucosinolates are known to be inducible by leaf herbivory (Textor and Gershenzon, 2008) as are **trichomes**, which are fine hairs that interfere with herbivore movement and feeding. The induction of trichomes can lead to a reduced performance of specialist herivores (Travers-Martin and Müller, 2014). Bandeili and Müller (2010) found that *A. rosea* developed best on the flowers of *Sinapis alba*, as these were not protected by trichomes compared to the leaves. The authors were not certain as to whether this was due to selective feeding, or coincidental upward movement, but it was clear that the less mechanically defended flowers resulted in fitter pests. Perhaps by selecting brassica cultivars that can produce denser trichomes when induced, and even produce some sort of mechanical defence in the flowers, *A. rosea* prevalence may be reduced.

This selection process may be some way off, but HGCA (2014) advise that high value, sensitive crops can be protected by barriers such as **insect-proof netting**. Although this may be impractical for OSR sized crop fields, it may be important for vegetable brassicas. As there is some doubt as to whether natural enemies are that effective for *A. dorsae*, it may be advisable to **plough** the soil if a preceding brassica crop has been subjected to a large (monitoring required) infestation of *A. dorsae*, so as to kill any pupating sawfly. This however still may not achieve full control, as it is possible that after harvest, second generation (or third in a hot summer), will be emerging HGCA (2014) and thus not in peril of soil tillage. This of course will reduce the natural enemy survival for the following crop.

SECTION 3. Potatoes: biological control strategies

See Section 2.1. for slug control, Section 1.2. for wireworm control, Section 1.1. for grain aphid control, and Section 2.4. for peach-potato aphid control.

3.1. Aphids (Aphididae spp.)

3.1.1. Introduction & life history

The buckthorn-potato aphid (*Aphis nasturtii* Kaltenbach), the grain aphid (*Sitobion avenae*), peach-potato aphid (*Myzus persicae* Sulzer), and the potato aphid (*Macrosiphum euphorbiae* Thomas) (all Hemiptera: Aphididae) are all pests of potato crops within the UK (HGCA, 2014).

Table 3.1.1.1. Life histories of four potato-attacking aphid species in the UK (HGCA, 2014).

Aphid species	Autumn	Winter	Spring	Summer
Macrosiphum euphorbiae (**potato aphid**)	Wingless forms feed and reproduce on the crop (**May-Oct**). A small autumn migration may occur (**Sep**).	Wingless adults and immature nymphs overwinter on weeds, potato sprouts, rose, and unprotected lettuce (**Nov-Apr**).	Wingless adults and immature nymphs overwinter on weeds, potato sprouts, rose, and unprotected lettuce (**Nov-Apr**). Winged adults migrate onto summer crops (**May-Jun**). Wingless forms feed and reproduce on the crop (**May-Oct**).	Wingless forms feed and reproduce on the crop (**May-Oct**). If heavy infestations occur, a further migration is likely (**Jul**).
Sitobion avenae (**grain aphid**)	BYDV is a risk (**Sep-Mar**) (pre-GS31) (HGCA, 2014).	Adults overwinter on crops and grasses, with no alternative host (**Dec-Mar**) BYDV is a risk (**Sep-Mar**) (pre-GS31) (HGCA, 2014).	Fresh migrations infest crops (**Apr**), and during dry, calm weather, populations can increase dramatically when feeding (**Apr- Aug**) (HGCA, 2014).	Direct crop feeding (**Apr- Aug**) (HGCA, 2014).
Aphis nasturtii (**buckthorn-potato aphid**)	Eggs overwinter on buckthorn (**Oct-May**). Winged adults return to buckthorn to lay eggs (**Oct-Nov**).	Eggs overwinter on buckthorn (**Oct-May**).	Winged adults move into potato crops and reproduce throughout the summer (**May-Oct**).	Winged adults move into potato crops and reproduce throughout the summer (**May-Oct**).
Myzus persicae (**peach-potato aphid**)	Adults infest OSR and vegetable brassicas during mild autumns and transfer viruses (**Sep-Dec**).	Asexual females overwinter in brassica and herbaceous crops and weeds (small proportion of eggs overwinter on peach and nectarine trees). Cold weather reduces survival. (**Nov-Feb**).	Adults migrate into a variety of summer crops, multiply quickly (**Mar-Aug**).	Populations peak (**Jul**) Another small peak (**Aug-Sep**).

3.1.2. Damage/presence

Despite being a relatively minor potato pest, *A. nasturtii* is capable of transmitting potato virus Y (PVY), and is a poor vector of potato leaf roll virus (PLRV). Although populations vary drastically from year to year, most of the direct damage occurs during tuber bulking in late July and August (HGCA, 2014). Not only is *S. avenae* damaging to cereal crops, it is also an efficient vector of (PVY) when in search of food (HGCA, 2014). The most common aphid species found on potatoes is *M. euphorbiae* which can cause yield reductions by sap-feeding but mostly transmission of PVY and PLRV (HGCA, 2014). Similar reductions in yield by PVY and PLRV transmission can result from *M. persicae*, alongside secondary tuber-borne infections of these viruses (HGCA, 2014).

3.1.3. Pest thresholds

For information on the monitoring of each of the listed species, AHDB Aphid News provides information on aphid migration, and the Potato Council website has a tool whereby *M persicae* aphid populations are found in certain regions (www.potato.org.uk/online-toolbox) (HGCA, 2014). Currently, no economic thresholds exist for potato-attacking aphids, but HGCA (2014) suggest that for *A. nasturtii,* chemical control is largely unwarranted.

3.1.4. Potential for control

For more information on the control of aphids, please also refer to Sections 1.1, 2.4, 4.3, and 5.1 for less specific but nevertheless potentially useful information on aphids pests of OSR and cereal crops respectively.

3.1.4.1. Chemical control

Perring et al. (1999) suggested the the transmission of PVY cannot be prevented, as the early stages of plant colonization cannot be targeted by chemical insecticides. In a Canadian field study, Boquel et al. (2015) similarly found that PVY transmission could not be reduced by insecticide use, as PVY acquisition was only affected by two insecticides on one aphid species. However, they did find that some insecticides may intermittently curb the spread of PVY, either by lessening PVY acquisition using a systematic insecticide (lambda-cyhalothrin and dimethoate), or by modifying aphid behaviour using a contact pesticide (lambda-cyhalothrin and pymetrozine). Despite decelerating the pread of PVY, Boquel et al. (2015) emphasise that due to the slow-acting nature and variabile impact on different aphid species, insecticides may be of limited use in reducing PVY spread in-field.

3.1.4.2. Biological control

HGCA (2014) highlight that parasitoid wasps, predatory flies, spiders, carabid beetles, rove beetles, and entomopathogenic fungi all have a role to play in biological control of aphids of potatoes.

For information on the potential of wolf spiders suppression of *M. persicae*, please see Section 5.1.4.2. For more information on the use of artificial floral resources to enhance hoverfly egg laying in-field, please see Section 4.3.4.2. For more general information relating to which natural enemies may be of particular use for aphid control, and how they might be encouraged, please refer to Section 2.4.4.2 and Section 1.1.4.2.

