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AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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GROWER SUMMARY

Headline

This project collated relevant current knowledge on aphid control in protected pepper crops. Information was collected using a systematic literature review and interviews with growers and crop protection specialists. The project identifies key gaps in knowledge and opportunities to improve control of aphid pests.

Background

Aphids are one of the most serious pests of protected pepper crops grown in the UK. There are four key species of aphid pest; the peach potato aphid (*Myzus persicae*), the foxglove aphid (*Aulacorthum solani*), the melon and cotton aphid (*Aphis gossypii*) and the potato aphid (*Macrosiphum euphorbiae*). Crop damage typically occurs when large populations of aphid retard and distort plant growth. In addition, honeydew produced by aphids can lead to the growth of sooty moulds on foliage and fruit. The foxglove aphid presents an additional problem in that its saliva contains toxins, which cause yellowing, twisting and distorting of the young leaves and necrotic spots on the fruit.

Growers of both conventional and organic crops rely heavily on the use of aphid parasitoids, in particular *Aphidius colemani*, to control aphid pests. Predators, such as *Aphidoletes aphidomyza*, are also widely used for aphid control. Pesticide usage survey data shows that aphid control is cited as the reason for 74% of insecticide usage. For aphid control in conventional crops there is a current reliance on the use of pymetrozine (Chess WG) and pirimicarb (e.g. Aphox), while in organic crops, fatty acids (e.g. Savona) are frequently relied upon.

Integrated Pest Management (IPM) is well established and widely used by UK protected pepper growers. Growers are, however, under pressure to continue to effectively manage aphid pests. These pressures include, hyperparasitoids, which disrupt biological control programmes, insecticide resistance in key aphid pests, the limited range of effective insecticides and concerns over pesticide residue levels. In order to meet these and other challenges, growers need more information, which can either be immediately implemented or used to identify knowledge gaps and opportunities. Where knowledge gaps and opportunities exist, there is the potential for targeted research and knowledge transfer activities to develop practical solutions with which to improve aphid control in protected peppers crops.

Summary

Objective 1: Review and collation of current knowledge of controls and biology of aphid pests affecting pepper crops

Task 1.1 Interviewing key industry representatives

A total of sixteen representatives of the UK protected pepper industry were interviewed. This included six conventional pepper growers, one organic pepper grower (who also maintained a conventional crop), one conventional chilli grower, seven representatives of biological and chemical control suppliers and one seed supplier. Each representative was interviewed by phone or in person using a semi-structured approach so that the same set of questions was asked in each case.

Task 1.2: Systematic retrieval of peer-reviewed scientific literature

Peer-reviewed scientific literature was obtained from online databases, including Web of Knowledge, CAB Abstracts and Science Direct. Databases were searched using a range of keywords, including the species names of biological controls and aphid pests, active ingredients etc. A total of 270 peer-reviewed scientific journal papers were reviewed.

Task 1.3: Retrieval of relevant 'grey' literature

'Grey' literature included AHDB Horticulture (formerly HDC), IOBC conference proceedings and other conference proceedings. A total of 22 AHDB Horticulture reports and factsheets, 12 conference proceedings, seven book chapters and two Defra reports were reviewed.

Task 1.4: Collation and summarising of key information

Peer reviewed scientific literature and relevant 'grey' literature was summarised and combined with results from the interviews with industry representatives.

All interviewed growers confirmed that they were managing aphid pests at the time of the interviews (August to September 2015). All but one of the interviewed growers considered aphids to be a major pest of protected pepper and chilli crops. Several interviewed growers indicated that lepidopteran pests were also a key concern. Growers and crop protection specialists confirmed that the most common aphid pests were *Myzus persicae*, *Aulacorthum solani*, *Aphis gossypii* and *Macrosiphum euphorbiae*.

Biological controls were used by all interviewed growers, with preventative releases made early in the season. Once aphids were recorded in the crop, growers increased release rates of biological controls accordingly. The most widely used biological control was the aphid parasitoid *Aphidius colemani*. The aphid predator *Aphidoletes aphidimyza* was also widely used. *Aphidius ervi* was frequently used, particularly for control of *Aulacorthum solani.* Other species of parasitoid wasp used included *Aphidius matricariae* and *Aphidius abdominalis.* Growers reported that some crops were naturally infested with *Praon* spp., and a few growers had purchased *P. volucre* in the last five years. Other than *Aphidoletes aphidimyza*, growers rarely used other aphid predators, although the interviewed organic grower did release the hoverfly *Episyrphus balteatus*. Few growers released the lacewing *Chrysoperla carnea,* despite biological control suppliers frequently mentioning this species during interviews.

With a reliance on aphid parasitoids in pepper crops, hyperparasitism is become a major problem for pepper growers. All interviewed growers were aware of hyperparasitism and confident in recognising its presence within the crop. When high rates of hyperparasitism are detected, releases of parasitoids are stopped and an insecticide application made to reduce hyperparasitoid, parasitoid and aphid numbers. After spraying, *A. aphidimyza* was often released to provide aphid control. This is the same approach as that decribed by crop protection specialists. Open rearing units (ORUs) were thought to exacerbate hyperparasitism problems by several growers and crop protection specialists while others thought that ORUs usefully maintained and boosted parasitoid numbers in the crop.

Interviewed growers only used insecticides to manage aphid pests when populations were sufficiently large that reliance on biological control was no longer economically viable or hyperparasitism rates were high. Conventional growers generally used pymetrozine (Chess WG), typically applied through the irrigation system, which was sometimes followed by an application of pirimicarb (e.g. Aphox). Organic growers used fatty acids (e.g. Savona). Growers were happy with the efficacy of available insecticides but there were concerns about the reliance on pymetrozine and pirimicarb. Indeed, *Myzus persicae* and *Aphis gossypii* are known to have developed resistance to carbamate insecticides, such as pirimicarb, as well as pyrethroid insecticides. The interviewed organic grower felt that fatty acids provided useful control of aphid pests but noted that *Aphis gossypii* in particular had a tendency to survive sprays. Although biopesticides present a potential alternative to currently used insecticides, few growers mentioned their use. The interviewed organic grower had, however, used maltdextrins (e.g. Majestik).

Pepper crops represent a difficult crop to spray effectively, particularly on lower leaf surfaces, due to the large drooping leaves of mature pepper plants, most of which hang at approximately 30° off vertical. Ultra low volume sprays are known not to penetrate the pepper crop canopy as effectively as high volume sprays. Coverage using high volume sprays can be improved by using a vertical spray boom with two types of nozzle, ‘lifters’ and ‘fillers’. The ‘lifter’ nozzles drive a spray underneath the near-vertical leaves and so lift them up to allow the ‘filler’ nozzles to cover the lower leaves further inside the canopy with a fine spray. Despite this modification, complete coverage of lower leaf surfaces may not be achieved.

Interviewed growers were aware of the importance of good hygiene practices both within and between crops. Despite this, none of the growers interviewed mentioned using physical barriers such as screens on glasshouse vents to prevent aphids entering the crop. Indeed, there was concern that such screens would be prohibitively expensive and would negatively affect environmental conditions within the glasshouse.

The majority of growers interviewed received information relating to aphid control from visiting supplier representatives. Most interviewed growers were happy to receive their information from suppliers but some expressed a wish to access their own information so they could receive a wider range of opinions. To this end, several growers researched their own information from websites such as the AHDB Horticulture website. Several growers commented that factsheets were very effective and could be circulated amongst staff.

Objective Two: Identify knowledge gaps in aphid control in pepper crops and opportunities to adopt controls used in other countries or on other crops for use in pepper crops in the UK

The completed interviews and literature review highlighted several knowledge gaps and opportunities to improve aphid control. Hyperparasitism was highlighted by interviewed growers and crop protection specialists as being a key concern due to the disruption that this causes to biological control programmes. Hyperparasitism is typically managed through the use of an insecticide application, which reduces aphid, parasitoid and hyperparasitoid numbers. Despite the importance of hyperparsitism there has been little research in this area. Preliminary work has, however, been completed investigating the potential of a system in which semiochemicals are used to manipulate hyperparasitoid behaviour. This approach could address grower concerns over the use of insecticides to manage hyperparasitism and would be of benefit to growers of other crops in which aphid parasitoids are regularly used.

One of the main benefits of improved biological control of aphid pests using predators would be a reduced reliance on the use of *Aphidius colemani*, which in turn may reduce the impact of hyperparasitism on aphid control. Opportunities include the use of flightless morphs of the two-spotted ladybird (*Adalia bipunctata*) and greater use of the lacewing *Chrsoperla carnea*. There is, however, still much to learn about the importance of interactions, both negative and positive, between different biological controls, in particular generalist predators, used in pepper crops. Where parasitoids are used, there are opportunities to improve their efficacy by exploiting attractants, to target their activity, and pre-conditioning wasps before release into the crop.

Growers currently rely on the use of pymetrozine (Chess WG) and to a lesser extent on pirimicarb (e.g. Aphox) and there is concern that over reliance on these two active ingredients may lead to development of insecticide resistance in aphid pests. Resistance has already been reported to pyrethroids and carbamates (e.g. pirimicarb) in *Myzus persicae* and *Aphis gossypii* populations. Reviewing the literature does, however, point to several active ingredients not currently registered for use in protected pepper crops grown in the UK but which may provide useful alternatives to currently used insecticides. These active ingredients include spirotetramat (e.g. Movento) and flonicamid (e.g. Mainman), which are effective against the aphid pests affecting pepper crops and are generally compatible with biological controls that may be used in these crops. In addition, several coded biopesticides have been identified as being effective against aphid pests through the SCEPTRE (HDC project CP 77) and MOPS (AHDB Horticulture project CP 124) projects. In other work, the biopesticide neem (NeemAzal) has recently been evaluated in organic pepper crops and gave good aphid control, reducing aphid numbers and preventing visible aphid damage. It should be noted that neem is not yet registered for use in the UK.

Despite the concerns highlighted in the interviews that fitting screens to vents and doors would be prohibitively expensive and would disrupt temperature and humidity control, the fact that this approach has been successfully demonstrated in protected lettuce crops indicates that it is worth further investigation. Similarly, although few growers discussed the importance of application technology, previous work has demonstrated the benefits of modifying spray equipment to improve coverage. Work to date has been focused on wide bed organic cropping systems and so further work in conventional cropping systems is required.

Financial Benefits

The home marketable production of protected peppers grown in the UK in 2014 was worth £200k per hectare, with 258 tonnes of peppers produced per hectare and a total of 23,700 tonnes of peppers produced across the UK in total (Basic Horticultural Statistics 2014). The cost of routine aphid control in a conventional pepper crop has been estimated at £5.8k per hectare per season. When aphid outbreaks occur, however, in the pepper crop the cost of control control increases substantially due to the increased number of biological control and insecticide applications, washing fruit damaged by honeydew and loss of yield. Together these costs may mean that aphid control exceeds 100k per hectare per season.

Action Points

Results from the interviews with growers and crop protection specialists indicate that aphid control in protected pepper crops is based on current best practice. The following action points, therefore, relate to gaps in knowledge and opportunities idenitified through this project:

- There is a lack of information on the biology and control of hyperparasitism. Interviewed growers were interested in alternatives to the current use of insecticides to manage hyperparasitism. Preliminary work investigating the use of semiochemicals to manipulate hyperparasitoid behaviour shows considerable promise but requires further work to develop a practical solution for growers. Improved control of hyperparasitism would be of benefit to a wide range of growers who regularly use aphid parasitoids to control aphid pests.

- Extending the range of biological controls, in particular the use of predators, used to control aphid pests may help to improve control and reduce hyperparasitoid problems by reducing the reliance on *Aphidius colemani*. Greater use of generalist predators would, however, increase the need for further work to investigate interactions between biological controls, such as intraguild predation.

- There are several insecticide active ingredients, such as spirotetramat and flonicamid and biopesticides, such as neem, that could provide useful control of aphid pests and reduce the reliance on, and possible development of resistance to, pymetrozine. Further work to determine the efficacy of these alternative insecticides and biopesticides as well as their compatibility with IPM programmes used in pepper crops is required.

- Assessing the potential of using screens over vents and doors to prevent sporadic invasion by large numbers of aphids is required to determine the cost-effectiveness of this approach. In particular, it will be important to confirm that environmental management can be successfully adjusted to compensate for any effect the screens may have on temperature and humidity in the glasshouse.

- Work in a wide bed organic cropping system has demonstrated that modification of spray equipment can improve spray coverage and as a result control of aphid pests. There is potential both to further improve spray coverage and to adapt these systems for use in conventional crops.

SCIENCE SECTION

Introduction

In 2013 there were 105 ha of protected peppers grown in the UK, of which only 3% remained untreated with pesticides. A total of 4,720 kg of pesticides were applied to pepper crops, approximately 65% (by weight) of which were insecticides, 15% disinfectants, 15% physical control agents and the rest fungicides. At the same time, biological controls were used on over 80% of the crop area. Protected pepper crops received on average 74 applications of biological control agents, 12 biopesticides, nine insecticides, four physical control agents and one fungicide during the growing season. Aphid control was cited as the reason for 74% of insecticide usage, indicating the importance of these pests to growers (Garthwaite *et al.,* 2013).

In 2013, the value of protected peppers in the UK was £200k per planted hectare (Defra Horticultural Statsitics 2014). The cost of routine aphid control in a conventional pepper crop has been estimated at £5.8k per hectare per season and when substantial problems with aphids occur in the crop, the cost of control strategies, including additional applications of biological controls and insecticide, washing fruit damaged by honeydew and loss of yield may exceed 100k per hectare per season (Jacobson *et al.,* 2010). Improved aphid control, therefore, both in terms of cost-effectiveness and reliability, is likely to provide growers with substantial financial savings. The purpose of this report is to review current management of aphid pests affecting protected pepper crops in the UK and to identify knowledge gaps and opportunities to improve aphid control. The report combines a review of the current scientific literature with a series of interviews with growers and crop protection specialists about their experiences, aphid control strategies and current perceived problems. This report aims to identify areas in which further research and/or knowledge transfer activities may provide practical solutions and improvements to the control of aphid pests in UK protected pepper crops.

Objectives

1. Review and collation of current knowledge of controls and biology of aphid pests affecting pepper crops
2. Identify knowledge gaps in aphid control in pepper crops and opportunities to adopt controls used in other countries or on other crops for use in pepper crops in the UK

Materials and methods

Objective 1: Review and collation of current knowledge of controls and biology of aphid pests affecting pepper crops

In order to produce a review of the current knowledge relating to the control of aphid pests of protected pepper crops, information was obtained from a wide range of sources. Peer-reviewed and 'grey' literature (including AHDB Horticulture (formerly HDC) reports and International Organisation for Biological and Integrated Control (IOBC) conference proceedings) was systematically searched using online databases. The information collected using this approach was supplemented and given context by interviewing key industry representatives, including growers, insecticide and biological control distributors and seed companies on their current perceptions of aphid control in protected pepper crops grown in the UK.

Task 1.1 Interviewing key industry representatives

A total of sixteen industry UK representatives were interviewed.

- Six conventional protected pepper growers
- One organic protected pepper grower
- One conventional chilli grower
- Seven representatives of biological control and insecticide suppliers (referred to in this report as 'crop protection specialists' unless otherwise stated)
- One seeds supplier

Interviewees were either contacted by telephone or visited in person. Each representative was interviewed using a semi-structured approach in which the same set of questions was asked. These questions were designed to cover areas such as aphid pests encountered within pepper crops, currently used aphid control measures, the success of these control measures and any perceived gaps in knowledge or available crop protection products that were felt to be essential for improved aphid control in UK protected pepper crops. Interview questions were designed in consultation with two industry consultants, Dr Richard Binks and Dr Rob Jacobson, to ensure that all relevant issues were covered.

Task 1.2 Systematic retrieval of peer-reviewed scientific literature

Peer-reviewed scientific literature was obtained from several online databases, including Web of Knowledge, CAB Abstracts and Science Direct. Databases were searched using a range of keywords, including the species names of biological controls and aphid pests known to affect pepper crops, active ingredients on which insecticide products are based and other crop protection practices used or of relevance to aphid control in protected pepper crops. Access to the literature was provided online through the Harper Adams University library.

Task 1.3 Retrieval of relevant 'grey' literature

Relevant 'grey' literature for this report was comprised of AHDB Horticulture/HDC reports, IOBC conference proceedings and other conference proceedings dealing with aspects of aphid control with a focus on, but not restricted to, UK pepper crops. Relevant literature was obtained either by searching the online databases CAB Abstracts and Web of Knowledge, or in the case of AHDB Horticulture/HDC reports, by searching on the AHDB Horticulture website. Access to the literature was provided online through Harper Adams University, AHDB Horticulture website and membership subscription to the IOBC.