3.1.4.3. Cultural control

Control of *R. padi* is important not only for BYDV transmission in cereals (see Section 2.1), but also for other viruses, including **potato virus Y (PVY)** (Radcliffe and Ragsdale, 2002; Sigvald, 1987). Even though this species does not colonize potato, *R. padi* can transmit PVY to seed potato field at high rates (Sigvald, 1987) when searching for a high quality host plant (Boiteau, 1997). Winged aphids are mostly responsible for spreading the viruses over considerable distances by the probing of the potential host plant (Radcliffe and Ragsdale, 2002). In South African seed potato-producing regions where *R. padi* is abundant, Schröder and Krüger (2014) identified that maize and wheat as prospective border crop plants, compared to lucerne and soybean. In the small scale field trials, aphids readily landed on lucerne, maize, and wheat rather than potato, but then colonized wheat and maize (Schröder and Krüger, 2014).

In a later laboratory-based study, Schroder et al. (2015) demonstrated *R. padi* preference to colonize wheat and maize again, but variably between cultivars, depending on the plant of origin. Establishing the most attractive cultivar of trap crop is essential to controlling viruses, such as PYV. Repeated alighting and settling spreads viruses like PYV (Swenson, 1968), however, probing as an evaluation of plant compatibility is sufficient for the aphid to lose the ability to transmit the virus, and is therefore unlikely to spread it any further (Difonzo et al., 1996). Consequently, planting a nonvirus host not only acts as a trap crop, but also a virus sink (Hooks and Fereres, 2006) and thus protect potato fields (Schroder et al., 2015). The use of a trap crop in this way can therefore also represent a significant source of aphids also (Hokkanen, 1991; Müller et al., 2001) and due to this, it is crucial to select a **trap crop** which does not support aphid population growth (Schroder et al., 2015). Schroder et al. (2015) observed that in a no-choice trial, reproductive success was higher on wheat than on maize by *R. padi*, when originating on wheat or maize. It appears that maize not only acts as an effective trap crop, successfully protecting potatoes, but also discourages population growth, at least more so than wheat, and as a summer crop, may not allow such prolonged aphid population growth as wheat (Schroder et al., 2015).

The use of seed potato varieties that are most resistant to aphid growth is an important factor to consider to alleviate the spread of aphids and PVY (HGCA, 2014). Those which are verified by the British Seed Potato Classification Scheme is vital to prevent the spread of PVY by the buckthorn-potato aphid (*A. nasturtii*) among others (HGCA, 2014). For more information on which natural enemies may be of particular use, and how they might be encouraged, please refer to Section 1.4.4.3 and Section 2.1.4.3.

3.1.5. Outlook

Table 3.1.5.1. A summarising table of management implications to control potato-attacking aphids in a sustainable manner.

Chemical control
• Insecticides cannot effect PVY transmission as they cannot prevent the early stages of plant colonization (Perring et al., 1999). • PVY spread may be decelerated by lambda-cyhalothrin (contact insecticide) and pymetrozine (systematic insecticide) application, or lambda-cyhalothrin and dimethoate (systematic insecticide) (Boquel et al., 2015).
Biological control
• Encourage parasitoid wasps, ladybirds, predatory flies, spiders, carabids, rove beetles, lacewings, and entomopathogenic fungi (HGCA, 2014).
Cultural control
• Use seed potato variety that is most resistant to aphid growth (Pelletier et al., 2010), and verified by the British Seed Potato Classification Scheme to reduce risk of Buckthorn-potato aphid transmitting PVY (HGCA, 2014). • To protect potatoes from PVY transmitted by probing bird cherry-oat aphids, use maize, lucerne, or wheat (Schröder and Krüger, 2014) as a non-virus host trap crop. Maize is preferred as it supresses aphid colony reproduction than on wheat (Schroder et al., 2015).

SECTION 4. Pea and beans: biological control strategies

4.1. Bruchid beetle (*Bruchus rufimanus*)

4.1.1. Introduction & life history

Bruchus rufimanus Linnaeus (Coleoptera: Chrysomelidae), otherwise known as the bruchid beetle, damages field bean seeds by reducing the value of the crop, whilst in broad beans as the presence of the larvae renders the crop as unmarketable (HGCA, 2014). Adults overwinter in hedgerows or other dense shrubby habitats (Oct-Apr) until the temperature reaches 15-20 °C, when the adults will fly into flowering bean crops (Mar-May). Oviposition occurs on the pods after the adults have fed on pollen for two weeks, and the temperature exceeds 20 °C (Jun-Jul). The larvae then hatch, and are able to feed on the seeds before pupation within the seed before eating their way out, which can occur in the field or in storage (Jun-Sep) (HGCA, 2014).

4.1.2. Damage/presence

Although the pest is more common in the south of the UK, it is familiar to find *B. rufimanus* as far north as Yorkshire. The risk of damage is greatest where the pest has prospered on a previous crop (HGCA, 2014).

4.1.3. Pest thresholds

HGCA (2014) suggest that the crop flowering period is the best time to survey the number of adults by simply tapping the flowering stems into the hand or a tray and counting the adults. Treatment should be considered if adults are discovered and when the temperature exceeds 20 °C on two consecutive days, and the the initial pods have been produced on the lower trusses (HGCA, 2014).

4.1.4. Potential for control

4.1.4.1. Chemical control

The protection method using synthesised plant protection products (including Vitavax 200 FS, Decis 2,5 EC, Fastac 100 EC, and Penncozeb 80 WP) alone did not significantly impact the degree of damage by *B. rufimanus* (Gospodarek et al., 2013). In light of this, more integrated control strategies may need to be implemented to control *B. rufimanus*.

4.1.4.2. Biological control

HGCA (2014) emphasise that the parasitoid wasp, *Triaspis luteipes* Thomson (Hymenoptera: Braconidae) attacks the larvae of *B. rufimanus*, and that small bore holes within the seeds may be due to the emergence of this natural enemy.

4.1.4.3. Cultural control

Crops in areas that have previously been subjected to high populations of *B. rufimanus* are at a greater risk than those away from ‘hotspots’ (HGCA, 2014). In this way, it may be necessary to modify the **rotation regime**, and avoid sowing field beans in these previously troubled areas. Szafirowska (2012) found that feeding by *B. rufimanus* was lessened by sowing broad beans later. Unfortunately, the delay in sowing was negated by a reduction in yield associated with the delayed growing season. A more useful management strategy presented by Szafirowska (2012), was to use a more **resistant cultivar**, such as an equivalent to the assumed to be Polish cultivar 'Makler'. Szafirowska (2012) found that 'Makler' reduced *B. rufimanus* feeding considerably compared to other more susceptible cultivars, independent of the sowing date or the growing method (conventional or organically grown).

Alternative approaches to reduce *B. rufimanus* occurrence may provide further control, if the techniques can be applied into conventional systems. Despite appearing unfeasible for large scale systems, Sabbour and Abd-El-Aziz (2007) found that **mustard and nigella oils** acted as oviposition deterrents, and reduced the fecundity of female bruchid beetles.

4.1.5. Outlook

Table 4.1.5.1. A summarising table of management implications to control bruchid beetles in a sustainable manner.