Task 1.4 Collation and summarising of key information

The key information collected from searched literature, whether peer-reviewed journal articles or 'grey literature' reports and conference proceedings, were recorded together within a database using Microsoft Excel. Any replicated material was removed. This provided a database of information on aphid control in protected pepper crops from which current knowledge and gaps in understanding could be identified. A total of 313 research articles/reports were used to produce the findings of this report, this included 270 peer-reviewed scientific journal articles, 22 AHDB Horticulture/HDC reports and factsheets, twelve conference proceedings, seven book chapters and two Defra reports.

Objective Two: Identify knowledge gaps in aphid control in pepper crops and opportunities to adopt controls used in other countries or on other crops for use in pepper crops in the UK

After the summary table of information on the control of aphids in protected pepper crops had been produced, opportunities to build on current knowledge and improve aphid control were identified and discussed within the report.

Results and Discussion

Review and collation of current knowledge of controls and biology of aphid pests affecting pepper crops

Summary of interviews of key industry representatives

Interview results

A total of 16 representatives of the UK protected pepper industry were interviewed, including six conventional protected pepper growers located in southern England, one organic grower (who also grew conventional peppers), one conventional chilli grower, seven crop protection specialists (including representatives of biological and chemical control suppliers) and one seeds supplier.

All growers interviewed reported that they currently (August and September 2015) had aphid pests within their protected pepper crops. All but one of the growers interviewed considered aphids to be a major problem affecting their pepper crops and targeted research to develop improved control measures was of interest to them. Similarly, all crop protection specialists interviewed also considered aphids to be a major pest problem in protected pepper crops within the UK and were interested in new crop protection products and/or improved techniques for managing these pests.

Interviewed growers were all using biological controls in a protective manner early in the growing season to control aphid pests. Release rates of predators and parasitoids were then increased in response to increases in aphid populations. Insecticide applications were only applied once aphid populations were sufficiently high that biological control became uneconomic. Insecticide applications were only applied by growers after seeking advice from an appropriate crop protection specialist and growers were generally reluctant to spray unless necessary. Many growers voiced concerns about the effect of the insecticides they used on populations of biological controls they had already established and making sure they met residue level targets in the harvested crop.

More detailed responses from the interviews are summarised in the following sections and combined with the findings from the literature review for each area of interest regarding aphid control in pepper crops.

Pepper Cultivars

Interview results

All protected pepper types and colours were represented across the businesses interviewed, including blocky, sweet point and baby peppers. Most growers produced several different types and colours of pepper within their business. With the exception of one individual, growers said that the pepper types and colours they chose to grow depended on the demands of the marketplace and what was required by customers rather than considerations towards which varieties were resistant to aphids or other pests/diseases. The exception was the organic grower who discarded varieties found to be particularly susceptible to aphids. This grower noted that such varieties could still be successfully grown in the conventional side of their business when the use of insecticides not available for use on organically grown crops could be used. The conventional chilli grower interviewed noted large differences in the susceptibility of different chilli varieties to aphid pests and selected varieties on this basis where possible.

Though only a single seed producer was interviewed they explained that their company did not develop varieties of pepper for aphid resistance. This decision was taken as it is considered that there are sufficient control measures to effectively manage aphid pests. Instead, pepper varieties are developed for viral resistance as well as good colour, growth and other physiological traits linked to crop quality and yield. It was not considered economically viable to select for traits related to aphid resistance rather than those related to resistance to plant pathogens or at the expense of traits related to fruit quality.

Literature review

There are several examples of selection of plant varieties for aphid resistance or tolerance in cultivated crops (Abdel-Hafiz, 2008; Hu *et al.,* 2013; Sarwar & Sattar, 2013; Liang *et al.,* 2015) but none of these relate to varieties of pepper. Despite this, there is some evidence that certain pepper varieties can increase nymphal development time in the peach-potato aphid (*Myzus persicae*)*,* slow population growth and exhibit reduced damage symptoms when colonised by aphids (Frantz *et al.,* 2004; La Rossa *et al.,* 2013). There is also evidence that certain pepper varieties may be less susceptible to infection with viruses vectored by aphid pests (Marte *et al.,* 1991).

Opportunities and knowledge gaps

Given the comments from the interviewed seed supplier, it seems unlikely that pepper varieties will be developed for resistance to aphid pests within the near future. With this in mind, it may be more useful to investigate whether any varieties of pepper currently grown in the UK differ in their susceptibility to each of the main aphid pests. Such a study would particularly benefit the organic pepper industry, where the natural resistance of a plant to infestation by aphids and other plant pests is of greater value than in conventional systems. While it is unlikely that large differences in susceptibility to aphid pests would be found between currently grown pepper varieties, an understanding of any such differences may aid in pest management decisions. It does, however, remain the case that the varieties and types of pepper grown are determined by the demands of the market, and to move away from such pepper varieties in order to improve management of aphid pests is unlikely to be feasible.

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Current key aphid pests of UK protected pepper

Interview Results

The main aphid pests of protected pepper crop identified by growers and crop protection specialists were the peach potato aphid (*Myzus persicae*), the foxglove aphid (*Aulacorthum solani*), the melon and cotton aphid (*Aphis gossypii*) and the potato aphid (*Macrosiphum euphorbiae*). *Myzus persicae* and *Aulacorthum solani* were the species most frequently cited by growers, but when *Aphis gossypii* was present in high numbers it was considered to be a major pest problem.

Several growers noted that *Myzus persicae* is nearly always present, but the aphid species causing the most problems varied from year to year. Most growers were confident in controlling *M. persicae* and felt that they have effective methods for control available to them. In contrast, growers commented that they had more problems controlling other aphid species such as *Aulacorthum solani.* Most growers reported a surge in aphid numbers between April and June, although all growers also stated that the timing of this sudden population increase was not predictable and varied from year to year.

Literature review

The literature also indicates that the main four aphid pests of protected pepper crops are *A. solani, M. persicae, Macrosiphum euphorbiae* and *Aphis gossypii* (e.g. Croft *et al.*, 2008; Sanchez *et al.,* 2011). While the use of biological controls and insecticide applications approved for conventional or organically grown crops can achieve effective control of aphids within pepper crops, populations are rarely completely eradicated and once a crop is infested, aphid problems may return periodically throughout the season as populations increase from small numbers of survivors after each control application.

Parthenogenic reproduction, vivipary and telescoping of generations mean that aphid populations are capable of increasing quickly (Kindlmann & Dixon, 1989). The reproductive traits of aphids together with an ability to produce winged and wingless offspring are important factors in explaining why several aphid species are important crop pests (Dedryver *et al*., 2010). Aphids damage crops directly, typically where large populations retard and distort plant growth (Sanchez *et al.,* 2007; van Emden, 2007). *Aulacorthum solani* presents an additional problem in that the saliva contains toxins which cause yellowing, twisting and distorting of the young leaves and necrotic spots on fruit in protected pepper crops even at low population densities (Kakimoto *et al.,* 2015). Honeydew secretions produced by aphids can also lead to the presence of sooty mould on foliage and fruit (Ajayi *et al*., 1983; Thomas *et al*., 1983). Even in the absence of sooty moulds, if aphid populations are high, fruit will require washing before sale to remove the honeydew, requiring additional labour and time. In addition, aphids act as vectors of a variety of plant viruses (Dedryver *et al.,* 2010), although aphid-borne viruses do not currently cause a problem within the UK protected pepper industry (Rob Jacobson, personal comms.). Aphid infestations can, therefore, result in a loss of yield, which combined with the cost of additional aphid controls and fruit washing can exceed 100k per hectare per season (Jacobson *et al.,* 2010).

When aphid populations increase, control with biological controls becomes uneconomic due to the sheer number of aphids within the crop, and growers usually resort to the use of an insecticide application to control these large aphid populations. The average number of insecticide applications used in a protected pepper crop per year is seven, with 74% of insecticide applications used to control aphids (Garthwaite *et al.*, 2013).

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Hygiene

Interview results

Several growers and crop protection specialists stressed the importance of glasshouse hygiene and removing weeds during the growing season to reduce aphid infestation. In addition, growers described the importance of removing dead plants and steam cleaning the glasshouse to remove any overwintering aphids and other insect pests before starting a fresh crop the following season. Some interviewees felt that this was a sometimes neglected topic and the benefits to aphid control were not highlighted enough. While there was one anecdote of *Aphidoletes aphidimyza* possibly surviving on weeds left within the glasshouse and re-infesting the following pepper crop, the same grower felt the benefits of the weeds were outweighed by the disadvantages in terms of pests and diseases surviving on the weeds.

Several growers also reported problems with ants protecting aphid populations from predators and parasitoids and as a consequence reducing the overall efficacy of biological control programmes. It was noted that there are no approved products available for controlling ants within protected pepper crops.

Literature review

Vegetation surrounding Spanish glasshouses has been shown to harbour large numbers of polyphagous aphid species, such as *Myzus persicae* and *Macrosiphum euphorbiae* as well as lower numbers of *Aulacorthum solani* (Sanchez *et al.,* 2011). *Myzus persicae* has also been shown to colonise weed species surrounding outdoor protected pepper crops in countries such as Chile (Rubiano-Rodriguez *et al.,* 2014). No similar study was found in which aphid populations surrounding UK protected pepper crops had been recorded. It is, however, known that although relatively weak fliers, aphids are capable of both short and long distance flights (Doring, 2014). Aphid populations found on vegetation immediately surrounding a glasshouse would, therefore, only partly explain the numbers of aphids likely to invade the crop.

Several studies have also shown that vegetation surround glasshouses can also provide a source of natural enemies. For example, Sanchez *et al.* (2011) showed that the abundance and species distribution of aphid parasitoids within Spanish glasshouses was similar to that found on weeds outside. A study by Amaral *et al.* (2013) showed that weeds near pepper crops in Chile were infested with large populations of natural enemies of aphids, including Neuroptera, Syrphidae and Coccinellidae. In another study, this time of lettuce rather than pepper, Sengonca *et al.* (2002) indicated that the presence of certain weed species can promote the presence of greater numbers of aphid predators within nearby crops, including *Adalia bipunctata* and *Chyrsoperla carnea.* It has been suggested that the presence of certain weed species near glasshouses may be beneficial if they promote the migration of greater numbers of parasitoids and predators into crops compared with aphid pests, or if they act as 'sinks' by attracting aphids away from the crop (Sanchez *et al.,* 2011). The authors who make these suggestions do, however, acknowledge that further research is required to determine whether this is indeed the case and which weed species could be used.

Opportunities and knowledge gaps

While further research could investigate aphid populations on weeds in or adjacent to UK protected pepper crops, it is probably unnecessary as most growers and crop protection specialists were aware that good hygiene is important for the control of a range of insect pests. In terms of certain weed species promoting the influx of predators and parasitoids into the crop, it is possible that this could be the case within UK protected pepper crops, but further research would be required to determine the potential of this approach.

There is currently a lack of approved products with which to control ants in protected pepper crops. There is, therefore, a requirement both for research to develop effective ways of controlling ants in protected pepper crops and for effective products to be registered for use. It is essential that any products used to control ants do not negatively affect biological controls used to control other pests.

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Physical barriers

Interview results

None of the growers interviewed mentioned using physical barriers such as screens and filters on glasshouse vents to prevent the infestation of the crop by aphids. One crop protection specialist suggested that given the cost of adding such screens to glasshouses and the effect on the temperature and humidity in the glasshouse, this approach was not economically viable in the UK where the presence of aphid-borne viruses within protected pepper crops is not currently an issue.

Most growers utilised sticky traps to monitor insect pests. Several growers and crop protection specialists noted, however, that few aphids are found stuck to these traps, which was felt reflected the fact that the majority of the aphid population is wingless.

Many growers also explained that despite research into the impact of varying the temperature in the glasshouse on predators, parasitoids and aphid pests, the temperatures within the glasshouse are set to maximise the physiological condition of the protected pepper crop. Growers would, therefore, not accept alteration of the temperature or humidity in the glasshouse for pest control reasons.

Literature review

HDC funded project PC 132, which was completed in 2001, laid the foundation for a new supervised pest control strategy for protected lettuce based on the use of screened glasshouse ventilators and doors to prevent the sporadic invasion of large numbers of winged aphids (Tatchell & Jacobson, 2001). The screens reduced aphid invasion to the point that biologically-based control systems became feasible. Management of the environmental conditions was modified to compensate for the screens and there was no significant difference in temperature, humidity or crop development compared with an adjacent similar unscreened glasshouse. The capital cost of screening, allowing for replacement at five year intervals, was estimated to be £1,230 per 1,000 m^2 per annum.

Much research has been done into the effects of temperature and humidity on the development, dispersal, oviposition and prey finding abilities of various biological controls used to control aphid pests (Shipp *et al.,* 2003; Nadeem *et al.,* 2012; Yamane *et al.,* 2012; Meisner *et al.,* 2014; Jerbi-Elayed *et al.,* 2015). The majority of aphid predator and parasitoid species, however, appear to perform well within a temperature range of between 22-27°C, although there is some variation between species (Auad *et al.,* 2014; Silva *et al.,* 2015). Generally this temperature range lies within that used to grow peppers in the UK, although every glasshouse will experience some localised temperature fluctuations in specific areas. It should also be noted that in one study varying the temperature in protected pepper crops infested with *Macrosiphum euphorbiae* did not appear to offer any significant control benefits, except at temperatures so high that plant performance was reduced (Flores-Mejia *et al.,* 2014).

Sticky traps are currently used to monitor pests in pepper crops, but are not used to control aphid populations. This is mainly because the majority of individuals within aphid populations are wingless and so are unlikely to encounter the sticky traps. Mass trapping, especially when combining sticky traps with an olfactory attractant, can, however, be a cost-effective means of controlling pests such as thrips (Samson & Kirk, 2013). As such there is the potential to improve the efficacy of sticky traps for monitoring even if it is unlikely that such an approach could be used as a means of controlling aphid pests.

Another interesting area of research is the use of spectral filters to disrupt the establishment and reproduction of aphids. Aphids have previously been reported to reduce flight activity in response to UV-deficient light (light sources in which certain wavelengths have been blocked using spectral filters) (Chyzik *et al.,* 2003; Legarrea *et al.,* 2012; Dáder *et al.* 2014; Dáder *et al.,* 2015). Aphids possess a compound eye with a UV receptor peaking at 320-330 nm, another with a peak in the blue region at 440-480 nm and a third green receptor that peaks at 530 nm (Döring & Chitka*,* 2007). It is hypothesised that removal of some of the UV spectrum from light disrupts the ability of aphids to orient within the crop (Dáder *et al.,* 2015). It is also possible that the removal of UV light may affect the insect indirectly by altering plant biochemical traits (Johansen *et al.,* 2011). Croft *et al.* (2006) demonstrated that *Myzus persicae* fecundity on lettuce and fuchsia was lower when crops were grown in polytunnels covered in UV opaque as opposed to UV transparent filters. It was suggested that the lower aphid fecundity in UV opaque covered tunnels might have been linked to a small decrease in temperature. A recent study has also shown that UV filters do not appear to have any effect on the oviposition and dispersal behaviours of *Aphidius colemani* in a protected pepper crop, although parasitoid emergence from the initial container was slightly reduced (Dáder *et al.,* 2015). As an additional benefit, UV filters appear to exert effects on a range of other insect pest species, including whitefly and thrips (Costa & Robb, 1999). UV-absorbing films are currently used commercially in tomato, cucumber and spice crops in Israel and have allowed growers to reduce insecticide use by 25-50% (Sampson *et al.,* 2001). These filters are not in use in UK protected pepper crops at present, although a study by Sampson *et al.* (2001) indicated that they had potential as a means of insect control under UK conditions.

Opportunities and knowledge gaps

The grower interviews indicated that environmental conditions within the glasshouse are always set to optimise crop yield and quality rather than to manage pests. Growers would, therefore, be reluctant to alter the environmental conditions in the glasshouse in response to the presence of pests and so further research into the effect of temperature on the efficacy of biological controls is unlikely to be of benefit to the UK pepper industry.

Rather than varying the temperature to improve parasitoid performance, growers may benefit more by paying close attention to the transport, storage and release conditions of any parasitoids and predators used within the pepper crop and ensure that biological controls are used within their use-by date and released by the methods described by distributors, as deviating from the recommended conditions can be detrimental to the performance of the insects (Fernandez & Nentwig, 1997).

The successful trials with glasshouse screens in commercial lettuce crops (Tatchell & Jacobson, 2001) indicate that the use of screens should be evaluated in UK pepper crops. While there are clearly concerns that such screens may affect environmental conditions within the glasshouse, the work in lettuce crops indicates that this can be effectively managed.

As mentioned earlier, yellow sticky traps are often used to monitor aphid populations in glasshouses but rarely catch enough individuals to have an impact on aphid populations. The effect of specially designed mosaic-green sticky traps on aphid capture within pepper crops has recently been investigated (Perez *et al.,* 2003). Such traps were designed to more closely resemble the absorbance spectrum of the pepper canopy as compared with the standard yellow traps. Over the three years of this study, approximately 15,000 aphids were captured, including large numbers of *Myzus persicae* and *Macrosiphum euphorbiae*, indicating that the traps were effective at trapping aphid pest species. It is possible that use of these specially designed mosaic green traps could improve aphid monitoring in pepper crops, but further research is required. It is unlikely that even modified sticky traps could provide an effective control of aphid populations as a stand alone measure, especially given the fact that aphid populations mainly consist of wingless individuals. Despite this, more efficient monitoring would allow growers to respond more quickly to the presence of aphid populations within the crop.

Sticky traps can also be wrapped around the stems of plants to control aphids, which drop from the plant as a defence against parasitoids or predators. Unfortunately the bands do not discriminate between parasitised and unparasitised aphids and so in a recent study investigating use of these bands combined with releases of *Aphidius ervi* and to control *Aulacorthum solani*, the parasitoid population was reduced by the presence of the bands (Gillespie & Acheampong, 2012). While the bands killed many aphids they do not appear suitable for combining with releases of parasitoids, as mortality caused by the bands merely replaced mortality caused by the parasitoids. Combining the sticky bands with predators rather than parasitoids, however, may be a more effective combination, as the bands would control aphids which drop in response to the predators but in theory the predators would remain on the crop. Further research is required to determine if these approaches have potential to control aphids and/or aphid hyperparasitoids.

The use of spectral filters as a means of managing aphid pests in UK protected pepper crops appears to have considerable potential. It is worth noting, however, that many of the studies mentioned in the literature review section (see above) were completed in polytunnels rather than in glasshouse environments. Further research into the efficacy of spectral filters against aphid pests in a glasshouse environment, along with the effects of these filters on crop physiology and yield is required to assess their suitability for UK glasshouse systems.

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Biological control

Interview results

Aphid parasitoids is the primary means by which aphid pests are controlled in protected pepper crops. The widely used species is *Aphidius colemani*, although many growers also used a second parasitoid species such as *A. ervi* for control of *Aulacorthum solani* and other aphid species. The most frequently used aphid predator was the aphidophagous midge *Aphidoletes aphidimyza,* followed by the lacewing *Chrysoperla carnea.* The majority of interviewed growers did not use parasitoid mixes, preferring to purchase and release one or two parasitoid species. The main reason for this was that parasitoid mixes were viewed as being prohibitively expensive. In addition, while the parasitoid mixes offer control against a wide range of aphid pests most growers felt that this was rarely an advantage as they were seeking to control one or two species at any one time.

Crop protection specialists generally discussed the use of a wider range of predators than growers were using within their crops, particularly in many conventional systems. Crop protection specialists were also generally more enthusiastic about the use of parasitoid mixes than growers.

None of the growers interviewed were using the two-spot ladybird *Adalia bipuntata* in their glasshouses. One grower explained that they did not use *A. bipunctata* because of the tendency of the adults to disperse out of the glasshouse vents, while the larvae often predated on each other during transit from the supplier to the farm. They felt, therefore, that other predator species were more cost effective. One crop protection specialist did not recommend *A. bipunctata* to protected pepper growers for these same reasons.

Naturally occuring predators and parasitoids were often observed within protected pepper crops. The species most commonly mentioned were *Aphidoletes aphidimyza, Praon* spp. and unspecified hoverfly species. *Praon* spp. were cited as being particularly effective, when present, by several growers, but unlike *A. aphidimyza* few growers commercially released this species, possibly as it is available as a mix of several parasitoid species rather than being available as a single species product. Large numbers of a wide range of unidentified species of spider were also present in the crops of all interviewed growers.

Several growers stressed the importance of rapidly receiving biological controls once an aphid problem is identified. A gap of even a few days between the detection of aphids within the crop and receiving the necessary biological controls can lead to a significant increase in the aphid population and crop damage.

Literature review

Biological control is an effective means of controlling aphid pests in both conventionally and organically grown crops and has the added benefit of reducing pesticide residues in harvested crops by helping to avoid additional insecticide applications. A range of biological controls are commonly used in protected peppers to manage crop pests. Some of the more commonly used species in UK pepper crops include *Amblyseius swirskii, Chrysoperla carnea, Orius laevigatus* and a range of aphid parasitoid species, including *Aphidius colemani* and *A. ervi* (Croft *et al.*, 2008).

Aphid parasitoids may be used either protectively within the crop, where releases are made before aphids are detected, or else released in response to the presence of aphids within the crop. Many growers combine these two strategies to control aphid pests in their pepper crops.

The parasitoid species most often used to control aphids within protected pepper crops are *Aphidius colemani, A. ervi* and *Aphelinus abdominalis* (Croft *et al.*, 2008) but *Aphidius matricariae* and *Praon volucre* are also commercially available and were used in some pepper crops by interviewed growers. Based on both the scientific literature review and industry interviews, *A. colemani* appears to be the most widely used parasitoid species for aphid control in protected pepper crops at present (Ramakers, 2004; Sanchez, 2011; Garthwaite *et al.*, 2013). This is largely due to the ability of this parasitoid species to effectively control both *Myzus periscae* and *Aphis gossypii* (Steenis, 1993; Perdikis *et al.,* 2004; Vasquez *et al.,* 2006; Prado & Frank, 2014). *Aphis gossypii* is by comparison less effectively controlled by *Aphidius matricariae* (Steenis, 1995). There is also some evidence that *A. colemani* is more effective at controlling *M. persicae* than the predators *C. carnea* and *Aphidoletes aphidimyza* when only a single biological control species is used (Wiethoff *et al.,* 2002).

The aphid pests *Aulacorthum solani* and *Macrosiphum euphorbiae* can be effectively controlled using *Aphidius ervi* (Sidney *et al.,* 2010a; 2010b). *Aulacorthum solani* is also parasitized by *P. volucre* (Silva *et al.,* 2015) while *M. euphorbiae* is also parasitized by *Aphelinus abdominalis* (Molck & Wyss, 2003). *Aphidius matricariae* appears to be an efficient parasitoid of *M. persicae* (Gavkare *et al.,* 2014) but less effective agaist *A. solani* (Quentin *et al.,* 1995).

With this host specificity in mind, aphid parasitoids may be sold either as individual species or as mixes of parasitoid species. Mixes of parasitoid species offer broad-spectrum aphid control. Studies in Germany on protected pepper crop indicated that the VerdaProtect product, a mixture of six parasitoid species sold by Viridaxis, was as effective at controlling aphid pests as releases of single species but was cheaper, quicker and easier to use (Dassonville *et al.,* 2012).

Parasitoid species may also enter the crop from surrounding vegetation and can contribute to the control of aphid pests (Ceballos *et al.,* 2009; Sanchez *et al.,* 2011). Both *Aphidius matricariae* and *P. volucre* have been recorded entering UK pepper crops naturally (Grower interviews; personal comms. Rob Jacobson and Richard Binks). Numbers of naturally occurring aphid parasitoids may, however, vary greately from year to year and glasshouse to glasshouse. These parasitoids do, however, contribute to a greater or lesser extent to aphid control in crops without the grower incurring an additional crop protection cost.

Aphidoletes aphidimyza, also known as the aphidophagous gall midge, is sold within the UK by several suppliers. Generally the insect is transported and introduced into the crop as pupae mixed with vermiculite, either in cardboard sachets, which can be hung on the plants, or in bottles, which can be either left open or shaken around the crop. When left to emerge from bottles it is interesting to note that studies have shown that adult *A. aphidimyza* can successfully emerge from pupae and reach the surface from under 15 cm of vermiculite (Scheldt & Mulder, 2000). Leaving the insects to emerge from open bottles, therefore, can be an effective means of releasing this biological control. The majority of interviewed growers, however, preferred to shake vermiculite and pupae out from bottles onto damp rockwool near the base of pepper plants. This approach allows for this predator to be bought in bulk in larger bottles, which is typically a cheaper option. It should be noted, however, that pupae introduced in this manner may be more vulnerable to being consumed by ants and mice. In addition, pupae shaken onto rockwool are more prone to desiccation if the rockwool is not kept moist (Scheldt & Mulder, 2000).

Adult *A. aphidomyza* emerge from the pupae and mate on the webs of spiders, which are numerous in protected pepper crops, after which the female lays eggs on plant stems and leaves (Schelt, 2007). The orange larvae are aphidophagous and so control relies on this life stage (Madahi *et al.,* 2013). The larvae do not generally disperse long distances, hence dispersal of *A. aphidimyza* throughout the crop is mainly by the adults. Adults have been recorded travelling as much as 45 m from the release point (Scheldt & Mulder, 2000). Female *A. aphidimyza* are attracted to the honeydew of *M. persicae* and will lay larger numbers of eggs on plants infested with aphids (Choi *et al.,* 2004), hence this biological control, like other aphid natural enemies, is able to home in on plants infested with aphids.

Although *A. aphidimyza* will predate on a number of aphid species, females show a preference for plants colonised by *M. persicae* over those colonised by *Aulacorthum solani* as oviposition sites (Jandricic *et al.,* 2011). This preference suggests that this predator may be less effective against *A. solani* when *M. persicae* is present. There is evidence within the literature that this predator will also contribute to control of *Macrosiphum euphorbiae* (Turanl

& Yoldas, 2002) and *Aphis gossypii* (Harizanova & Ekbom, 1997), making *A. aphidimyza* a very useful control of aphids in protected pepper crops.

Whilst an efficient aphid predator, *Aphidoletes aphidimyza* is vulnerable to some insecticides (e.g. Stara *et al.,* 2011; Tamas *et al.,* 2013) and so, whilst often included in Integrated Pest Management (IPM) programmes, care must be taken on how this biological control is integrated with the use of insecticides. There is also evidence that the larvae and eggs of *A. aphidimyza* are susceptible to intraguid predation by other biological controls such as predatory mites (Messelink *et al.,* 2011) and predatory bugs such as *Orius* spp. (Moayeri *et al.,* 2013).

The lacewing *C. carnea* is a more generalist predator than *A. aphidimyza*. *Chrysoperla carnea* larvae will feed on a range of crop pests, including whiteflies, thrips, psyllids, mealybugs and caterpillars (Syed *et al.,* 2005; Mansoor *et al.,* 2013), but will prey preferentially on aphids and in the scientific literature have been shown to control *Myzus persicae*, *Macrosiphum euphorbiae* and *Aphis gossypii* in protected peppers (Tulisalo & Tuovinen, 1975; Barbosa *et al.,* 2008; El-Khawas & Salwa, 2010) and *Aulacorthum solani* in lettuce (Quentin *et al.,* 1995; Rossmann & Fortmann 1989). *Chrysoperla carnea* is such an effective predator of *Myzus persicae* that it is capable of eradicating small populations, although as with all biological controls, it struggles to eradicate the entire population at higher pest densities (Barbosa *et al.,* 2008).

In comparison with other biological controls, *C. carnea* gave a similar level of control of aphids in a pepper crop compared with *Aphidoletes aphidimyza* and *Adalia bipunctata* (Tatchell *et al.*, 2002). *Chrysoperla carnea* was, however, the only species in this study, which significantly reduced the numbers of aphids on the growing tips of peppers. Despite this and other literature indicating that *C. carnea* can effectively control aphid pests, it was rarely used by growers in their crops for the control of aphids.

The two spot ladybird *A. bipunctata* is sold as both larvae and adults and will feed on a range of aphid species, including *Myzus persicae* (Jalali & Michaud, 2012), *Aulacorthum solani* (Lommen *et al.,* 2008), *Macrosiphum euphorbiae* (Sengonca *et al.,* 2002) and *Aphis gossypii* (Seko *et al.,* 2014). *Myzus persicae* feeding on pepper are noted as a particularly suitable prey (Jalali & Michaud, 2012). This species of predator is also effective at temperatures between 19-27°C (Jalali *et al.,* 2010), temperatures which can be expected within UK pepper glasshouses. Despite this no growers interviewed mentioned using *A. bipunctata* in their protected pepper crops.

One problem with introducing *A. bipunctata* is that adults have a tendency to disperse from their point of release (Lommen *et al.,* 2008). This is less of a problem when controlling aphids in a larger crop area but can make spot treatment of problem areas difficult. In addition, as with all other biological controls, *A. bipunctata* adults and larvae are susceptible to some insecticides that may be used on the pepper crop (Jalali *et al.,* 2009; Garzon *et al.,* 2015).

According to the grower interviews, parasitoids are more widely used in pepper crops grown in the UK than predators. In addition, when predators are used, they are often used in combination with parasitoids rather than alone. One study showed that a combination of preventative releases of *Aphidius colemani* combined with the release of *Aphidoletes aphidimyza* shortly after aphid detection was more effective at controlling *M. persicae* in a protected pepper crop than *A. aphidimyza*, *Aphidius colemani* or *C. carnea* released individually (Wiethoff *et al.,* 2002). While using both predators and parasitoids together can potentially lead to intraguild competition and predation, as discussed below, the ability of the generalist predators to control multiple pest species, including pests other than aphids, may outweigh these problems.

As with parasitoids, predators may naturally move into pepper crops from surrounding vegetation (Calvo *et al.,* 2009; Amaral *et al.* 2013). Two interviewed growers described naturally occurring *Aphidoletes aphidimyza* making a large contribution to the control of aphids within the crop. Various species of hoverfly will also enter protected pepper crops from surrounding vegetation and also contribute to aphid control (Pineda & Marcos-Garcia, 2006; 2008a; 2008b; Amoros-Jimenez *et al.,* 2014). It is worth noting that hoverflies such as *Episyrphus balteatus* are also commercially available and can be released into crops for the control of aphids, but this is not a common practise in the UK (Croft, 2008) and was only being used by a single interviewed grower. Some species of spider have been shown to consume aphids and so contribute to aphid control in wheat fields (Sherawat & Abida, 2014), apple orchards (Ricard *et al.,* 2012; Marliac *et al*., 2015) and *M. persicae* in cabbage fields in the autumn (Suenaga & Hamamura, 2015). Although spiders are frequently observed within UK protected pepper crops in large numbers (personal observations and interviews) the species of spider, which inhabit protected pepper crops and their contribution to controlling the aphid population has not been studied in detail.

Opportunities and knowledge gaps

Methods to improve the efficacy of aphid predators already licenced and available for use in the UK could be of immediate benefit to UK pepper growers. These benefits may be through improved aphid control but are more likely to be through reduced reliance on aphid parasitoids, which in turn may reduce the impact of hyperparasitism on aphid control.

During the interviews, two crop protection specialists described a novel use of *C. carnea* to control aphid infestations in the crop. This approach involved infesting nearby hedgerows close to the glasshouse with *C. carnea* early in the season before aphid infestations in the pepper crop occurred. The theory was that the *C. carnea* were able to survive on a variety of insect prey species found within the hedgerows, but also reduced the numbers of aphids migrating from the hedgerows into the crop during the spring. While the crop protection specialists acknowledged that many growers were initially cautious about spending money on biological controls in this way, they noted that growers who had used this approach felt it helped to reduce aphid numbers in the crop and were happy to use this approach again. Further research to investigate the potential of this approach is required to determine its effectiveness.

Another opportunity to improve the efficacy of aphid predators involves the two-spot ladybird, *Adalia bipunctata.* During the interviews growers indicated that the main reason they do not use *A. bipunctata* in the glasshouse is the tendency of adults to migrate away from the glasshouse after release. Experiments using naturally flightless morphs of *A. bipunctata* in microcosms indicate that, in this environment at least, flightless *A. bipunctata* can give better control of *M. persicae* than *A. bipunctata* that are able to fly (Lommen *et al.,* 2008). There was, however, no difference in control of *Aulacorthum solani* between morphs. The authors hypothesised that this was due to *A. solani* dropping from the plant in response to disturbance by the predators and felt that in a large scale trial the flightless *Adalia bipunctata* would also have given better control of *Aulacorthum solani.* Another study showed that flightless *Adalia bipunctata* controlled *Aphis gossypii* more effectively than *Adalia bipunctata* that were able to fly, but again the release of flightless adults did not produce a difference in the control of *Aulacorthum solani* (Seko *et al.,* 2014). The release of *Adalia bipunctata* larvae was more effective at controlling *Aulacorthum solani* than the release of flightless adults in this study. Flightless ladybird morphs are, however, not currently sold in the UK. Further research would be required to evaluate the dispersal and efficacy of flightless ladybirds before their use could be recommended in UK protected pepper glasshouses.