Chemical control
• Protection using non-chemical products may not reduce the damage by the pest (Gospodarek et al., 2013).
Biological control
• Encourage parasitoid wasps (HGCA, 2014). • Encourage fungal pathogens (Sabbour and Abd-El-Aziz, 2007).
Cultural control
• Risk is greater where pest has occurred on previous crops (HGCA, 2014), so crop rotation modification may be required. • Mustard and nigella oil vapours act as strong repellents to the pest (Sabbour and Abd-El-Aziz, 2007). • Delay sowing to reduce damage to seeds, although this may lead to a reduced yield (Szafirowska, 2012). • Select resistant cultivars to pest damage irrespective of sowing date (Szafirowska, 2012).

4.2. Pea and bean weevil (*Sitona lineatus*)

4.2.1. Introduction & life history

Adult feeding of the pea and bean weevil, *Sitona lineatus* Linnaeus (Coleoptera: Curculionidae), rarely causes economic damage. However, the damage caused by larval feeding on root nodules does effect the crop yield (HGCA, 2014). Adults emerge from pupation, and overwinter in grasses and leguminous crops (clover and lucernce for example) (Aug-Mar), and migrate into crops when temperatures exceed 15 °C for short periods (Mar-May). Eggs are laid and are then washed onto the ground, and subsequently into the soil at the crop base (Apr-Jul) where the eggs hatch and the larvae feed on the root nodules (Apr-Aug). The larvae then pupate in the soil (Jun-Sep), and emerge as adults in search of overwintering sites (HGCA, 2014).

4.2.2. Damage/presence

Adult *S. lineatus* are vectors of the broad bean stain virus (BBSV), as well as the broad bean true mosaic virus (BBTMV), which impacts the product quality and when the infection occurs early, considerable yield losses (HGCA, 2014).

4.2.3. Pest thresholds

For more information regarding the monitoring of *S. lineatus*, please refer to HGCA (2014). Using the method outlined by HGCA (2014), a threshold of > 30 weevils recorded on any one day within spring-sown peas and and field beans would warrant control.

4.2.4. Potential for control

4.2.4.1. Chemical control

HGCA (2014) suspects that *S. lineatus* may be resistant to pyrethroids in the UK. Away from artificial pesticides however, it has recently been suggested that in field peas within fields with a high **nitrogen content**, the use of an insecticide seed treatment will not influence plant nutrition and thus the yield, having been attacked by *S. lineatus* (Cárcamo et al., 2015). Below ground herbivory of field peas by *S. lineatus* was shown to significantly lessen the plant nitrogen content during the initial flowering period, and also reduce the soil available nitrogen pool, vital for future crops (Cárcamo et al., 2015). In this way, Cárcamo et al. (2015) suggest that the application of fertiliser such as manure, on nitrogen-poor fields, may reduce the detrimental effect of *S. lineatus* on the nitrogen cycle, and the crop damage that the pest causes.

4.2.4.2. Biological control

Carabid beetles may be able to contribute significantly to the biological control of *S. lineatus.* In laboratory-based trials, Vankosky et al. (2010) found that *Bembidion quadrimaculatum* Linnaeus (Coleoptera: Carabidae), being smaller in stature than other carabid beetles that were trialled, consistently removed more *S. linneatus* eggs (94.6%) than larger beetles, including *Pterostichus melanarius* (17.4%). *B. quadrimaculatum* is present in the UK, and may therefore be a useful biological control agent against *S. lineatus.* However, Vankosky et al. (2010) also found that the presence of the larger *Pterostichus melanarius* resulted in intraguild predation in 47% of the tests, indicating that the presence of larger **carabid** beetles may reduce the control of *S. lineatus* due to predation of smaller *Bembidion* spp. Vankosky et al. (2010) also found that the rove beetle, *Poecilus scitulus* LeConte (Coleoptera: Staphylinidae) also predated *S. lineatus* eggs, albeit less so than with *B. quadrimaculatum*. Though not present in the UK, the staphylinid provides hope for a similar role played by British rove beetles. HGCA (2014) also mention that spiders, predatory flies, and parasitoid wasps can have a role to play in *S. lineatus* suppression.

As carabid beetles are clearly important predators of *S. lineatus*, Ropek and Jaworska (1994) explored the effects of entomopathogenic nematodes of the genus *Steinernema* spp. on carabids. They found during the period of greatest period of *Pterostichus cupreus* Linnaeus (Coleoptera: Carabidae) occurred when *S. lineatus* was feeding and egg laying in legumes. In June, Ropek and Jaworska (1994) found that *Bembidion properans* Steph. (Coleoptera: Carabidae) was most abundant, and destroyed the eggs or young-instar larvae of *S. lineatus*. No observed effect of the **entomopathogenic nematode** was observed in either of the non-target species was found, indicating that entomopathogenic nematodes may useful in reducing pest populations, but at the same tame posing no risk to non-target species, contrary to many pesticide applications.

4.2.4.3. Cultural control

A US study by Hanavan and Bosque-Pérez (2012) explored the effect of tillage practices on damage to pea crops by *S. lineatus*. The study found that because the **no-tillage** soils were wetter, and therefore were delayed in their spring planting, the pea crops under conventional tillage emerged earlier and was subjected to significantly more feeding damage by *S. lineatus*. HGCA (2014) also confirm that newly emerging are most susceptible, due to the earlier growth stage of the crop (Cárcamo et al., 2015). Significantly more emerging *S. lineatus* adults and immature pests were found in conventional tillage, and probably favoured the pea crops under conventional tillage due to the more developed root nodules in the warmer and drier conventionally tilled fields (Hanavan and Bosque-Pérez, 2012).

A study by Jaworska (1998) sheds light on how useful cultivar selection can be, as the study found that the activity and natural mortality of *S. lineatus* during the egg laying period was linked to their preferred host plant. Feeding activity and average body weight was markedly reduced, while susecpticbility to entomopathogenic nematodes was enhanced when *S. lineatus* preferred early field pea or other pea cultivars, over bean cultivars. This highlights the importance of selecting **cultivars** that discourage *S. lineatus* growth.

HGCA (2014) provide further cultural advice to reduce the occurrence of *S. lineatus*, by suggesting that growers may have to modify their **cropping regime**. It was postulated that growers should avoid cropping peas and field beans in close proximity to other legumes, particularly clover and lucerne, uncultivated grassland, and fields which have recently been cropped with peas or field beans.

4.2.5. Outlook

Table 4.2.5.1. A summarising table of management implications to control pea and bean weevils in a sustainable manner.

Chemical control
• Pea crops grown in high-N containing soil is unlikely to be affected by the pest, and therefore should not require insecticide treatment (Cárcamo et al., 2015).
Biological control
• Encourage spiders, rove beetles, predatory flies, and parasitoid wasps (HGCA, 2014). • Encourage carabid beetles, particularly small *Bembidion* spp., and rove beetles, which predate on pest eggs (Vankosky et al., 2010). • Consider the use of entomopathogenic nematodes, to which some appear to have no effect on predatory carabid beetles (Ropek and Jaworska, 1994).
Cultural control
• Avoid cropping peas and field beans in close proximity to other legumes (particularly clover and lucerne), uncultivated grasses, and fields which have recently been cropped with peas and field beans (HGCA, 2014). • Any crops newly emerging in early spring are at risk from damage (HGCA, 2014), due to the younger growth stage of the crop (Cárcamo et al., 2015). • Zero-tillage pea fields created unfavourable conditions for the pest, and results in reduced colonization, survival, and damage by the pest (Hanavan and Bosque-Pérez, 2012). • Select resistant cultivars, which may enhance pest susceptibility to entomopathogenic nematode attack (Jaworska, 1998).