Recently it has been suggested that predatory mirids could be used to control aphids. A study by Messelink *et al.* (2015) indicated that *Macrolophus pygmaeus* can significantly reduce aphid populations in pepper crops, although complete eradication was not achieved. Perez-Hedo & Urbaneja (2015) also recently demonstrated that three mirid species were capable of establishing and reproducing in protected pepper crops as well as effectively controlling *Myzus persicae* under semi-field conditions. While *Macrolophus pygmaeus* is available for use in the UK, non-native mirid species would be unlikely to gain a licence for release into UK protected pepper crops. The use of non-native mirid species is, therefore, unlikely to present a viable opportunity with which to improve aphid control. There is, however, the possibility of further research to assess methods of improving aphid control using *M. pygmaeus* alongside other biological controls.

As described earlier, *Aphidius colemani* is capable of effectively controlling *Myzus persicae* and *Aphis gossypii* (Steenis, 1992; Ramakers, 2004; Sanchez *et al.*, 2011). It has been suggested that *Aphidius colemani* has a wider host range than *A. matricariae*, which in turn at least partly explains why *A. colemani* is more widely used (Steenis, 1992; Steenis, 1995; Rabasse, 1999). Despite this, Schelt *et al.* (2011) found *A. matricariae* to be significantly faster at controlling *M. persicae* than *A. colemani,* although notably both species still gave good control. Other studies have also shown that good control of *Aphis gossypii* is possible when *Aphidius matricariae* is used (Zamani *et al.,* 2006; Sanchez *et al.,* 2011). Sanchez *et al.* (2011) recently hypothesised that if *A. matricariae* were released rather than *A. colemani* better control of *M. persicae* would be achieved within glasshouses, although this statement was based on glasshouse observations in Spain, where the warmer climate may potentially exert effects on the parasitoid-prey tritrophic interactions in a manner different to the cooler UK.

It may also be possible to improve the efficacy of parasitoid species already used by UK protected pepper growers by altering parasitoid behaviour. A study by Benelli *et al.* (2014) made several suggestions for the improving the efficacy of the parasitoid *A. colemani,* including improved mating success of the parasitoids, use of attractants for monitoring, using aphid produced attractants (kairomones) to attract parasitoids into the crop and use of sensitisation or associative learning to optimise efficacy of mass-reared wasps.

Kairomones are involved in host choice by aphid parasitoids. *Aphidius ervi* will oviposit into parafilm ‘dummies’ containing aphid haemolymph but not those containing only distilled water (Larocca *et al.,* 2007). The females appear to detect the unspecified kairomones using gustatory sensilla located on the tip of the ovipositor. *Aphidius rhopalosiphi* appears to respond to chemicals located on the aphid cuticle (Muratori *et al.,* 2006). When the unspecified chemicals were removed using solvents, such as methanol, the host recognition response no longer occurred, while when the physical cues provided by the cuticle were removed with heat treatment the parasitoid continued to exhibit a host recognition response. Some parasitoids have also shown a positive response to aphid honeydew (Longley & Jepson, 1996) as has the hoverfly species *E. balteatus* (Leroy *et al.,* 2014) and ladybirds (Ide *et al.,* 2007). In addition, a range of economically important parasitoid species appear to respond to aphid sex pheromones (Powell & Pickett, 2003). Releasing aphid sex pheromones has been shown to increase the rates of paratisation by *P. volucre* and *A. rhopalosiphi* on plants up to 1 m away from the point source of the pheromone in an arable field margin for example (Glinwood *et al.,* 1998). Another study, however, indicated that components of the aphid sex pheromone actually repels *C. carnea* from otherwise attractive plant volatile 'baits', a surprising finding given the preference of these predators for aphid prey (Koczor *et al.,* 2015). In addition, a recent study indicated that the aphid alarm pheromone, previously considered a kairomone, only altered the foraging behaviour of predators on aphid colonies when released at unnaturally high concentrations (Joachim & Weisser, 2015). Despite this finding, when aphid alarm pheromone was released in an outdoor grown pepper crop in Egypt it both lowered *Myzus persicae* populations and increased attraction of the predatory insects *C. carnea* and *Coccinella undecimpunctata* (Khidr *et al.,* 2011). The role of different chemicals released by aphids, and that then acts as kairomones by attracting natural enemies, is, therefore, complex and should be studied within the cropping system in which the chemicals are to be used.

There is also a considerable amount of evidence to indicate that aphid parasitoids are attracted to plant volatiles produced following aphid infestation (e.g. Powell & Pickett, 2003; Tan & Liu, 2014). For example, a recent study indicated that treating protected pepper plants with cis-jasmone, a naturally occurring plant defence activator, increased the foraging time of *A. ervi*. It should, however, be noted that treatment with cis-jasmone did not affect the rate at which populations of *M. persicae* and *Aulacorthum solani* increased (Dewhirst *et al.,* 2012).

In almost any protected pepper crop where multiple biological controls are released to control a range of pests, there is the potential for these species to interact with each other. This is particularly the case when generalist predators are used. Northfield *et al.* (2014) has suggested that only beneficial effects occur from using multiple predator species. This study, however, was based on a cabbage crop using field cages, an environment very different to protected pepper crops.

Several studies have indicated that some predators used as biological controls may inhibit aphid control by disrupting other predators or parasitoids when released together in a crop. The eggs of *A. aphidimyza*, for example, are readily consumed by the predatory mites *Neoseiulus cucumeris, Iphiseius degenerans* and *Amblyseius swirskiii* (Messelink *et al.,* 2011), all of which are commonly used in protected pepper crops. In the case of *A. swirskii* this led to an increase in aphid densities compared with treatments where only *Aphidoletes aphidimyza* was introduced into the crop. The majority of interviewed growers mentioned that they utilise *Amblyseius swirskii* to protect their crops from two-spotted spider mite (*Tetranychus urticae*), hence the presence of *A. swirskii* in a crop could negatively effect the efficacy of *Aphidoletes aphidimyza.* The same study also demonstrated that female *A. aphidimyza* readily oviposit on plants colonised by *A. swirskii,* indeed they exhibited a preference for them (Messelink *et al.,* 2011).

There is also some evidence that the presence of *C. carnea* may be detrimental to populations of *Aphidoletes aphidimyza. Aphidoletes aphidimyza* females exhibit reduced oviposition on aphid-infested plants that have also been previously infested with first-instar *C. carnea* larvae, although the authors note that the response was weak (Ruzicka & Havelka, 1998). *Orius laevigatus* will also feed on *A. aphidimyza* under certain conditions (Hosseini *et al.,* 2010). In one trial during this study *O. laevigatus* caused a reduction of 81% percent in the *A. aphidimyza* population, even though aphid prey were present (Hosseini *et al.,* 2010). Both *A. aphidimyza* and *Orius* species have also been observed feeding on *M. persicae* mummies parasitized by *Aphidius* spp. in pepper crops (Jacobson, 2011). Intraguid predation is, therefore, likely to occur to some degree in protected pepper crops in which several predatory species are used.

In general, even though intraguild predation may occur between biological controls within pepper crops, there are few studies that have investigated how much of an effect these interactions have on aphid control. A study by Yano (2005) suggested that the effects of intraguild predation may be less pronounced in glasshouse than field systems, but it is not known how the results of this study would relate to the UK protected pepper crops. It is possible that the benefits of having a range of predators and parasitoid species in protected pepper crops outweigh the negative effects of any incompatibilities between the species and in many cases growers have little choice but to use a combination of biological controls in order to manage a range of pests.

An opportunity to maximise the value protected pepper growers obtain from their biological control products is to ‘reuse’ the biological controls from late season crops. HDC project PC 240 (Jacobson, 2010) developed methods of collecting natural enemies from areas of surplus in tomato crops for redistribution into areas of need. These ‘free’ insects were already conditioned to the tomato crop and established more quickly than purchased individuals. While it is important to ensure that natural enemies collected in this manner are carefully separated from any pest insects and plant material to prevent virus transmission from the original crop, methods for this strategy have now been validated for commercial tomato crops (Jacobson, 2010), although not yet with predators or parasitoids of aphids. If methods similar to these could be adapted to ‘reuse’ the natural enemies present within pepper crops, without spreading hyperparasitoids, then there could be a significant financial saving.

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Hyperparasitism

Interview results

All growers were aware of the existence of hyperparasitism and confident in their ability to recognise the problem when present within their crops. All mentioned that hyperparasitism, when it occurred, was difficult to control and that if not successfully managed led to problems with managing aphid pests.

The main strategy employed to control hyperparasitism was to stop releases of parasitoids and to apply an insecticide such as pymetrozine to reduce hyperparasitoid, parasitoid and aphid numbers in the glasshouse. Growers were aware that this approach could affect populations of other biological controls within the glasshouse but generally felt there were few other options available to them. Growers generally introduced the aphid specific predator *Aphidoletes aphidimyza* after the insecticide application to provide aphid control and prevent a rapid increase in aphid populations in the absence of a large parasitoid population. The interviewed organic grower used a similar approach but typically used an application of soft soaps (referred to as fatty acids from here) instead. The organic grower had also used maltodextrin (in the form of Eradicoat) in the past for this purpose. These strategies for dealing with hyperparasitoids were also described and recommended by many crop protection specialists.

One crop protection specialist very rarely encountered hyperparasitism in the crops they oversaw. This individual suggested that this could be due to the aphid populations being kept extremely low. Since large aphid and parasitoid populations did not build up there were few mummies available for hyperparasitoids, so potentially these crops were less attractive than those with many aphid mummies.

One grower interviewed, noted that they always experienced hyperparasitoid problems when nearby wheat crops were being harvested. The grower wondered if the insects were being dispersed as a result of disturbance through harvesting and so entered the glasshouse in greater numbers.

Growers indicated that they would be supportive of funded research to provide them with practical alternative solutions to control hyperparasitoids within the glasshouse and avoid the need for insecticide applications.

Literature review

Hyperparasitoids are secondary insect parasitoids that develop within primary parasitoids. Since hyperparasitism results in the death of the primary parasitoid, the presence of hyperparasitoids within a pepper crop has a detrimental effect on biological control programmes. Hyperparasitoids can be divided into two different categories based on their ovipositional and larval feeding behaviours (Sullivan, 1987). Endophagous hyperparasitoids oviposit into the primary parasitoid larva when it is developing in the aphid host, but before the aphid becomes mummified. The egg then hatches after the mummy is formed and the hyperparasitoid larva feeds on the primary parasitoid. Ectophagous parasitoids oviposit onto the surface of the primary parasitoid after the aphid host is killed and mummified. The hyperparasitoid larvae then feeds externally on the aphid host while both larvae remain within the mummy.

The majority of European ectohyperparasitoid species attack a wide range of aphid parasitoid species, independent of the aphid host, with only a couple of species thought to be host specific. The majority of endohyperparasitoid species, however, appear to be highly host specific, attacking either a single primary parasitoid genus independent of the aphid host species, or a single aphid host species independent of the primary parasitoid (Jacobson, 2011). It follows, therefore, that hyperparasitoids may attack a range of commercially sold parasitoid species, although during the interviews with both growers and crop protection specialists, the majority of hyperparasitoid problems appeared to affect *Aphidius colemani*. It has been hypothesised that *A. colemani* may be more susceptible to hyperparasitism than some other parasitoid species due to its relatively large size (Acebes & Messing, 2013), although this was tested by comparing the rates of hyperparasitism found in this species with a smaller Hawaiian species, *Binodoxys communis,* rather than another UK species. In the UK, *Alloxysta brevis, Alloxysta brachyptera, Alloxysta fulviceps, Alloxysta victrix, Dendrocerus carpenter, Dendrocerus aphidium, Dendrocerus laticeps, Dendrocerus serricornis, Asaphes suspensus, Asaphes vulgaris* and *Pachyneuron aphidis* have all been recorded in UK pepper crops by Jacobson (2011 & 2012).

A study by Jacobson (2011) indicated that rates of hyperparasitism in protected pepper crops may be high. Of live wasp emergence from *Aphidius* spp. mummies collected from a conventional pepper crop in September 2010, 21% were *Aphidius* spp. (not hyperparasitised) and 79% were hyperparasitoids. Another collection from an *Aphelinus abdominalis* open rearing unit yielded 28% adult *A. abdominalis* and 72% hyperparasitoid adults. In the latter case there was a high percentage of adult wasp emergence from collected mummies (93%) while in the former successful adult emergence was much lower (27%). Other mummy collections from organic crops in Somerset yielded a more variable range of hyperparasitism (8-63%) suggesting that other factors may influence rates of hyperparasitism within the crop.

The majority of the literature available on aphid hyperparasitoids concentrates on identifying the presence and abundance of hyperparasitoids in different aphid-plant systems and their general ecology (Jacobson, 2011; Schooler *et al.,* 2011; Gagic *et al.,* 2012; Acebes *et al.,* 2013; Gomez-Marco *et al.*, 2015). There is an apparent lack of research investigating control strategies for hyperparasitoids. However, work completed in HDC funded project, PC 295b, (Jacobson, 2011a) and a spin-off MSc project at Imperial College and Rothamsted Research (Tickle, 2011) tested the response of *Asaphes suspensis* to volatiles collected from mummified *Aulacorthum solani* reared on sweet pepper and parasitised by *Aphidius* spp. There was a significant response to the treatment. These studies have perhaps paved the way for more generic studies ultimately aimed at managing hyperparasitoids in a wide range of crops by incorporating the semiochemical in hyperparasitoid traps.

Opportunities and knowledge gaps

Given that the current mainstay of aphid control in UK protected pepper crops is the use of parasitoids, particularly *Aphidius colemani*, disruption of this control by hyperparasitoids is one of the main problems, which both conventional and organic UK pepper growers face. Despite this there are large gaps in the available research regarding the biology and control of hyperparasitoids within UK pepper crops. Several interviewed growers and crop protection specialists felt that funding further research into the biology, causes and control of hyperparasitism within pepper crops would be of benefit to UK pepper growers. It is particularly difficult to find literature referring to control strategies for hyperparasitoids and this subject appears somewhat neglected. Growers expressed a wish for non-chemical means of managing hyperparasitism in order to avoid the side-effects of insecticides applications on biological control of aphids and other crop pests. The studies with semiochemicals by Jacobson and Tickle (described above) are, therefore, of potentially great interest to the UK industry. This work could pave the way for a system of managing hyperparasitoids by incorporating a semiochemical into hyperparasitoid traps. Such research would benefit a wide range of other UK crops in which aphid parasitoids are regularly released.

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Open rearing units (Banker plants)

Interview results

Several growers were using open rearing units (ORUs) (also known as banker plant systems) in the glasshouse, mainly to increase *Aphidius colemani* populations. For a full description of the ORU system see the literature review section below. Opinions about the use and efficacy of ORUs were divided for both growers and crop protection specialists. Those who did not use ORUs stated reasons of cost, time and effort taken to maintain the ORUs effectively, lack of efficacy of ORUs in increasing parasitoid populations, concerns about hyperparasitism being encouraged, concerns about general pest presence within the ORUs and in general feeling unhappy with the gain seen from the investment made. In contrast, one grower felt that having ORUs gave a positive, innovative image of the business to customers. Other growers felt that ORUs were contributing at least partially to the control of aphids within the glasshouse and felt that the time and financial investment in the system was worthwhile.

One crop protection specialist questioned whether rearing parasitoids on one aphid species would cause them to show a preference for the aphid species within the ORUs rather than the pest aphid species within the crop. They also expressed concern about how effictively parasitoids dispersed from ORUs into the crop compared with when parasitoids are purchased and released into the crop by the grower.

Several crop protection specialists noted that the efficacy of ORUs at contributing to aphid control seems to decrease if the plants used in the ORU are neglected. Others commented that glasshouse conditions are not always optimal for the plant species used in ORUs and that this may affect plant quality.