4.3. Aphids (Aphididae spp.)

4.3.1. Introduction & life history

The black bean aphid, *Aphis fabae* Scopoli and the pea aphid *Acyrthosiphon pisum* Harris (both Hemiptera: Aphididae) legume-attacking aphid species in the UK. *A. fabae* attacks field beans and sugar beet, whilst *A. pisum* feeds on field beans and peas (HGCA, 2014).

Table 4.3.1.1. Life histories of four legume-attacking aphid species in the UK (HGCA, 2014).

Aphid species	**Autumn**	**Winter**	**Spring**	**Summer**
Aphis fabae (**black bean aphid**)	Winged adults migrate to spindle (**Sep-Nov**). Eggs overwinter on spindle, but in mild winters, active stages may overwinter on legumes or winter beans (**Oct-Jun**).	Eggs overwinter on spindle, but in mild winters, active stages may overwinter on legumes or winter beans (**Oct-Jun**).	Eggs overwinter on spindle, but in mild winters, active stages may overwinter on legumes or winter beans (**Oct-Jun**). Winged adults are produced and migrate into a range of summer crops (**May-Jun**).	Winged adults are produced and migrate into a range of summer crops (**May-Jun**). Breeding continues, and more winged adults are formed dur to crowding, and migrate to other crops (**Jun-Oct**). Breeding peaks (**Jul-Aug**).
Acyrthosiphon pisum (**pea aphid**)	Winged adults migrate to overwintering sites (**Sep**). Eggs overwinter on forage crops and in mild winters, active stages may overwinter (**Oct-Jan**).	Eggs overwinter on forage crops and in mild winters, active stages may overwinter (**Oct-Jan**). Eggs hatch (**Feb-Mar**).	Eggs hatch (**Feb-Mar**). Wingless generations reprodcuce on overwintering plants (**Apr**). Winged adults migrate to pea and legume crops (**May**).	Aphids feed and reproduce on peas and legumes (**Jun-Aug**). Peak populations (**Jun-July**).

4.3.2. Damage/presence

Damage by *A. fabae* mostly arises from direct feeding, although the aphid is also a vector of the bean leaf roll virus (BLRV), pea enation mosaic virus (PEMV), and bean yellow mosaic virus (BYMV) in leguminous crops. In peas, *A. pisum* can reduce yields by ruining flowers, inducing failed pod filling, and by generally reducing the plant efficiency. *A. pisum* is also a vector of important diseases within legumes, including the pea seed-borne mosaic virus (PSbMV), pea enation mosaic virus (PEMV), and bean leaf roll virus (BLRV) (HGCA, 2014).

4.3.3. Pest thresholds

HGCA (2014) advise that bean crops should be regularly checked for *A. fabae* from early flowering until pod formation, particularly in the headlands where colonies seem to form first. For *A. pisum*, the crop should be checked between May and July. For further information, please see AHDB Aphid News (HGCA, 2014).

Table 4.3.3.1. Thresholds for control of legume-attacking aphids via several methods, for spring cereals and oilseeds (HGCA, 2014). Although this guidance advises thresholds for chemical control, which is not encouraged in the scope of this report, these thresholds can be used as loose guidance for immediate cultural control, and future plans to bolster biological control.

Aphid species	Crop	Threshold
Aphis fabae (black bean aphid)	Field beans	5 larvae per 12 pipes
Acyrthosiphon pisum (pea aphid)	Field beans	None established
	Vining peas	>15 % of plants infested
	Combining peas	>20 % plants infested at early flowering

4.3.4. Potential for control

4.3.4.1. Chemical control

For information regarding decelarated PSbMV, PEMV, and BLRV transmission, see Table 1.1.5.1, Table 2.1.5.1, and Table 3.1.5.1.

4.3.4.2. Biological control

HGCA (2014) describe some of the key natural enemies of the aphids that attack pea and field bean crops as ladybirds, spiders, fungal pathogens, parasitoid wasps, and hoverflies. A novel and relatively simple approach by Day et al. (2015) used **artificial flowers** to enhance hoverfly oviposition in UK broad bean fields infested with *A. pisum*. Significantly more hoverfly eggs were laid on broad bean crops infested with *A. pisum* in close proximity to yellow artificial flowers with and without pollen and honey resources, when compared to positions without the flowers. This work strongly suggests that oviposition, and subsequent aphidophagous hoverfly larvae can be enhanced in fields with artificial flowers. The presence of the artificial flowers, comprised of brown plastic flowerpot saucers (19 cm diameter) painted with fluorescent paint, screwed horizontally onto a wooden stake cross section, and containing *Populus deltoides* Bartram pollen, and/or a sucrose cube soaked in 25% solution of clover honey, may be particularly important early in early spring, when floral resources are rare and aphid populations are low (Day et al., 2015).

4.3.4.3. Cultural control

An Iranian field experiment was conducted by Azimi and Amini (2015) whereby **intercropping** and fertilizer application was found to significantly reduce pest aphid populations. Broad bean monocropping harboured the greatest mean numbers of *A. fabae*, while intercropping, particularly on a broad bean - intercrop ratio of 1:1. At this ratio, the densities of *Coccinella septempunctata* and *Hippodamia veriegata* Goeze (both Coleoptera: Coccinellidae). The intercrop used was *Lallemantia iberica* Fisch. et Mey, otherwise known as 'Dragonhead'. Although a 1:1 intercropping ratio may not be feasible, a 2:1 ratio also significantly reduced aphid presence on crop, but to a lesser extent.

In the same paper, Azimi and Amini (2015) also found that the application of **biofertilizer** reduced the mean number of *A. fabae*, particularly when combined with broad bean - 'Dragonhead' intercropping ratio of 1:1. In this way, a combination of cultural techniques may help to reduce aphid populations in field.

4.3.5. Outlook

Table 4.3.5.1. A summarising table of management implications to legume-attacking aphids in a sustainable manner.

Chemical control

- For information regarding decelarated PSbMV, PEMV, and BLRV transmission, see Table 1.1.5.1, Table 2.1.5.1, and Table 3.1.5.1.

Biological control

- More predatory hoverfly eggs are laid on broad bean when artificial flowers are placed in field margins infested with pea aphid (Day et al., 2015). This may be particularly important early in the season when wild flowers are rare and aphid populations are low (Hickman and Wratten, 1996).
- Encourage ladybirds, spiders, fungal pathogens, and parasitoids (HGCA, 2014).

Cultural control

- Intercropping (e.g. using 'Dragonhead' of the mint family) in field beans significantly reduced pest populations, and enhanced predator communities (ladybirds) compared to a field bean monoculture (Azimi and Amini, 2015).
- The application of biofertilizers reduced pest populations, particularly when combined with intercropping (Azimi and Amini, 2015).