Literature review

Attempts to increase the numbers of parasitoids and predators within the crop are sometimes made using an ORU or banker plant system (Jacobson & Croft, 1998; Frank, 2010; Parolin *et al.,* 2012; Andorno & Lopez, 2014; Jandricic *et al.,* 2014b). This involves introducing a different plant species into the glasshouse, which serves as a host for an aphid species that does not feed on the crop, for example the bird cherry-oat aphid, *Rhopalosiphum padi*, on oats. The *R. padi* then act as a host for a parasitoid or predator, which is capable of parasitising or feeding on pest aphid species along with the aphid species found within the ORU. Once there are a reasonable number of aphid mummies or predators present within the ORU it is placed within the pepper crop and the parasitoids/predators allowed to move freely between the ORU and the crop. This forms a 'reservoir' population of parasitoids or predators within the ORU, even when the pepper-infesting aphids, such as *Myzus persicae,* are absent or only present at low numbers (Yano, 2006). Parasitoids or predators are also, in theory at least, constantly released into the crop in a protective manner without the need for manual release of these biological controls (Jacobson & Croft, 1998; Parolin *et al.,* 2012), although it should be noted that all growers interviewed in this study who utilised ORUs still felt they also needed to release parasitoids and predators into the glasshouse.

ORUs have been used successfully to increase the populations of aphid parasitoids such as *Aphidius colemani* (Jacobson & Croft, 1998; Jandricic *et al.,* 2014b) and *A. matricariae* (Bennison, 1992) and predators such as *Aphidoletes aphidimyza* (Bennison, 1992; Abe *et al.,* 2011) and the commercially released hoverfly species *Episyrphus balteatus* (Pineda & Marcos-Garcia, 2008b). ORUs may also be used to support populations of predators that may feed on aphids and other pests within the glasshouse, such as *Orius insidiosus*, which is used to control thrips (Wong & Frank, 2012).

Information from the literature review on ORUs confirmed the opinions of growers in that ORUs appear to work well in some cases, enhancing populations of aphid parasitoids or predators, while in other cases they appear to have few beneficial effects (Bennison, 1992;

Jacobson & Croft, 1998; Nagasaka *et al.,* 2010; Abe *et al.,* 2011; Wong & Frank, 2012). In a study by Andorno & Lopez (2014) introducing ORUs decreased the *M. persicae* population on arugula but had no effect on the *M. persicae* population in protected peppers. In another study *R. padi* was reared on different plant species within ORUs in glasshouse systems (Jandricic *et al.,* 2014b). The plant species on which *R. padi* was reared affected both aphid and parasitoid performance. Jacobson & Croft (1998) found that an *Aphidius colemani* ORU system gave better control of *Aphis gossypii* in summer than late spring. This suggests that there are complex interactions between when the ORUs are used, the crop plant, ORU plant species, ORU aphid and crop pest species and the predator or parasitoid species. It is, therefore, likely that whether ORUs contribute significantly to aphid control will be determined by several factors.

Andorno & Lopez (2014) mention that ORU plants should be renewed every two weeks until the pest aphid population increases and adult parasitoids are observed within the glasshouse. This is because it is important to ensure that the pest aphid population is larger than the population of aphids within the ORU if the *Aphidius colemani* are to leave the ORU and successfully parasitise the pest aphid population. Renewal of the ORUs every two weeks, however, creates a lot of additional work for growers and may explain the neglected, older plants observed by one interviewee.

Opportunities and knowledge gaps

A major concern on the use of ORUs is that this approach may increase hyperparasitism problems, due to the high density of aphid mummies created (Croft *et al.*, 2008; Nakasaka *et al.*, 2010; Mitsunaga *et al.,* 2014). It has been suggested that increasing the temperature around the banker plants and developing a refuge for mummified aphids might minimise this problem (Mitsunaga *et al.,* 2014) but further research is required. Solving this problem would improve confidence in the use of ORUs and in turn potentially improve aphid control.

Some concern has also been expressed that when using ORU systems, parasitoids reared on a different host to the major crop pest may then preferentially parasitise the non-pest species rather than the pests within the crop. There is some evidence for parasitoids preferring to oviposit within the aphid species and host plants in which they themselves developed or in which they have had previous successful oviposition experiences (Storeck *et al.,* 2000; Kruidhof *et al.,* 2015). A recent study, however, indicated that *A. colemani* reared in an ORU containing *R. padi* exhibited a preference for ovipositing in *M. persicae* within the crop over other *R. padi* within the ORU (Prado & Frank, 2014). It was hypothesised that this preference was due to increased rates of offspring survival and female size when *M. persicae* rather than *R. padi* was used as a host. According to the Prado and Frank (2014) study, ORUs utilising *R. padi* should have a positive effect on *M. persicae* control but further research is needed into any potential parasitoid preferences exhibited for *R. padi* over other aphid pests of protected pepper, such as *Aulacorthum solani, Aphis gossypii* and *Macrosiphum euphorbiae.*

In a study by Wong & Frank (2012) the authors noted that high numbers of spiders were infesting the ORUs and that the presence of spiders reduced *O. insidiosus* abundance within the ORU. Whether the numbers of spiders can be altered by the use of different plant species within ORUs, and whether the presence of spiders within ORUs would affect the efficacy of other biological controls used to target aphids is an area which requires further research.

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Chemical control

Interview results

The majority of growers interviewed used pymetrozine (Chess WG) or pirimicarb (e.g. Aphox) for aphid control when an insecticide application was required. Chess was the most frequently cited product used by growers. When asked as to why they used Chess, growers generally commented on its effectiveness, ease of application and the minimal effect on the majority of biological controls used. Most, but not all, growers who used pirimicarb used it to control aphid species, which they felt Chess was less effective against, such as *Aulacorthum solani.* Chess was sometimes sprayed, but in most cases was applied through the irrigation system. Growers found this application method convenient and felt it reduced effects on biological controls. Pirimicarb was normally applied as a high volume spray. Interviewed growers were generally happy with how effective the insecticides they had available to use were, but were keen to avoid the use of insecticides wherever possible.

The interviewed organic grower applied a fatty acid (typically Savona) when aphid populations were too large to be controlled economically using biological controls alone. They found that an application of fatty acids helped but expressed some concern that it did not always give consistent control of aphids. They had also experienced trouble controlling aphids using maltodextrin and were keen for the development of new insecticide options suitable for the control of aphids in an organic system. This grower expressed particular concern on their reliance on Savona for control of large damaging aphid populations in organic systems.

The interviewed conventional chilli grower stated that from next year all insecticides licenced for use on UK protected pepper crops will be licenced for use on chillis. This would provide access to a much wider range of products to chilli growers than have previously been available. The main products that the chilli grower used at present were Chess and fatty acids, similar to many pepper growers.

Literature review

As of September 2015 a total of 92 insecticide products were available for use in commercial protected pepper crops, this includes products licenced for all edible crops, in the UK (Table 1 in Appendix). Twenty nine of these products have been granted an Extension of Authorisation for Minor Use (EAMU, previously SOLA) for the control of aphids in protected pepper crops. In total these products represent 24 different active ingredients. Several of these active ingredients share a common mode of action, for example acetamiprid and thiacloprid are both neonicotinoids. It should be noted that there are no established thresholds for aphid pests in pepper crops and when insecticide applications are justified e.g. http://www.redtractor.org.uk/. Deciding whether an insecticide application is justified is, therefore, based on the judgement of the grower and/or the advice of a supplier/crop protection specialist.

According to the Defra Pesticide Usage Report, the most widely used insecticide in protected pepper crops by area of application in 2013 was pymetrozine, followed by fatty acids, pirimicarb, indoxacarb and spiromesifen. The three most widely used insecticides in protected pepper crops in this year were, therefore, for the control of aphids.

Some of the most widely used insecticides approved for use in conventional and organically grown crops are discussed in the following section. Please note that the IRAC resistance groups of insecticides can be found at the IRAC website http://www.irac-online.org/. In addition, information on the compatibility of biologiocal controls with insecticides can be found on both the Koppert http://www.koppert.com/ and Biobest http://www.biobestgroup.com/ websites.

Pymetrozine

Pymetrozine, in the form of Chess WG, continues to be an effective method of controlling aphids in pepper crops (Wyss & Bolsinger, 1997a; Duncalfe *et al.,* 2015). The exact mode of action of pymetrozine is still not fully understood but the compound appears to affect the chordotonal nerve receptors in locusts (Ausborn *et al.,* 2005). Pymetrozine inhibits probing and feeding by aphids and other Hemiptera (He *et al.,* 2011; Boquel *et al.,* 2015). Treated insects cease to feed and die of dehydration and starvation, hence pymetrozine can take slightly longer to exert effects on aphid populations compared with some other insecticides (Parker *et al.,* 2006). Pymetrozine is highly systemic and travels through the phloem from the roots to the leaf tissue, thus protecting the growing points of plants (Wyss & Bolsinger, 1997b). This ability is used to the advantage of growers utilising the recently granted EAMU for treating protected pepper crops with pymetrozine via the irrigation system (Jacobson *et al.,* 2010).

Pymetrozine is an attractive chemical for use within IPM programmes as it is compatible with a wide range of biological controls (Jansen *et al.,* 2011). There are, however, some documented adverse effects on parasitic wasps within the scientific literature. Direct contact with pymetrozine has been found to decrease oviposition and fecundity of female *Trichogramma ostriniae* (Li *et al.,* 2015), while the development of *Aphidius ervi* larvae within *Macrosiphum euphorbiae* that had been fed on an artificial diet containing sublethal doses of pymetrozine was negatively affected and the sex ratio of emergent larvae biased towards males (Joseph *et al.,* 2011). Application through the irrigation system, however, avoids direct contact with parasitoids and other natural enemies (Jacobson *et al.,* 2010)

An additional benefit of this active ingredient is that resistance to neonicotinoids in *Myzus persicae* (populations of neonicotinoid resistant *M.* persicae have not been found in the UK and are currently only found in southern Europe) does not appear to confer resistance to pymetrozine. There is also no resistance to pymetrozine in *M. persicae* populations found in the UK (Foster & Blackshaw, 2012). In a recent HDC-funded study, failure to control *Macrosiphum euphorbiae* in strawberry plants treated with pymetrozine was observed

(Fountain *et al.*, 2015). The evidence from this study was, however, not strong enough to indicate clear evidence of resistance to pymetrozine. The current good practice of the growers interviewed in this study, where insecticides are only used when aphid populations reach a size at which biological control is no longer economically viable, should slow and hopefully prevent the development of resistance to pymetrozine. Given the current reliance on pymetrozine, however, the presence of resistance to this insecticide would be of serious to growers.

Carbamates

Carbamates are similar in mode of action to organophosphates and as such are acetylcholinesterase inhibitors. The carbamate pirmicarb (e.g. Aphox) is currently one of the mostly widely used insecticides to control aphids in UK protected pepper crops. This insecticide is particularly used for the control of *Aulacorthum solani*, which is more difficult to control with pymetrozine than the other aphid pests affecting pepper crops. Carbamates such as pirimicarb can act either through direct contact or ingestion. The mode of action involves the inhibition of acetylcholinesterase, an enzyme essential to normal nervous function. An uncontrolled series of nerve impulses is produced, followed by paralysis and death. In addition to the main toxic effects, pirimicarb has also been shown to exert sublethal effects on the fecundity of some aphid species at low doses (Xiao *et al.,* 2015).

Pirimicarb can have negative effects on adult *A. ervi* (Araya *et al.,* 2010) and other parasitoid species (Borgemeister *et al.,* 1993; Umoru & Powell, 2002; Moens *et al.,* 2012) and also appears to negatively affect *E. balteatus* larvae (Jansen, 1998). There is evidence, however, that some parasitoids can survive pirimicarb applications whilst developing within aphid mummies (Milevoj & Stukelj, 1996; Moens *et al.,* 2012). In addition, pirimicarb does not appear to be harmful to a wide range of predators (Jansen, 2000; Angeli *et al.,* 2005). Pirimicarb can, therefore, be used within IPM systems with careful management, depending on the biological controls being used within the crop.

Myzus persicae and *Aphis gossypii* populations with resistance to carbamates have been found in the UK for many years (Devonshire *et al.,* 1998). Carbamate resistance in *M. persicae* can be due to overproduction of one of two possible carboxylesterases, E4 or FE4, which both hydrolyse and sequester the insecticide before it reaches the acetylcholinesterase target (Devonshire & Moores, 1982; Devonshire *et al.,* 1983). The level of resistance is correlated with the amplification of the E4 and FE4 genes, leading to the R_1, R_2 and R_3 successively more resistant phenotypes (Field *et al.,* 1999). This form of resistance is reversible, particularly in the absence of the insecticides (Field, 2000) and does not provide high levels of resistance to all carbamates, including pirimicarb (Foster *et al.,* 2002). Interestingly, this form of resistance is now extremely rare in UK populations of *M. persicae* (Foster & Blackshaw, 2012). More recently target site based resistance known as modified acetylcholinesterase (MACE) has developed and this provides high levels of resistance to pirimicarb (Bass *et al.,* 2014). This results from a serine to phenylalanine substitution known as S431F in the acetylcholinesterase (Andrews *et al.,* 2002). MACE resistance to pirimicarb continues to be common in *M. persicae* populations in the UK (Foster & Blackshaw, 2012).

The presence or absence of MACE resistance has been shown to affect the behaviour of *M. persicae,* with *M. persicae* carrying MACE resistance aggregating more densely on the growing points of plants than susceptible *M. persicae* (Tatchell *et al.,* 2002). This difference in aggregation behaviour in turn appears to reduce the ability of *Aphidius colemani* to control the densely aggregated MACE resistant *M. persicae* colonies compared with the non-MACE resistant populations. Interestingly, the ability of *C. carnea* to control *M. persicae* is unaffected by the presence or absence of MACE resistance (Tatchell *et al.,* 2002; Kift *et al.,* 2005), suggesting that this predator may give better control of *M. persicae* than *A. colemani* when MACE resistant *M. persicae* is present within the glasshouse.

Aphis gossypii populations can also exhibit resistance to carbamates such as pirimicarb (Ahmad & Arif, 2008; Furk & Hines 1993). The main mechanisms of carbamate resistance in *A. gossypii* have been identified as insensitivity of acetylcholine esterase to being inhibited by these compounds and increased carboxylesterase activity (Sun *et al.,* 1987; Han *et al.,* 1998; Saito & Hama, 2000; Li *et al.,* 2003). In addition, reduced cuticular penetration to carbamates occurs in some *A. gossypii* populations (Sun *et al.,* 1987; Gubran *et al.,* 1992) and there is evidence of enhanced activity of mixed function oxidases also playing a role in carbamate resistance (Saito *et al.,* 1995).

There is also recent evidence of control failure occurring in *Macrosiphum euphorbiae* populations in Tunisia, which was suggested to be due to resistance (Raboudi *et al.,* 2012). It was suggested that this resistance appears to be caused by a mutation causing acetylcholine esterase insensitivity, A302S, identical to that found in *A. gossypii.* High esterase levels did not appear to play a role in pirimicarb resistance in the populations sampled in this study. A study completed in the same year, however, which involved screening aphids collected from various countries did not find any evidence of practically-significant levels of resistance to pirimicarb or any other screened insecticide in *M. euphorbiae* (Foster & Blackshaw, 2012). There is no record of pirimicarb resistance in *A. solani* populations within the literature at present.

Pyrethroids

Pyrethroids, such as lambda-cyhalothrin and deltamethrin, are voltage-gated sodium channel modulators. By altering the activation and inactivation kinetics of these channels they disrupt normal nervous signalling, causing paralysis and death (Soderlund & Bloomquist, 1989). Pyrethroids can be very effective against a range of aphid species including those found in UK protected pepper crops such as *M. euphorbiae* (Foster *et al.,* 2014; Fountain *et al.,* 2015). Resistance to pyrethroids is found in UK populations of *M. persicae* (Foster & Blackshaw, 2012) and thus pyrethroid use has reduced when alternative chemicals are available.

Pyrethroid resistance occurs in both *M. persicae* and *Aphis gossypii.* In *M. persicae* pyrethroid resistance is primarily through target site resistance known as 'knockdown resistance' (Martinez-Torres *et al.,* 1999). There are two forms of 'knockdown resistance' known as kdr and super-kdr. These forms of resistance are both caused by an amino acid substitution in the voltage gated sodium channels in the insect neurones due to a mutation. Several different resistance-causing amino acid substitutions have been identified, most of which are in the transmembrane regions of the receptor proteins, which form the binding site for pyrethroids (Rinkevich *et al.,* 2013). The first of these mutations to be discovered, known as L1014F, is a leucine to phenylalanine replacement in the transmembrane segment IIS6 of the sodium channel (Martinez-Torres *et al.,* 1997). This mutation gives rise to a moderate level of pyrethroid resistance known as kdr (Foster *et al.,* 2014). A second mutation, M918T was later discovered close to the L1014F mutation (Eleftherianos *et al.,* 2008). This mutation has only ever been found in the presence of L1014F and confers enhanced pyrethroid resistance known as super-kdr (Bass *et al.,* 2014). An alternative super-kdr mutation conferring resistance to lambda cyhalothrin, M918L, was also recently found in *M. persicae* in France (Fontaine *et al.,* 2011; Panini *et al.,* 2015).

Some pyrethroid resistant populations of *A. gossypii* also carry the L1014F mutation conferring kdr (Marshall *et al.,* 2012). In addition, a modification at the M918L position in the voltage-gated sodium channel conferring super-kdr resistance has also been discovered in *A. gossypii* populations (Carletto *et al.,* 2010). There appears to be a fitness cost to pyrethroid resistance in both *M. persicae* and *A. gossypii* with increased pyrethroid resistance correlated with a lower reproductive rate (Hollingsworth *et al.,* 1997; Gillespie *et al.,* 2009), suggesting that in the absence of insecticide pressure the resistance mechanism may decrease in aphid populations. The presence of the kdr mutation in UK *M. persicae* was thought to be decreasing, dispite continued use of pyrethroids in a wide range of crops, but the discovery of the new super-kdr mutation (M918L) indicates that there has instead been a switch to the 'new' super-kdr mutation in UK populations of *M. persicae* (Foster & Blackshaw, 2012).

Pyrethroids such as lambda-cyhalothrin are harmful to a wide range of biological controls (e.g. Jalali *et al.,* 2009; Pathan *et al.,* 2010). Exposure to sublethal doses of lambda-cyhalothrin has also been reported to decrease oviposition behaviour in the parasitoid *Aphidius ervi* (Desneux *et al.,* 2004a). In another study, however, exposure to deltamethrin had no effect on oviposition by the parasitoids *A. matricariae* and *Diaeretiella rapae* (Desneux *et al.,* 2004b) leading the authors to hypothesise that some parasitoids may be at least partially tolerant to deltamethrin. Despite this, the combination of aphid population resistant to these insecticides and incompatibility to most biological controls used in pepper crops meant that none of the growers interviewed used pyrethroid insecticides in their crops.

Neonicotinoids

Neonicotinoids act as agonists of the nicotinic acetylcholine receptor. This class of compounds is highly systemic and when applied as a root drench will travel through the plant via the xylem, giving good coverage of much of the plant tissue without requiring a foliar application (Maienfisch *et al.,* 2001). Until recently seed treatment products belonging to this group of insecticides were important in the control of aphids and other sucking pests in a variety of crops grown in the UK. European Legislation Council Directive 79/117/EEC resulted in the ban of many products based on the active ingredients imidicloprid, thiamethoxam and clothianidin within the UK (N.B. now subject to Regulation (EC) No 1107/2009). The ban on the use of these neonicotinoids is due to concerns that these insecticides are adversely affecting the health of honeybees and other insect pollinators, although the findings of research in this area have been conflicting (Godfray *et al.,* 2014; Samson-Robert *et al.,* 2014; Barbosa *et al.,* 2015). Neonicotinoids are, however, still licenced for use within protected pepper crops within the UK in the form of products based on the active ingredients acetamiprid and thiacloprid.

The continued effectiveness of neonicotinoid insecticides against aphid pests is, however, a cause for concern with the emergence of resistance in *M. persicae* populations. Resistant populations have so far been confined to peach and apricot crops in France and Spain (Slater *et al.,* 2012), Italy (Bass *et al.,* 2015; Panini *et al.,* 2014). In addition, neonicotinoid resistant *Aphis gossypii* have recently been detected on protected pepper and cucumber crops in Japan (Matsuura & Nakamura, 2014a), Australia (Herron & Wilson, 2011) and the USA (Gore *et al.,* 2013). No neonicotinoid resistant populations of either species have been detected in the UK to date.

Both neonicotinoid resistant *M. persicae* and *A. gossypii* populations from Asia carry the same point mutation within the nicotinic acetylcholine receptor, the target site at which neonicotinoid compounds bind (Bass *et al.,* 2011; Koo *et al.,* 2014; Kim *et al.,* 2015). The mutation, known as R81T, involves an arginine to threonine substitution in the loop D region of the β subunit (Bass *et al.,* 2011). This region modulates neonicotinoid binding and the presence of a threonine at this position is equivalent to the situation found in vertebrates.

In addition to the mutation within the nicotinic acetylcholine receptor, neonicotinoid resistant *M. persicae* populations have also been found to have enhanced expression of the cytochrome CYP6CY3 (Philippou *et al.,* 2009; Puinean *et al.,* 2010). There is also some evidence of reduced penetration of the cuticle by neonicotinoids in some *M. persicae* populations (Puinean *et al.,* 2010; Bass *et al.* 2014). There is no evidence as yet of neonicotinoid resistant *A. gossypii* exhibiting enhanced P450 expression or reduced cuticular penetration (Bass *et al.,* 2015). In addition to the R81T mutation, neonicotinoid resistant *A. gossypii* also carry a second mutation, L80S, next to the R81T site in loop D, which also appears to contribute to neonicotinoid resistance (Kim *et al.,* 2015). The mechanism of neonicotinoid resistance in *A. gossypii* from the USA and Australia remains to be determined (Bass *et al.,* 2015). Finally there is some evidence that neonicotinoid resistant *M. persicae* may show a dispersing behaviour away from neonicotinoid treated plant tissue, which is not shown by susceptible aphids (Fray *et al.,* 2014), although this requires further testing with a greater range of susceptible aphid clones.

As the distribution of neonicotinoid resistant *M. persicae* remains constrained to areas where peach and closely related crops are cultivated it has been postulated that the lack of holocyclic (sexual and asexual forms of reproduction) lifecycle in Northern Europe may be limiting the spread of resistant populations (Bass *et al.,* 2015). This is currently being further investigated. Given the impressive ability of aphids to migrate on wind currents and through plant imports, the presence of neonicotinoid resistant *M. persicae* remains a future threat to the UK farming industry.

With current concerns on the use of neonicotinoids and the impact that this may be having on insect pollinators and emergence of neonicotinoid resistance in aphid populations it is unclear how widely neonicotinoids will continue to be used in UK protected pepper crops in the future.

Spiromesifen

Spiromesifen is a spirocyclic phenyl-substituted tetronic acid particularly active against whitefly and tetranychid spider mite species (Bielza *et al.,* 2009) but will also provide some control of aphids and thrips (Seal *et al.,* 2006; Zhao *et al.,* 2012; Cheng *et al.,* 2013). Spiromesifen is an inhibitor of lipid biosynthesis (Bretschneider *et al.,* 2003; Cheng *et al.,* 2013). Such compounds are more effective against larval forms of insects than adults as the insects may die when attempting to moult, but effects can be seen in adults too. For example, adult female whitefly are unable to oviposite normally and produce smaller eggs (Kontseclalov *et al.,* 2009). Spiromesifen is compatible with biological controls, showing few negative effects on the parasitoid *Eretmocerus mundus* and the predator *Orius laevigatus* for example (Bielza *et al.,* 2009). Recent work by Zhao *et al.* (2012) indicated that making slight adjustments to the structure of spiromesifen produced some derivatives which were even more effective against *Aphis fabae* than *Tetranychus cinnabari,* suggesting that in the future it may be possible to tweak such chemistry to give improved control of aphid pests.

Fatty acids

The use of fatty acids as insecticides has been practiced for many years (Fulton, 1930). The exact mode of action of fatty acids remains unknown but is likely to be physical in nature. Whilst effective at controlling aphids (Pinnock *et al.,* 1974; Fournier & Brodeur, 2000; Karagounis *et al.,* 2006; Jacobson *et al.,* 2009; Sandeep & Srinivasan, 2014), applications of fatty acids may be harmful to biological controls such as adult *Aphidius colemani* and *Orius* spp. (Bostanian & Akalach, 2004; Croft *et al.*, 2008). For this reason, while fatty acids are compatible with IPM programs and are a useful tool available to organic growers, their use requires close attention to the timing of applications. In addition, fatty acids can be successfully combined with entomopathogenic fungi such as *Lecanicillium muscarium* (Cuthbertson *et al.,* 2008) or mineral oils (Ilovai *et al.,* 2003).

Opportunities and knowledge gaps

Given the current reliance on pymetrozine to control aphid pests in pepper crops, the availability of insecticides with different modes of action would help to prevent, or at least delay, the development of resistance. There are several commercially available insecticides, which give good control of aphid pests, but are not currently licenced for use in protected pepper crops in the UK. Some of these insecticides are licenced for use in the UK in crops other than pepper while others are not currently approved for use. AHDB Horticulture project CP 124 (Managing Ornamental Plants Sustainably (MOPS) - Developing Integrated Plant Protection Strategies) is currently ongoing but aims to test a range of conventional insecticides and biopesticides. This work complements the previous HDC project CP 077 (Sustainable Crop & Environment Protection - Targeted Research for Edibles). Although only in the first year, project CP 124 has already highlighted a conventional insecticide, a fast acting neurotoxin, which has good activity against *M. persicae* on pansy.

Spirotetramat

One compound, which may be of interest to UK protected pepper growers, is spirotetramat. This compound performed well against *M. persicae* on pansy when tested as part of the AHDB Horticulture MOPS project (Pope, 2015). Spirotetramat is a tetramic acid derivative which, similar to spiromesifen, is a lipid biosynethsis inhibitor. The compound appears to work by inhibiting acetyl-CoA carboxylase, a key enzyme in fatty acid biosynthesis (Lummen *et al.,* 2014). The main effect is on juvenile insects as they attempt to moult, although there are also effects on adult fecundity (Bruck *et al.,* 2009). Spirotetramat is particularly effective against sucking insect pests, including aphids, whiteflies, scales, mealybugs and thrips (Bruck *et al.,* 2009) but since this insecticide is translocated via both the xylem and phloem there may also be effects on soil dwelling pests from foliar applications.

There is evidence of spirotetramat being moderately harmful to predatory mites such as *Typlodromus pyri* (Bruck *et al.,* 2009). Spirotetramat is, however, only classified as slightly harmful to lacewings, spiders and *Orius* spp. and does not appear to be harmful to parasitoid adults or *Episyrphus* spp. larvae (Bruck *et al.,* 2009; Moens *et al.,* 2011; Satar *et al.*, 2012; Garzon *et al.,* 2015). This suggests that spirotetramat would be compatible with IPM systems used in protected pepper crops. There is no known resistance to spirotetramat in aphids at present, although lab-generated resistant strains of *A. gossypii* have been described, which suggests a range of potential resistance mechanisms, which could eventually occur, most of which were metabolic (Xi *et al.,* 2015).

Flonicamid

Another compound currently licenced for use in the UK and which may be of interest to pepper growers within the UK is flonicamid. Flonicamid has been positioned in IRAC Group 9, together with pymetrozine, as a modulator of chordotonal organs and shows good activity against aphids (Morita *et al.,* 2014; Roditakis *et al.,* 2014; Pezzini *et al.,* 2015). Recent work has indicated that flonicamid may, however, have a slightly different mode of action to pymetrozine and so will be given a new IRAC mode of action classication (Slater pers comm.). Flonicamid was included in the current MOPS project and gave good control of *M. persicae* on pansy (Pope, 2015). Similar to pymetrozine, flonicamid has good systemic activity and rapidly inhibits feeding in treated aphids, causing death by starvation (Morita *et al.,* 2014; Koo *et al.,* 2015).

Flonicamid has been reported as being compatible with a range of aphid predators (Garzon *et al.,* 2015), predatory mites (Morita *et al.,* 2014) and the aphid parasitoid, *Aphidius rhopalosiphi* (Jansen *et al.,* 2011). A more recent study, however, has shown that while there was no acute toxcity from exposure to flonicamid, this insecticide did reduce the feeding activity of *Amblyseius swirskii* and *Eretmocerus eremicus* (Roditakis *et al.,* 2014). Flonicamid may also show mild toxicity to *O. insidiosus* when used at high rates (Pezzini *et al.,* 2015).

There is no resistance to flonicamid in the UK or in Europe at present (Foster & Blackshaw, 2012). The reclassification of flonicamid to a different mode of action to pymetrozine will mean that this active ingredient is of greater benefit to growers in terms of resistance management.

Chlorantraniliprole

Another compound of interest is chlorantraniliprole, which currently has on-label authorisation for use in apple and pear orchards and has an EMAU for use in protected tomato for control of *Tuta absoluta* in the UK. While chlorantraniliprole is mainly marketed for use against Lepidoptera (Cameron *et al.,* 2015) it has a broad spectrum of activity and is also effective against aphid pests (Hannig *et al.,* 2009; Ou *et al.,* 2012). Chlorantraniliprole is a diamide, with the mode of action involving binding to the insect ryanodine receptor (Luo *et al.,* 2014). This compound is extremely fast-acting (Hannig *et al.,* 2009) and is highly systemic (Cameron *et al.,* 2015).

As chlorantraniliprole is effective against both Lepidoptera and aphids it could be a useful tool for UK protected pepper growers. It is worth noting, however, that resistance to chlorantraniliprole has recently been detected in some lepidopteran species (Guo *et al.,* 2014; Roditakis *et al.,* 2015). In addition chlorantraniliprole can negatively effect the predatory bug *O. insidiosus* (Gontijo *et al.,* 2015). Chlorantraniliprole also reduced the efficacy of *Lysiphlebus testaceipes,* a parasitoid of North American cereal aphids (Moscardini *et al.,* 2014). Further research is, therefore, required to assess the suitability of chlorantraniliprole to UK protected pepper crops.

Cyantraniliprole

Cyantraniliprole is not currently licenced for use in the UK. For a review of the chemistry and uses of cyantraniliprole see Selby *et al.* (2013). Cyantraniliprole is effective against both *M. persicae* and *Aphis gossypii* and this efficacy appears to be unaffected by the presence of resistance to organophosphates, carbamates, pyrethroids and neonicotinoids (Foster *et al.,* 2012). In addition, this compound is active against western flower thrips (*Frankliniella* *occidentalis*) and even at lower concentrations causes a variety of beneficial sublethal effects, including reduced fecundity, feeding and oviposition (Bielza & Guillen, 2015).

Cyantraniliprole reduces feeding in *M. persicae* even at sublethal doses (Jacobson & Kennedy, 2013a) and so may also reduce virus transmission even when control is not complete. Results for studies which have attempted to reduce tomato spotted wilt virus transmission by the thrips species *Frankliniella fusca* and *F. occidentalis* in pepper have, however, proved inconsistent (Jacobson and Kennedy, 2011; 2013b). Further research would, therefore, be required to determine whether a reduction in aphid transmitted viruses in pepper could also be achieved.

In terms of effects on biological controls, cyantraniliprole appears to be compatible with the minute pirate bug *O. insidiosus* (Funderburk *et al.,* 2013) and the parasitoid *Bactericera cockerelli* (Liu *et al.,* 2012) but further research into the effects on aphid parasitoids and other biological controls is required. The wide spectrum of activity coupled with apparent compatibility with biological controls suggests that cyantraniliprole may be suitable for use in IPM systems used in pepper crops.

Sulfoxaflor

Another recently developed compound capable of controlling sucking pests, such as aphids, is sulfoxaflor (Babcock *et al.,* 2011). Sulfoxaflor is not currently licenced for use in the UK. Similar to neonicotinoids, this compound targets the nicotinic acetylcholine receptors (Cutler *et al.,* 2013) but in a slightly different way compared with other nicotinic acetylcholine receptor-binding insecticides (Sparks *et al.,* 2013). *Myzus persicae* with high levels of resistance to imidacloprid also exhibit resistance to sulfoxaflor (Cutler *et al.,* 2013), although conversely *Aphis gossypii* populations resistant to imidacloprid in the USA appear to remain susceptible to sulfoxaflor (Gore *et al.,* 2013). IRAC have classed sulfoxflor in Group 4 with the neonicotinoids.