4.4. Other prominent pea and bean pests

4.4.1. Bean seed flies (*Delia* spp.)

Damage by *Delia platura* Meigen and *Delia florilega* Zetterstedt (both Diptera: Anthomyiinae) can be sporadic but localised, and within beans, the most serious damage is caused during the spring. Seeds of other crops are also susceptible, particularly if sown later in spring or the early summer (HGCA, 2014). Oviposition usually occurs on freshly disturbed soil, particularly if organic residues are present, though this is not an essential stimuli. Any factors that delay the speed of germination will render the crop more vulnerable to attack by *Delia* spp. As pupae, bean seed flies overwinter in the soil (Jan-Feb), and begin feeding, emerging and mating (Mar-Sep). Females lay eggs just below the soil surface (Mar-Sep), and the larvae eventually pupate at depth in the soil (Mar-Dec) (HGCA, 2014). For more information on monitoring and the associated thresholds for control, please refer to HGCA (2014).

HGCA (2014) acknowledge spiders, entomopathogenic fungi, and parasitoid wasps as important natural enemies of *Delia* spp. Balog et al. (2008) also recognised the importance of a parasitoid rove beetle, namely *Aleochara bipustulata* in Hungarian *Delia* spp., which occurred abundantly in areas of woodland in mountainous areas of medium height, and is nevertheless present across the UK. Although laboratory studies have shown that *A. bipustulata* is cannabilistic, it may be a useful biological control agent of bean seed flies due to its closely synchronised development time with its host, despite showing a preference for *D. radicum* (cabbage root fly) (Balog et al., 2008).

The **burying** of the previous crop's organic matter may be of crucial for the control of *Delia* spp., as HGCA (2014) state that this action will reduce the risk of pest ovisposition. For vegetable crops, or small scale production, it has also been suggested that a fine mesh netting will also reduce the incidence of pests on the crop (HGCA, 2014). As an alternative approach, Josso et al. (2013) suggested that the use of a **finger weeder** reduced the emergence of *D. radicum* (cabbage root fly), thought to be due to the increasing access of carabids and parasitoid wasps to the below ground pest. Indeed, the paper does not focus on the *Delia* spp. which are problematic in bean and pea crops, but a similar technique may yield similar deleterious affects in *D. platura* and *D. florilega*.

4.4.2. Pea moth (*Cydia nigricana*)

The pea moth, *Cydia nigricana* Fabricius (Lepidoptera: Tortricidae) is one of the most damaging pests of peas within the UK. The larvae feed on peas within the pod, causing economic injury through the combination of contamination and quality reductions. *C. nigricana* overwinters in a cocoon underground (Oct-Mar), until the caterpillar emerges to form a second cocoon nearer the surface and soon after pupates (Apr-May). The moths emerge (May-Jun) and oviposit on their host pea plants (Jun-Aug). The eggs then hatch and these caterpillars feed on the young pods (Jun-Aug), until they bore out and form a cocoon for overwintering (Jul-Sep).

In vining peas, total crop rejection can also result from damaged peas, and reudctions in merchant prices paid are proportionate to the observed damage (HGCA, 2014). Any pea crop in flower, or in pod in June or July is liable to attack, and infestations are more likely where there have been previous crop damage. This is the only time that HGCA (2014) suggest that chemical control may be necessary.

HGCA (2014) state that four species of parasitoid wasp are known to attack *C. nigricana*. A german study by Dalen et al. (2015) recognised that semiochemical stimuli is important for one of its parasitoids, *Glypta haesitator* Gravenhorst (Hymenoptera: Ichneumonidae), to locate the pest. Twenty four identified volatile chemicals emitted from the pea crop as herbivore-induced plant volatiles (HIPVs). Dalen et al. (2015) also reported that parasitism by *G. haesitator*, which is present within the UK, was as high as 29%, whilst the total parasitism of the pest in both growing regions was as high as 71%, highlighting the importance of parasitoid wasps in the suppression of *C. nigricana*. HGCA (2014) also mention that entomopathogenic fungi are known to attack *C. nigricana*.

Pea moth populations can grow to high levels in areas where the pea crops are grown to complete maturity in the field, and due to this, any areas where peas are grown to be combined can act as a pest reservoir (HGCA, 2014). Unharvested green peas on the other hand should be ploughed in before the larvae have exited the dried pods (HGCA, 2014). Early maturing pea varieties and early or late-sown peas may miss the peak flight period for *C. nigricana*, and thus escape damage (HGCA, 2014).

SECTION 5. Vegetable crops grown outdoors: biological control strategies

5.1. Aphids (Aphididae spp.)

5.1.1. Introduction & life history

The currant-lettuce aphid, *Nasonovia ribisnigri* Mosley, lettuce root aphid, *Pemphigus bursarius* Linnaeus, potato aphid, *Macrosiphum euphorbiae* Thomas, and willow-carrot aphid, *Cavariella aegopodii* Scopoli (all Hemiptera: Aphididae) are all known to attack vegetable crops, among others, and their life histories can be seen in Table 5.1.1.1 overleaf.

5.1.2. Damage/presence

N. ribisnigri is the most important foliage aphid of lettuce, and rapid colony development can stunt growth and even reduce the marketability of the crop, but does not usually transmit the lettuce mosaic virus (HGCA, 2014). As a vector of diseases of many crops, *M. persicae* transmits cauliflower mosaic virus (CaMV).

5.1.3. Pest thresholds

For more information on aphid monitoring, please see AHDB Aphid News, and the HDC Pest Bulletin (HGCA, 2014). There are currently no established thresholds for any of the listed aphids on vegetables (HGCA, 2014).

5.1.4. Potential for control

5.1.4.1. Chemical control

Resistance to primicarb and pyrethroid insecticides has been detected in the UK for *N. ribisnigri*, but at present, this is not having a great impact on controlling levels in the field. No resistance has been confirmed for *P. bursarius, M. euphorbiae,* or *C. aegopodii* (HGCA, 2014).

5.1.4.2. Biological control

In a Japanese cabbage field study, Suenaga and Hamamura (2015) found that the wolf spider, *Pardosa astrigera* was able to significantly supress *M. persicae* densities in the autumn. Crucially, the cabbage yield did not increase despite the supression of this pest (combined with diamond-back moth predation). Understanably, cabbage systems are very different to potato systems, but the study does highlight the importance of wolf spiders in the predation of aphids in the autumn.

5.1.4.3. Cultural control

HGCA (2014) advise that Lombardy poplar should not be used as a windbreak close to lettuce cultivation areas to prevent *P. bursarius* damage. Some lettuce varieties including Avoncrisp and Avondefiance have been confirmed as resistant to *P. bursarius*, although the material has not been used to develop more modern cultivars (HGCA, 2014).

5.1.5. Outlook

Other than the information in this section, please refer to Section 1.1.5, Section 2.4.5, Section 3.1.5, and Section 4.3.5.

Table 5.1.1.1. Life histories of five pest aphid species of vegetables in the UK (HGCA, 2014).