Flupyradifurone

A new compound currently in development is flupyradifurone. This butenolide also acts as an agonist at the nicotinic acetycholine receptors, similar to the neonicotinoid class of chemicals. Despite this, Nauen *et al.* (2015) has shown flupyradifurone to be active against neonicotinoid resistant *Bemisia tabaci* and is not metabolised by CYP6CM1, a P450 which confers metabolic resistance to both neonicotinoids and pymetrozine in this pest. IRAC currently classes this compound in the same mode of action group as the neonicotinoid insecticides and so the possibility of rapid development of resistance, especially given the history of resistance in *M. persicae*, could be of concern. Nevertheless flupyradifurone has been shown to reduce transmission of tomato yellow leaf curl virus by *Bemisia tabaci* in tomato (Smith & Giurcanu, 2014; Smith & Nagle, 2014) and further research into the ability of this insecticide to control aphids in peppers may be of interest.

Mineral oils

Mineral oil has been used in potato crops in Europe for many years as a means of controlling aphids (Hansen & Nielsen, 2012) and has been shown to reduce Potato Virus Y (PVY) transmission by aphids in potatoes (Martin-Lopez *et al.*, 2006; Fageria *et al.*, 2014). The protective mode of action of mineral oil is unclear but virus retention in the stylets appears to be shortened (Wrobel, 2007). It should be noted that in a study by Hansen and Nielsen (2012) mineral oil was found to be ineffective at reducing PVY spread in potato over several years While the majority of work with mineral oils has been carried out in potato, at least four studies have shown mineral oil to reduce *M. persicae* populations (Stansly & Conner, 2005; Yankova *et al.,* 2009) and PVY spread in pepper (Marco, 1993; Ibrahim *et al.,* 1998). Martoub *et al.* (2011) found that mineral oil was insecticidal when applied to *Macrosiphum euphorbiae* at a concentration of 3% and above. Surprisingly, however, at concentrations lower than 3% survival remained unaffected and fecundity was enhanced. These contrasting results highlight the lack of knowledge on the mode of action of mineral oil. Further research is needed to determine whether this technology could be adapted for aphid control in pepper crops.

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Biopesticides

Interview results

Few growers mentioned using entomopathogenic fungi such as *Beauveria bassiana.* Crop protection specialists, however, frequently mentioned this pathogen in relation to the control of aphids. Despite few interviewed growers utilising these fungal pathogens, there was interest in the potential of entomopathogenic fungi to control aphid pests and more products based on these organisms would be welcomed.

A small number of growers also mentioned that entomopathogenic fungi occasionally naturally infested aphid populations in their pepper crops. These pathogens were thought to probably enter the crop in the form of infected insects or spores from surrounding vegetation. While these naturally occuring entomopathogenic fungi did not control the aphid populations on their own, they did contribute usefully to aphid control.

The organic grower interviewed, mentioned using the starch maltodextrin in previous years for aphid control, although they had since switched to using fatty acids. Other than this few growers mentioned using botanical biopesticides.

Literature review

There is no standard definition of what constitutes a biopesticide, but Gwynn *et al.* (2009) states that within the UK the term ‘biopesticide’ generally includes products with active substances based on micro-organisms, botanicals, semiochemicals including pheromones and another category of ‘other’ which is judged on a case-by-case basis. The UK Chemicals Regulation Directorate (CRD) does not maintain a publicly available list of biopesticides licensed for use within the UK, as the term biopesticide is not clearly defined in legislation and they do not wish to allow for confusion (CRD, personal comms, 24 August 2015). This report therefore only deals with biopesticides commonly used in protected pepper crops in the UK for the purposes of aphid control.

There are four main types of registered biopesticides, which are commonly used in UK protected pepper crops; *Lecanicillium muscarium,* an entomopathogenic fungus (marketed as Mycotal), *Beauveria bassiana* (Naturalis-L and Botanigard WP), natural pyrethrins (e.g. Pyrethrum 5EC) and maltodextrin (e.g. Majestik) (Chemicals Regulation Directorate Online Pesticide Database, 6 September 2015). Similar to biological controls, biopesticides provide an attractive option to growers due to the lack of residues that result from their use and their specificity (Gwynn *et al.,* 2009).

Entomopathogenic fungi are of particular interest as they only infect specific insect species dependant on strain, and so exert little effect on biological controls. In addition, once a crop has been sprayed with an entomopathogenic fungus the infected insects become a source of infection as the fungus produces spores on the dead insects (Shrestha *et al.,* 2015). *Lecanicillium muscarium* is sold as Mycotal in the UK for the control of whitefly (Down *et al.,* 2009) while *L. longisporum* (previously known as *Verticillium lecanii*) was previously sold for the control of aphids under the trade name Vertalec (Kim *et al.,* 2010).

Different strains of the entomopathogenic fungus *B. bassiana* are more effective against different insect pests. *Beauveria bassiana* is generally marketed for the control of whiteflies and thrips in the UK, but may also exert some control of aphids, particularly the strains GHA

(Botaniguard) and JW-1 (Naturalis-L) (Jandricic *et al.,* 2014c; Sandeep & Srinivasan, 2014). Recent studies, however, of a strain of *B. bassiana* against the lettuce aphid *Nasonovia ribisnigri* and *Myzus persicae, Aphis solani* and *Macrosiphum euphorbiae* failed to give satisfactory control of any aphid species and so the study was discontinued (reviewed in Jacobson & Chandler*,* 2000). Currently available entomopathogenic fungi tend to give only moderate levels of control of aphid populations and so research has been directed at developing new strains, which show greater efficacy than those currently available to growers (Jandricic *et al.,* 2014c; Shrestha *et al.,* 2015). Despite this, *B. bassiana* is mentioned here because during the interviews crop protection specialists mentioned it favourably in the context of aphid control. This entomopathogenic fungus also has the added benefit that it can be used to control pests other than aphids in the glasshouse.

There is evidence that entomopathogenic fungi may decrease the efficacy of some parasitoids within the glasshouse or field depending on timing of application (Aqueel & Leather, 2013). Spraying *Myzus persicae* with *B. bassiana* before exposing the aphids to the parasitoid *Diaeretiella rapae* 24 h later significantly reduced parasitism rates and parasitoid emergence compared with a control kept free of *B. bassiana* (Martins *et al.,* 2014)*.* Application of three different *Lecanicillum* strains reduced the longevity of adult *Aphidius colemani* at high concentrations but produced no ill effects at lower concentrations (Aiuchi *et al.,* 2012). Therefore, despite some potential negative effects, entomopathogenic fungi and parasitoids can be used in combination to control *M. persicae* but may require careful management to time applications.

In addition to commercially sold entomopathogenic fungi it is not uncommon for other species and strains of fungal pathogens to enter the crop naturally from surrounding vegetation and migrating insect pests (Godfrey *et al.,* 2001; Jacobson *et al.,* 2009; Mafrino *et al.,* 2014; Pell *et al.,* 2014). Although such organisms are rarely identified to species or genera within a commercial setting their effects on the aphid population are usually beneficial.

The term 'botanicals' relates to plant extracts (Gwynn *et al.,* 2009). There are references to many different products in the literature, although relatively few of these are licenced for use in the UK (Hori, 1999; Castresan *et al.,* 2013; Roh, 2015). One of the most commonly used botanicals in the UK are natural pyrethrins. These are plant products with insecticidal properties derived from the white pyrethrum flower *Chrysanthemum cinerariaefolium* (renamed as *Tanacetum cinerariifolium*) (Matsuda, 2012). The synthetic pyrethroid chemicals were designed on the basic structure of natural pyrethrins hence their modes of action are similar (Katsuda, 2012). Natural pyrethrins work through direct contract, are not systemic and break down quickly under natural conditions (Jacobson *et al.*, 2009). As they are a botanical product, natural pyrethrins are suitable for use within organic pepper systems (Kalaitzaki *et* *al.,* 2015) and are capable of giving good control of aphids (Kim *et al.,* 2009; Kalaitzaki *et al.,* 2015). It should be noted that with widespread resistance to pyrethroid insecticides in *M. persicae* populations, this biopesticide would not be effective against this pest (Foster and Blackshaw, 2012). Natural pyrethrins have broad spectrum activity and are generally harmful to biological controls such as parasitoids. Parasitoid larvae developing within mummies can, however, remain unaffected by natural pyrethrins and because this insecticide has such short persistence parasitoids usually emerge unharmed (Jacobson & Morley, 2007). In a study by Jacobson *et al.* (2009) after an application of Pyrethrum 5EC approximately 80% of *Aphidius* and 70% of *Praon* successfully emerged from aphid mummies collected from the crop. This suggests that a combination of parasitoids with a single application of natural pyrethrins when aphid populations are high can provide an effective means of managing aphids in organic pepper crops. It is worth noting though that in the same study the *Orius* population, established within the same crop to control thrips, decreased rapidly and had not recovered 34 days after the Pyrethrum 5EC treatment. This suggests that natural pyrethrins are not ideal when growers have successfully established *Orius* within the crop.

The activity of natural pyrethrins can be improved by the presence of synergists such as piperonyl butoxide, but this chemical is not compatible with organic systems. Recent work by Joffe *et al.* (2015) trialled some natural products, which also act as synergists of natural pyrethrins with some success. There is also some recent evidence that altering the formulation and adjuvants of natural pyrethrins into a microemulsion may increase the efficacy against *Aphis gossypii* compared with commercial formulations (Kalaitzaki *et al.,* 2015).

Another widely used product in the UK is maltodextrin, a starch-based plant extract commonly used to control aphids and other insects in a range of crops, including protected peppers (Cuthbertson *et al.,* 2008). The mode of action of maltodextrin is thought to be primarily physical rather than chemical (Croft *et al.*, 2008). Maltodextrin is approved for use in UK organic systems, making it a suitable alternative to conventional insecticides when aphid populations are sufficiently high that biological controls are no longer economically viable. There are no residual toxic effects of maltodextrin on biological controls, although direct contact with the spray will reduce resident biological control populations (Croft *et al.*, 2008). Predators and parasitoids may, however, be reintroduced immediately after treatment and can successfully recolonize plants (Root *et al.,* 2008).

Opportunities and knowledge gaps

There are far fewer biopesticides registered for use in the UK than in the EU as a whole or in the US (Gwynn *et al.,* 2009). The recent SCEPTRE (HDC project CP77) trialled a large number of biopesticides in a variety of crops. This project identified an unnamed biopesticide product as being effective in reducing aphid pest numbers, including *Aulacorthum solani*, in protected peppers. Two other unnamed products also gave control of thrips. In the current MOPS project (Pope, 2015) three novel biopesticides gave good control of *M. persicae* on pansy, with one of these products proving to be as effective as Movento.

A biopesticide of particular interest is neem (e.g. NeemAzal), which has recently been evaluated in organic pepper crops in Switzerland and gave good aphid control, reducing aphid numbers and preventing visible aphid damage (Daniel *et al.,* 2013). The authors recommend examining the effect of combining NeemAzal with releases of biological controls to observe whether this improves the efficacy of the treatment, as although aphid damage was prevented 100% control was not achieved and aphids remained on the plants in low numbers. Neem based insecticide products vary slightly in composition, but usually contain the limonoid azadirachtin, which is extracted from the seeds of the neem plant, *Azadirachta indica*, and causes an antifeedant effect in many insect orders (Lowery *et al.,* 1997; Fournier & Brodeur, 2000).

In other work, neem seed oil and neem seed extract applied as a spray effectively reduced *M. persicae* populations on pepper to the same extent as natural pyrethrins (Lowery *et al.,* 1993). There is also evidence that neem applied as an oil can reduce virus transmission by *M. persicae* in pepper (Lowery *et al.,* 1997). At present neem extracts and azadirachtin are not licenced for use in the UK. Given that this botanical would probably be available for use in organic systems, if licenced, it could provide a particularly useful alternative to fatty acids and maltodextrin for the control of aphids.

Entomopathogenic fungi potentially offer scope for new aphid control solutions. As mentioned before, *B. bassiana* is currently sold in the UK for control of whitefly and thrips, but will also provide some control of aphid pests (Jandricic *et al.,* 2014c; Sandeep & Srinivasan, 2014). Developing new strains which are better adapted to the control of aphids may be one way to improve aphid control in UK protected pepper crops. The commercially available strains of *B. bassiana* were originally selected to target whitefly (Jacobson & Chandler, 2000) and so it is possible that use of a different strain might achieve improved control of aphids in pepper crops. This improved control may, however, at least in part require the development of better application technology to achieve improved coverage on the lower surface of leaves.

Recent research in the USA tested the efficacy of different strains of *Beauveria, Metarhizium* and *Isaria* against *Myzus persicae, Aphis gossypii* and *Aulacorthum solani* (Jandric *et al.,* 2014c). While none of the 'novel' strains managed to completely control and eradicate any of the aphid species, the highest mortalities achieved were 62% for *M. persicae* and 56% for *A. gossypii,* several of the 'novel' strains of these entomopathoegnic fungi did outperform the commercial strains GHA and JW-1 (Jandricic *et al.,* 2014c). *Aulacorthum solani* appeared to be more difficult to control than *M. persicae* and *Aphis gossypii* with the strains tested, and there was certainly variation in the ability of different fungal strains to control different aphid pests. It is important to note that this study was not a glasshouse trial, where a wide range of factors may affect the efficacy of entomopathogenic fungi, but this research does suggest that it may be possible to develop new strains of currently licenced entomopathogenic species for use in UK protected pepper crops. Such strains would contribute to resistance management of conventional insecticides and could also provide an alternative to these insecticides when hyperparasitoids limit the use of aphid parasitoids within a crop.

The use of novel entomopathogenic fungi such as *Erynia neoaphidis* (previously known as *Pandora neoaphidis*) has also been investigated (Shah *et al.,* 2000; Pell *et al.,* 2004). It is not uncommon for this pathogen to enter crops naturally. *Erynia neoaphidis* is an attractive candidate for use against aphid pests because it is able to infect a wide range of species, including *M. persicae,* on a range of crop plants (Pell *et al.,* 2004). Unfortunately culturing this organism for commercial use has proven difficult and this has limited its use so far. Efficacy may also be variable (Shah *et al.,* 2000). The development of fungal strains adapted for use against the common aphid pests and the environmental conditions within the glasshouse may improve the efficacy of such entomopathogenic species, but would require further research.

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Application techniques

Interview results

In general growers did not discuss application strategies for conventionally approved pesticide products in depth (such as nozzle type, application rates etc.). Growers generally used high volume sprays to apply pirimicarb (e.g. Aphox) and sometimes pymetrozine (Chess WG). Chess was, however, typically applied via the irrigation system, a method also discussed by several crop protection specialists. Growers who applied Chess via the irrigation system generally did so because of the convenience compared with the time and labour required to apply a spray and also the reduced impact on biological controls. One grower had specifically designed their spray equipment so that the angle of the nozzles increased the ability to spray the undersides of the leaves of the pepper crop and more fully penetrate the canopy.

Literature review

Because of the large, drooping leaves of mature pepper plants, most of which hang at approximately 30° off the vertical (Jacobson *et al.,* 2010) and the tendency of aphids to locate to areas underneath the foliage, it can be difficult to achieve full spray coverage of all surfaces of pepper plants when applying insecticides. Aphids may therefore survive sprays partially by their choice of location on the plant and the difficulties associated with spraying such areas.

In a recent study by Jacobson *et al.* (2009) indoxacarb applied as an ultra low volume spray was not as effective at penetrating the pepper crop canopy as a high volume spray. Jacobson *et al.* (2010) describe in some detail, with diagrams, the modifications to a sprayer, which improved coverage within a wide bed organic growing system. The most important modification involved a vertical spray boom with two types of nozzle, 'lifters' and 'fillers'. The role of the lifter nozzles was to drive a spray underneath the near-vertical leaves and so lift them up momentarily. This allowed the filler nozzles to then cover the lower leaves further inside the canopy with a fine spray. The angle of the lifter nozzles, 60° from the horizontal and aimed into the spray cone of the filler nozzle on the tier above, additionally created turbulence in a manner that increased the movement and so spray coverage of the pepper canopy. In addition the robotic sprayer was set to travel at 25% of the maximum speed.

Even with the leaves sprayed to runoff by this method it should be noted that the denseness of the canopy meant that the undersides of some leaves still remained untreated. Application of 1.5% Savona by this modified apparatus, however, reduced the aphid population by 90% one day after the spray had been applied and even after the aphid population began to increase again it was still two thirds lower than the original population size 42 days after treatment (Jacobson *et al.,* 2010).

When searching the literature it was noted that research into insecticide application techniques tends to be aimed at specific problems, not all of which will be applicable to UK protected pepper crops. This highlights the need for crop specific pesticide application technology research.