Aphid species	Autumn	Winter	Spring	Summer
Macrosiphum euphorbiae (**potato aphid**)	Wingless forms feed and reproduce on the crop (**May-Oct**). A small autumn migration may occur (**Sep**).	Wingless adults and immature nymphs overwinter on weeds, potato sprouts, rose, and unprotected lettuce (**Nov-Apr**).	Wingless adults and immature nymphs overwinter on weeds, potato sprouts, rose, and unprotected lettuce (**Nov-Apr**). Winged adults migrate onto summer crops (**May-Jun**). Wingless forms feed and reproduce on the crop (**May-Oct**).	Wingless forms feed and reproduce on the crop (**May-Oct**). If heavy infestations occur, a further migration is likely (**Jul**).
Nasonovia ribisnigri (**currant-lettuce aphid**)	Winged aphids migrate back to winter hosts, and eggs are laid. In warm locations, adults can survive and slowly reproduce on te wild hosts (**Oct-Nov**).	Overwinters as an egg on currants or gooseberry bushes (**Dec- Feb**).	Eggs hatch and the nymphs infest the tops of the young shoots (**Mar-Apr**). Colonies are forming, and winged adults migrate onto wild hosts (**May-Jun**).	Colonies are forming, and winged adults migrate onto wild hosts (**May-Jun**). Several generations are produced over the summer (**Jul-Sep**).
Pemphigus bursarius (**lettuce-root aphid**)	Winged aphids migrate to poplar (**Aug-Oct**). Aphids overwinter as eggs on black and Lombardy poplar trees (**Nov-Feb**).	Aphids overwinter as eggs on black and Lombardy poplar trees (**Nov-Feb**).	Eggs hatch and nymphs feed on developing petioles, forming galls for nymphal development (**Mar-May**).	Winged aphids occur over 4-5 week peiod, and migrate to lettuce and wild hosts (**Jun-Jul**). Live young are produced as soon as they arrive on lettuce, and they move into the roots, where populations increase with a number of generations (**Jun-Aug**). Winged aphids migrate to poplar (**Aug-Oct**).
Cavariella aegopodii (**willow-carrot aphid**)	Winged aphids migrate to willow to mate and lay eggs (**Oct-Nov**).	Aphids mainly overwinter as eggs laid on willow buds (**Dec-Jan**). Eggs hatch (**Feb-Mar**).	Feeding and reproduction occurs on willow (**Mar-Apr**).	Winged adults are formed and migrate to carrot and other hosts over 5-6 weeks (**May-Jul**). Further winged generations disperse to wild hosts (**Aug-Sep**).
Myzus persicae (**peach-potato aphid**)	Adults infest OSR and vegetable brassicas during mild autumns and transfer viruses (**Sep-Dec**).	Asexual females overwinter in brassica and herbaceous crops and weeds (small proportion of eggs overwinter on peach and nectarine trees). Cold weather reduces survival. (**Nov-Feb**).	Adults migrate into a variety of summer crops, multiply quickly (**Mar-Aug**).	Populations peak (**Jul**) Another small peak (**Aug-Sep**).

5.2. Moths and butterflies (Lepidoptera spp.)

5.2.1. Introduction & life history

A number of Lepidopteran pests damage a host of vegetable crops, among others, and although they are being covered as a taxonomic order in this section, it is important that they are not treated as a group, rather as individuals with separate ecologies. One moth species that is not a resident of the UK, but a summer migrant from continental Europe, can be sporadically damaging to oilseeds and vegetable brassicas. The arrival of the diamond-back moth, *Plutella xylostella* Linnaeus (Lepidoptera: Plutellidae), is variable, but the main risk period of egg laying and damage is between June and August, and to a lesser extent in May and September (HGCA, 2014). The silver Y moth, *Autographa gamma* Linnaeus (Lepidoptera: Noctuidae), is another immigrant pest which damages a broad array of crops. Overwintering overseas (Oct-Mar), the moths arrive (Apr), with immigration peaking in late spring (May-Jun). Eggs are laid and the hatched caterpillars feed (May-Jul), until pupation (Jul-Aug) and an eventual migration southwards as adults emerge from pupation (Aug-Sep) (HGCA, 2014). Other Noctuid moths, otherwise known as cutworms, also damage a large host of crops, and many are UK residents (HGCA, 2014).

5.2.2. Damage/presence

Lepidopteran pests can be damaging to a vast array of crops, and often cause damage due to larval feeding or by leaving indiscriminate frass (droppings) rendering the crop as less or completely unmarketable. Table 5.2.2.1 describes some of the most important lepidopteran pests in the UK, and the crops that are attacked. Please refer to HGCA (2014) for pest specific damage that is caused.

Table 5.2.2.1. Crops at risk from lepidopteran pests in the UK (HGCA, 2014).

Lepidopteran pest	Crops liable to damage
Mamestra brassicae (**cabbage moth**)	Vegetable brassicas
Noctuidae (**cutworms**)	Vegetable brassicas, potatoes, carrots, alliums, peas, sugar beet, lettuce
Plutella xylostella (**diamond-back moth**)	Oilseeds, vegetable brassicas
Cnephasia asseclana (**flax tortrix moth**)	Peas, sugar beet, lettuce
Evergetis forficalis (**garden pebble moth**)	Vegetable brassicas
Hepialus humuli (**ghost moth**)	Cereals, carrots, lettuce
Pieris brassicae (**large white butterfly**)	Vegetable brassicas
Acrolepiopsis assectella (**leek moth**)	Alliums
Cydia nigricana (**pea moth**)	Peas (see Section 4.2.2)
Autographa gamma (**silver Y moth**)	Oilseeds , vegetable brassicas, carrots, peas, field beans, sugar beet, lettuce
Pieris rapae (**small white butterfly**)	Vegetable brassicas
Korscheltellus lupulinus (**swift moth**)	Cereals, carrots, lettuce

5.2.3. Pest thresholds

Despite no validated UK thresholds for most lepidopteran pests, there are varying methods for the monitoring of each pest. For more information, please see HGCA (2014).

5.2.4. Potential for control

5.2.4.1. Chemical control

As *P. xylostella* is an important pest worldwide, there are populations, particularly in tropical regions, that have developed resistance to pesticide groups with which they have been exposed to repeatedly. At present, there is no evidence the insecticides resistance in migrating moths is present for the insecticides used in the UK (HGCA, 2014). To alleviate the chemical insecticide input into systems, there may be promising advances in using 'eco-friendly' insecticides. Vanlaldiki et al. (2013) found that the bio-pesticide known as **'neem'**, was able to reduce larval *P. xylostella* populations, whilst having little effect on the ladybird *Coccinella septempunctata*.

Another bio-pesticide which has relatively limited effect on non-target species when compared to conventional insecticides, is the **microbial insecticide** *Bacillus thuringiensis* (Bt). Magalhães et al. (2014) found that the use of different Bt-containing insecticides could cause complete mortality of *P. xylostella* on kale crops. Moreover, the use of the Bt insecticidese also appeared to benefit the predatory shieldbug, *Podisus nigrispinus* Dallas (Hemiptera: Pentatomidae). Following the Bt application, Magalhães et al. (2014) found that *P. nigrispinus* predated more *P. xylostella* and fed less often on the kale crop itself, highlighting the enhanced interaction of other natural enemies. Although *P. nigrispinus* is not present in the UK, the observed interaction may be repeated by UK natural enemies of *P. xylostella*. The use of Bt may also be useful in the control of the cabbage moth (*Mamestra brassicae*), cutworms (Noctuid moths), the silver Y moth (*Autographa gamma*), the large white butterfly (*Pieris brassicae*), the leek moth (*Acrolepiopsis assectella*), and the small white butterfly (*Pieris rapae*) (HGCA, 2014).

5.2.4.2. Biological control

Two endoparasitoid **wasps**, *Cotesia vestalis* (syn. *plutellae*) Haliday and *Dolichogenidea sicaria* Telenga (both Hymenoptera: Braconidae) were found to be potentially useful biological control agents of *P. xylostella* (Malcicka and Harvey, 2015). Although it is unclear as to whether either wasp is present in the UK, the wasps were found in the study by Malcicka and Harvey (2015) and was based in the Netherlands, and therefore it may be that they may be unrecorded residents of the UK as opposed to being absent. Mustată and Mustată (2010) underline the importance of the parasitoid complexes that provide pest supression of cabbage pest Lepidopterans, including cabbage moth (*Mamestra brassicae*), cutworms (Noctuid moths), the silver Y moth (*Autographa gamma*), the large white butterfly (*Pieris brassicae*), the leek moth (*Acrolepiopsis assectella*), and the small white butterfly (*Pieris rapae*). The natural mortality of *P. brassicae* can be naturally high, mostly due to the parasitic wasp, *Cotesia glomerata* Linnaeus (Hymenoptera: Braconidae), whilst the use of introduced egg parasitoids, *Trichogramma* spp. (Hymenoptera: Trichogrammatidae) has been explored overseas (HGCA, 2014). Similarly, natural mortality of *P. rapae* is also high due to parasitism by parasitoid wasps (HGCA, 2014).

In a Japanese field study, Suenaga and Hamamura (2015) found that ***Pardosa*** *astrigera* was able to significantly supress *P. xylostella* densities in the spring. Crucially, the cabbage yield did not increase despite the supression of this pest, combined with *Myzus persicae* (peach-potato aphid) predation in the autumn. However, the study does highlight the importance of wolf spiders in the predation of cabbage pests in spring and autumn. HGCA (2014) also mention that predatory flies are important in the suppression of some Lepidopteran pests.

Far removed from conservation biological control, Gökçe et al. (2015) isolated **entomopathogenic nematodes** from a population of cutworms (or more specifically, *Agrotis segetum* Denis & Schiffermüller larvae) and applied the nematodes (identified as *Steinernema websteri* (Rhabditida: Steinernematidae)) to *A. segetum* larvae in microcosms. Using the nematode concentration of 500 infective juveniles per gram of dry sand, 100% mortality of *A. segetum* was achieved, and therefore poses a potentially useful biological control agent against cutworms.

5.2.4.3. Cultural control

Xia et al. (2015) explored the use of intercropping vegetable brassicas (cauliflower in this case) with tomatoes has shown promise, as the ratio of *P. xylostella* to parasitoid wasps (namely *Cotesia vestalis*) to *P. xylostella* increased in the **intercropping** fields compared to monoculture fields. Although there were no significant differences among the three intercropping ratios, the authors suggested that the 30% intercropping ratio of tomato plants ismost optimal for control of cauliflower pests in general (Xia et al., 2015). More manually, HGCA (2014) suggested using a fine mesh netting, although it was pressed that this does not always prevent egg laying onto the net itself, and subsequently, the hatched larvae can crawl through the net and onto the crop.

Young cutworm larvae are very susceptible to **irrigation** while feeding on the above-ground foliage, and because of this, a strategically timed irrigation even can provide highly effective control of cutworms (HGCA, 2014). Crop rotations may also be important, for the like of the leek moth (*Acrolepiopsis assectella*), as locating new allium crops away from previously infested areas is vital to prevent reinfestation, though this is probably more important in the warmer south of the UK (HGCA, 2014).

5.2.5. Outlook

Table 5.2.5.1. A summarising table of management implications to control diamond-back moths in a sustainable manner. The management techniques may also transfer to the control of other lepidopteran pests.

Chemical control
• Although pests are resistant to many insecticide groups, there is no evidence that those migrating to the UK are highly resistant to chemicals approved for pest control (HGCA, 2014). • Consider bio-insecticides (e.g. Bt), which can cause complete mortality of the pest, and encouraged predators like shield bugs to predate more pest and feed less on kale crop (Magalhães et al., 2014). • Promise for control of pest using 'eco-friendly' neem-based insecticides, which can reduce larval pest populations, and have little effect of ladybird (predator) populations (Vanlaldiki et al., 2013).
Biological control
• Encourage parasitoid wasps (Malcicka and Harvey, 2015). • Encourage spiders (particularly wolf spiders) for early spring pest suppression (Suenaga and Hamamura, 2015).
Cultural control
• A fine net meshing does not fully prevent egg laying (HGCA, 2014). • Intercropping vegetable brassicas (e.g. cauliflower) with tomatoes has been shown to increase the number of parasitoids compared to pest moths (Xia et al., 2015), although it is unknown whether the specific species are present in the UK.

5.3. Thrips (Thripidae spp.)

5.3.1. Introduction & life history

Thrips angusticeps Uzel (field thrips) attack pea and bean crops, while *Kakothrips pisivorus* Westwood (pea thrips) attack just pea crops, and *Thrips tabaci* Linnaeus (onion thrips) (all Thysanoptera: Thripidae) attacks alliums vegetable brassicas and sugar beet (HGCA, 2014). These often damaging pests can cause considerable damage, and vary in their life histories, as can be seen in Table 5.3.1.1.

Table 5.3.1.1. Life histories of three thrip pests of vegetables in the UK (HGCA, 2014).

Aphid species	Autumn	Winter	Spring	Summer
Thrips angusticeps (**field thrip**)	Overwinter as short winged adults in the soil (**Oct-Feb**).	Overwinter as short winged adults in the soil (**Oct-Feb**).	Thrips emerge from soil to feed on young (**Mar-May**).	Adult thrips with normal sized wings migrate to other crops (**May-Sep**).
Kakothrips pisivorus Westwood (**pea thrip**)	Nymphs overwinter in soil (**Aug-Apr**).	Nymphs overwinter in soil (**Aug-Apr**).	Nymphs overwinter in soil (**Aug-Apr**). Nymphs pupate (**May**). Winged adults emerge and move into crops, laying eggs in flowers and pods, and nymphs hatch to feed on the crop (**May-Jun**).	Winged adults emerge and move into crops, laying eggs in flowers and pods, and nymphs hatch to feed on the crop (**May-Jun**). Peak populations (**Jun**). Nymphs enter soil to overwinter (**Jul**).
Thrips tabaci (**onion thrip**)	Overwinter as adult stage in host crops (e.g. leek) but also other crops (e.g. cereals) (**Oct-Apr**).	Overwinter as adult stage in host crops (e.g. leek) but also other crops (e.g. cereals) (**Oct-Apr**).	Overwinter as adult stage in host crops (e.g. leek) but also other crops (e.g. cereals) (**Oct-Apr**).	Females lay eggs on hosts or having dispersed to new sites, and eggs hatch undergoing four development stages (**May-Sep**).