As previously mentioned, there is currently an EAMU for the application of Chess WG (pymetrozine) via the irrigation system. This method of application was popular among the interviewed growers and is described in detail by Jacobson *et al.* (2009; 2010; 2011). During this study, application of Chess at the maximum recommended rate in mature protected pepper crops gave good control of *M. persicae.* Due to the fact that pymetrozine is highly systemic, application via the irrigation gives good coverage of the entire plant as the chemical moves upwards via the phloem (Wyss & Bolsinger, 1997). In addition adverse effects on biological controls are reduced as in theory only phloem feeding insects come into contact with high concentrations of the chemical. Applications of other insecticides via drip irrigation in peppers have also been shown to be cheaper than foliar applications and can give equally good control of insect pests, although this method is best suited to phloem-feeding species and may take slightly longer to give control than foliar applications (Royer *et al.,* 1988).

During the study by Jacobson *et al.* (2010) the irrigation was turned off in mid-afternoon to allow the plants and their rockwool growing medium to partially dry out before application. The treatment was applied in the late afternoon during cloudy conditions. No more irrigation runs were performed that day and the drainage was reduced the next day to maximise uptake and minimise product being flushed through the growing medium. During the interviews various growers described slightly different application techniques based around this theory. Several described drying the plants out slightly for several hours before application to improve uptake but the time of day and weather conditions during application varied from grower to grower.

Opportunities and knowledge gaps

Any investment in spray technology is likely to represent a large financial outlay but the potential to improve spray coverage of the underside of the leaves and as a result improve aphid control may make this investment worthwhile. Further research into the development of new spray technologies able to give better coverage of the dense foliage of protected pepper crops would be beneficial. For example the application equipment developed for extra-wide bed organic systems by Jacobson *et al.* (2010) could be modified and used to improve the coverage of foliage in conventional crops. Further development of spray technologies in terms of nozzle selection and direction of airstream to try and 'lift' the leaves slightly as sprays are applied could improve the coverage of the foliage and hence the efficacy of insecticide applications for the control of aphids in the UK protected pepper industry. In addition to foliar applications, recommendations for growers about best practise for applying Chess through the irrigation system in protected peppers may also be a benefit to the industry.

References

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Information, communication and technology transfer of aphid control strategies

Interview results

The most common method used by growers to obtain information about aphid control strategies was through visiting representatives from biological and chemical control suppliers. Many growers stated that they preferred to receive information this way, but some expressed concern that they did not want to be entirely dependent on this route for sources of information. Many growers were interested in obtaining their own information about aphid control from other sources. Growers who did obtain their own information mainly did so through AHDB Horticulture factsheets and the AHDB Horticulture website. Factsheets were considered a simple and useful way of summarising information and in some cases were put up in communal areas to train other members of staff.

One individual expressed the view that access to scientific papers could be difficult for growers as current relevant papers are rarely accessible for free and so it was felt that if relevant papers could be summarised and the summaries made available to growers via the AHDB Horticulture website this would be a benefit to them.

Another growers suggested that if mobile phone apps could be utilised to map the location of pests within the glasshouse to give a clear location to visiting supplier representatives and consultants and track pest spread this might be of use to the industry.

Should aphid control be a focus of pest management research and knowledge transfer in protected peppers?

The vast majority (all but one) of interviewed growers were actively controlling aphid pests when interviewed and felt strongly that improvements to aphid control would benefit their business. All interviewed crop protection specialists also felt that aphid pests of pepper crops were a major problem and that improvements in aphid control would benefit the industry.

Conclusions

- The most important challenge affecting aphid control in protected pepper crops grown in the UK is hyperparasitism. This is due largely to the reliance on aphid parasitoids, in particular *Aphidius colemani*, to control aphid pests. Despite this, there is a lack of information on the biology and control of hyperparasitism. The majority of growers expressed a wish for alternatives to the use of insecticide applications with which to manage hyperparasitism. Preliminary work investigating the use of semiochemicals to manipulate behaviour and potentially trap hyperparasitoids shows considerable promise but requires further work to develop a practical solution for growers. Improved control of hyperparasitism would be of benefit to a wide range of growers who regularly use aphid parasitoids to control aphid pests.
- Extending the range of biological controls, in particular the use of predators, used to control aphid pests may help to improve control and reduce hyperparasitoid problems by reducing the reliance on *Aphidius colemani*. Wingless forms of *Adalia bipunctata* and *Chrysoperla carnea* are two predators that may warrant further investigation. Greater reliance on generalist predators would, however, increase the need for further work to investigate interactions between biological controls and the impact of intraguild predation.
- There are several insecticide active ingredients, such as spirotetramat (e.g. Movento) and flonicamid (e.g. Mainman), that could provide useful control of aphid pests and reduce the reliance on, and possible development of resistance to pymetrozine. Further work determine the efficacy of these alternative insecticides as well as their compatibility with IPM programmes used in pepper crops is required.
- In addition to insecticides, there are several biopesticides, such as neem and coded products, identified through the SCEPTRE and MOPS projects that could provide useful alternatives to conventional insecticides for aphid control in pepper crops. Currently the most promising biopesticides appear to be botanicals but novel species

or strains of entomopathogenic fungi also have potential. In all cases, further work is required to determine the efficacy of these biopesticides and their compatibility with IPM programmes used in pepper crops.

- Assessing the potential of using screens over vents and doors to prevent sporadic invasion by large numbers of aphids is required to determine the cost-effectiveness of this approach. In particular, it will be important to confirm that environmental management can be successfully adjusted to compensate for any effect the screens may have on temperature and humidity in the glasshouse.
- Another glasshouse modification that may be worth further investigation is the use of spectral filters as a means of disrupting aphid behaviour. While a potentially interesting area to investigate, it would be essential that these filters do not disrupt the foraging behaviour of parasitoids and predators or affect crop growth.
- Several studies have demonstrated the importance of good spray coverage when using contact insecticides. Work in a wide bed organic cropping system has demonstrated that modification of spray equipment can improve spray coverage and as a result control of aphid pests. There is potential both to further improve spray coverage and to adapt these systems for use in conventional crops. Spray coverage is likely to become more important if there is greater uptake of biopesticides.

Knowledge and Technology Transfer

Knowledge transfer activities within this project included:

- Final project report to AHDB Horticulture
- Presentation of key findings in the report to growers at the Cucumber Growers Association and Pepper Technology Group meeting in Waltham Abbey on Thursday 8th October 2015.

Appendices

Table 1 Insecticidal products currently available (September 2015) for use in UK protected pepper crops, obtained from Liason (Fera).

Product	MAPP number	Active Substance	Marketing Company	Method of Application	Final Use Date	EAMU
Acaramik	14344	Abamectin	Rotam Agrochemical Europe Limited	Ground spray	31/10/2016	1217/15
Acaramik	14344	Abamectin	Rotam Agrochemical Europe Limited	Ground spray	31/10/2016	1217/15
Dynamec	13331	Abamectin	Syngenta Bioline Ltd.	Ground spray	31/12/2021	0422/07
Dynamec	13331	Abamectin	Syngenta Bioline Ltd.	Ground spray	31/12/2021	0422/07
Aceta 20 SG	16919	Acetamiprid	Euro Chemicals s.r.o.	Ground spray	31/10/2019	
Aceta 20 SG	16919	Acetamiprid	Euro Chemicals s.r.o.	Ground spray	31/10/2019	
Acetamex 20 SP	15888	Acetamiprid	MAC GmbH Agricultural Products	Ground spray	31/10/2019	
Gazelle	12909	Acetamiprid	Certis	Ground spray	31/10/2019	
Gazelle SG	13725	Acetamiprid	Certis	Ground spray	31/10/2019	
Sangue	16042	Acetamiprid	Agroquimicos Genericos	Ground spray	31/10/2019	
Vulcan	16689	Acetamiprid	Pan Agriculture Ltd.	Ground spray	31/10/2019	
Biocure	16432	*Bacillus thuringiensis* var. kurstaki	Russell IPM Limited	Ground spray	31/12/2021	
Dipel DF	14119	*Bacillus thuringiensis* var. kurstaki	Interfarm (U.K.) Ltd.	Ground spray	31/12/2021	1060/09
Dipel DF	14119	*Bacillus thuringiensis* var. kurstaki	Interfarm (U.K.) Ltd.	Ground spray	31/12/2021	
Lepinox Plus	*16269*	*Bacillus thuringiensis var. kurstaki*	Fargro Ltd.	Ground spray	31/10/2021	2707/14
Lepinox Plus	16269	*Bacillus thuringiensis* var. kurstaki	Fargro Ltd.	Ground spray	31/10/2021	
Lepinox Plus	16269	*Bacillus thuringiensis* var. kurstaki	Fargro Ltd.	Ground spray	31/10/2021	2707/14
Naturalis-L	14655	*Beauveria bassiana* ATCC-74040	Belchim Crop Protection Limited	Ground spray	31/10/2021	
Botanigard WP	17054	*Beauveria bassiana* GHA	Certis	Ground spray	13/04/2018	

Botanigard WP	17054	*Beauveria bassiana* GHA	Certis	Ground spray	13/04/2018	
SB Plant Invigorator	-	Carbonic acid diamide/urea	Fargro Ltd.	Ground spray		
Garlic Barrier Garshield	-	Citrus fruit extract/garlic	Aston Horticulture	Ground spray		
Bandu	16153	Deltamethrin	Headland Agrochemicals Ltd.	High volume	30/04/2019	
Cleancrop Decathlon	16154	Deltamethrin	Agrii	High volume	19/02/2017	
CMI Delta 2.5 EC	16695	Deltamethrin	CMI Ltd.	High volume	30/04/2019	
Decis	16124	Deltamethrin	Bayer CropScience Limited	High volume	30/04/2019	
Decis Protech	16160	Deltamethrin	Bayer CropScience Limited	High volume	30/04/2019	
Dimilin Flo (08769)	8769	Diflubenzuron	Chemtura Europe Ltd.	Ground spray	31/12/2021	2433/99
Agri 50 E	-	Dodecylphenol ethoxylate	Plant Solutions Ltd.	Ground spray		
Fytoclean	16788	Fatty acids	Russell IPM Limited	Ground spray	28/02/2017	
Safers Insecticidal Soap	7197	Fatty acids	Safer Ltd	Ground spray	31/12/2021	
Savona	6057	Fatty acids	Koppert (UK) Ltd.	Ground spray	28/02/2017	
Savona	6057	Fatty acids	Koppert (UK) Ltd.	Ground spray	30/09/2016	0892/15
BubbleRPEL	-	Garlic	Parripak Foods Ltd	Ground spray		
Garlic Barrier AG	-	Garlic	Garlic Farms (UK) Ltd	Ground spray		
Garlic Barrier AG	-	Garlic	Garlic Farms (UK) Ltd	Ground spray		
Garlic Barrier AG Granular	-	Garlic	Garlic Farms (UK) Ltd	Ground spray		
Garlic Barrier AG Grannular	-	Garlic	Garlic Farms (UK) Ltd	Ground spray		

Garlic Barrier AG Anthyllis	-	Garlic	Aston Horticulture	Ground spray		
Garlic Barrier AG Granules	-	Garlic	Aston Horticulture	Granular application		
Omex Garland	-	Garlic/sulphur	Omex Agriculture Ltd	Ground spray		
Explicit	15359	Indoxacarb	DuPont (UK) Ltd.	Ground spray	30/04/2020	
Explicit	15359	Indoxacarb	DuPont (UK) Ltd.	Ground spray	30/04/2020	
Picard 300 WG	16714	Indoxacarb	Agrifarm CropScience Limited	Ground spray	30/04/2020	
Rumo	14883	Indoxacarb	DuPont (UK) Ltd.	Ground spray	30/04/2020	
Rumo	14883	Indoxacarb	DuPont (UK) Ltd.	Ground spray	30/04/2020	
Steward	13149	Indoxacarb	DuPont (UK) Ltd.	Ground spray	30/04/2020	
Steward	13149	Indoxacarb	DuPont (UK) Ltd.	Ground spray	30/04/2020	
Hallmark with Zeon Technology	12629	Lambda-cyhalothrin	Syngenta UK Ltd	Ground spray	30/06/2018	1994/12
Mycotal	16644	*Lecanicillium muscarium* strain Ve6	Koppert BV	Ground spray	31/10/2021	
Mycotal	16644	*Lecanicillium muscarium* strain Ve6	Koppert BV	Ground spray	31/10/2021	2680/14
Mycotal	16644	*Lecanicillium muscarium* strain Ve6	Koppert BV	Ground spray	31/10/2021	
Mycotal (04782)	4782	*Lecanicillium muscarium* strain Ve6	Koppert (UK) Ltd.	Ground spray	31/05/2016	2749/14
Mycotal (04782)	4782	*Lecanicillium muscarium* strain Ve6	Koppert (UK) Ltd.	Ground spray	31/05/2016	
Eradicoat	17121	Maltodextrin	Certis	Ground spray	03/08/2019	
Eradicoat (13724)	13724	Maltodextrin	BCP Certis	Ground spray	31/12/2016	
Majestik	14831	Maltodextrin	Certis	Ground spray	31/12/2016	
Sea Breeze	-	Natural plant extracts	Aston Horticulture	Ground spray		

Agrotech Pirimicarb 50 WG	12269	Pirimicarb	Agrotech Trading GmbH	Ground spray	31/10/2016	
Aphox	10515	Pirimicarb	Syngenta UK Ltd	Ground spray	31/12/2021	2315/10
Aphox	10515	Pirimicarb	Syngenta UK Ltd	Ground spray	31/12/2021	
Clayton Pirimicarb 50	12910	Pirimicarb	Clayton Plant Protection	Ground spray	31/12/2021	
Cleancrop Miricide	11776	Pirimicarb	United Agri Products	High volume	31/12/2021	
Cleancrop Miricide	11776	Pirimicarb	United Agri Products	Ground spray	31/12/2021	2332/10
Hockley Pirimicarb WG	15529	Pirimicarb	Hockley International Ltd	Ground spray	31/12/2021	
Milentus Pirimicarb	12268	Pirimicarb	Milentus BV	Ground spray	31/12/2021	
Phantom	11954	Pirimicarb	Syngenta UK Ltd	Ground spray	31/12/2021	
Phantom	11954	Pirimicarb	Syngenta UK Ltd	Ground spray	31/12/2021	2360/10
Piri 50	14956	Pirimicarb	Euro Chemicals s.r.o.	Ground spray	31/12/2021	
Pirimate	14539	Pirimicarb	European Agrichemicals Ltd	Ground spray	31/01/2017	
Pirimate 500	15995	Pirimicarb	Becesane s.r.o.	Ground spray	31/12/2021	
Pirimex 50 WG	15964	Pirimicarb	MAC GmbH Agricultural Products	Ground spray	31/12/2021	
Pirimicarb 50	14295	Pirimicarb	Goldengrass Limited	Ground spray	31/12/2021	
Route One Primro 50 WG	15315	Pirimicarb	Albaugh Europe SARL	Ground spray	31/12/2021	
Standon Pirimicarb 50	13290	Pirimicarb	Standon Chemicals Ltd.	Ground spray	31/12/2021	
Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Irrigation line applied	30/06/2018	2024/09
Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Vertical boom	30/06/2018	2024/09
Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Lance	30/06/2018	2024/09

Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Ground spray	30/06/2018	0501/07
Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Vertical boom	30/06/2018	2024/09
Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Irrigation line applied	30/06/2018	2024/09
Chess WG	13310	Pymetrozine	Syngenta Bioline Ltd.	Lance	30/06/2018	2024/09
Pyrethrum 5 EC	12685	Pyrethrins	Agropharm Limited	Ground spray	31/12/2021	
Pyrethrum 5 EC	12685	Pyrethrins	Agropharm Limited	Ground spray	31/12/2021	1005/09
Pyrethrum 5 EC	12685	Pyrethrins	Agropharm Limited	Ground spray	31/12/2021	1005/09
Pyrethrum 5 EC	12685	Pyrethrins	Agropharm Limited	Ground spray	31/12/2021	1005/09
Spruzit	13438	Pyrethrins	Certis	Ground spray	31/12/2021	
Conserve	12058	Spinosad	Fargro Ltd.	Ground spray	31/10/2020	
Oberon	11819	Spiromesifen	Bayer CropScience Limited	Ground spray	30/04/2017	2149/06
Oberon	11819	Spiromesifen	Bayer CropScience Limited	Ground spray	30/04/2017	2149/06
Agrovista Reggae	13706	Thiacloprid	Agrovista UK Ltd	Ground spray	31/10/2019	0474/08
Calypso	11257	Thiacloprid	Bayer CropScience Limited	Knapsack application	17/08/2018	2151/14