5.3.2. Damage/presence

T. angusticeps attacks pea and bean crops upon early emergence, consuming within the tightly rolled leaves from the growing point throughout the season, and also damage sugar beet foliage. *K. pisivorus* on the other hand targets pea crops during and after flowering, to the detriment of the pods. Less specifically, *T. tabaci* will attack leek, salad onion, stored cabbage and sugar beet, and thrip presence on the plants will render the crop unmarketable (HGCA, 2014).

5.3.3. Pest thresholds

For information regarding the thresholds and subsequent thresholds for control, please refer to HGCA (2014).

5.3.4. Potential for control

5.3.4.1. Chemical control

Pyrethroid resistance of the the onion thrip (*Thrips tabaci*) was confirmed in 2006 for the UK, however at present, no other thrip species are known to be resistant to the insecticide (HGCA, 2014). For other contact insecticides, new application techniques may yet improve the efficiency and thus the sustainability of **spraying techniques**, if insecticides truly are necessary. A row application technique ensures that contact insecticides and fungicides are applied much more evenly within leek (Beck et al., 2015). Indeed, this technique may be important for other allium crops, when non-chemical techniques have failed to protect the crop.

5.3.4.2. Biological control

HGCA (2014) emphasise that some of the natural enemies that supress thrip populations include spiders, ladybirds, predatory flies, and lacewings. The extent to which large-scale systems effect the ability to which these predators respond to their prey, *T. tabaci* (onion thrip), was assessed within fields of monoculture in USA by Fok et al. (2014). The authors found although predator abundance was low in small- and large-scale systems, the **small-scale systems** beared a predator abundance that was berween 2.5-13 times greater than that of the large-scale systems. The small-scale systems were characterised by multiple vegetable crops (Fok et al., 2014), and therefore highlights the benefit of smaller and more diverse systems on biological control agents.

Alternative biological control approaches that may be feasible on small scale vegetable systems have been proposed by some. Muvea et al. (2015) explored the effects of endophytic fungi that have colonized healthy plant tissues, and how this can induce an induced systematic resistance against biotic and abiotic stressors. **Endophyte**-colonized onion plants were found to trigger an antixenotic repellent response to the onion thrip, *T. tabaci*, when attacked, and was suggested that this repellent response could be harnessed in the field (Muvea et al., 2015).

5.3.4.3. Cultural control

In order to control field and pea thrips (*Thrips angusticeps* and *Kakothrips pisivorus* respectively), **late-emerging** crops should be sown in high risk areas (HGCA, 2014). Resistant cultivars should also be considered, however, onion thrips in the UK are confirmed to have developed a resistance to certain previously **resistant cultivars**. At present, there is no varietal resistance confirmed for the UK (HGCA, 2014). Perhaps most promising of all, is the success resulting from **intercropping**, whereby intercropping in onion crops can reduce onion thrip populations by over 50% in leeks. Similarly, **undersowing** with clover has also been found to reduce onion thrip populations, however, both techniques may be rather financially contraining (HGCA, 2014). Lastly, HGCA (2014) also mention the benefits of well timed **irrigation** to reduce thrip populations, a strategy that has been adopted by growers in many countries.

5.3.5. Outlook

Table 5.3.5.1. A summarising table of management implications to control thrips in a sustainable manner.

Chemical control
• Onion thrip resistance to pyrethroid insecticides were confirmed for the UK in 2006. At present, there is no evidence of resistance by the other thrip species (HGCA, 2014). • Row application technique ensures more even application of fungicide and contact insecticides in **leek**, compared to a conventional spray boom technique (Beck et al., 2015).
Biological control
• Encourage spiders, ladybirds, predatory flies, and lacewings (HGCA, 2014) via the diversified, small scale agroecosystems (Fok et al., 2014). • Consider inoculating crops (e.g. onions) with fungal endophytes, which can improve plant resistance to pest damage (Muvea et al., 2015).
Cultural control
• For field thrips (attacks pea and bean crops) and pea thrips (attack pea crops), sow late-emerging crops in high-risk areas (HGCA, 2014). • Onion thrips in the USA have been confirmed to be resistant to certain varieties of onion, though no varietal resistance is confirmed in the UK (HGCA, 2014). • Consider intercropping in **onion** crops, where pest infestations can be reduced by 50% or more (HGCA, 2014). • Many countries use irrigation as a means of pest reduction (HGCA, 2014).

5.4. Other vegetable pests

5.4.1. Leaf miner flies

In OSR, *Scaptomyza flava* Fallén (Diptera: Drosophilidae) (brassica leaf miner) damage is unlikely to justify insecticide treatment, despite the unsightly mining marks, as usually, the only leaves that are mined into are the first true leaves, which often senesce over winter (HGCA, 2014). OSR can also be attacked by the cabbage leaf miner, *Phytomyza rufipes* Meigen (Diptera: Agromyzidae). Again, as *P. rufipes* only attacks the outer leaf petioles, which usually die over winter, it is not regarded as an important pest, and does not require insecticide treatment (HGCA, 2014). More information on the life cycle and monitoring of *S. flava* can be found in (HGCA, 2014).

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Appendix

Please refer to this page list when trying to ascertain the range of crops that a certain pest will attack.

Table A. The main crops and their respective pests within the UK. This table can be a useful tool, for understanding the range of crops that can be damaged by certain pests. It is also useful for switching between sections of this report, as aphid species can attack many different crops, and therefore management described in one section may be important in another. Please note that some minor pests have not be listed in this table.

	Oilseeds	Vegetable brassicas	Cereals	Potatoes	Carrots	Alliums	Peas	Field beans	Sugar beet	Lettuce
Bean seed flies		x	x			x	x	x		
Bird cherry-oat aphid			x							
Black bean aphid							x	x		
Brassica leaf miner	x	x								
Brassica pod midge	x									
Bruchid beetle								x		
Buckthorn-potato aphid				x						
Cabbage aphid	x	x								
Cabbage root fly	x	x								
Cabbage seed weevil	x									
Cabbage stem weevil	x	x								
Cutworms		x		x	x	x	x		x	x
Diamond-back moth	x	x								
Flea beetles	x	x								
Frit fly			x							
Gout fly			x							
Grain aphid			x	x						
Leatherjackets	x		x				x	x	x	
Orange wheat blossom midge			x							
Pea and bean weevil							x	x		
Pea aphid							x	x		
Pea moth							x			
Peach-potato aphid	x	x		x					x	x
Pollen beetle	x	x								
Potato aphid		x		x					x	x
Rape winter stem weevil	x									
Rose-grain aphid			x							
Saddle gall midge		x								
Silver Y moth	x	x			x		x	x	x	x
Slugs	x	x	x	x	x	x	x	x	x	x
Thrips		x				x	x	x	x	
Turnip sawfly	x	x								
Wheat bulb fly			x							
Wireworms			x	x	x	x	x	x	x	x