SCEPTREPLUS

Final Review Report

Trial code:	SP 39
Title:	**Capsids: review of control measures to identify new leads for efficacy trials**
Crop	Cross sector: relevant crops include strawberry, cherry, raspberry, blackberry, apple, pear, hops, blackcurrant, cucumber, celery, beet, potato, tomato
Target	Capsid bugs (Miridae) as crop pests
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Organisation:	NIAB EMR
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Report date:	31 January 2019
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ORETO Number: (certificate should be attached)	N/A

I the undersigned, hereby declare that the work was performed according to the procedures herein described and that this report is an accurate and faithful record of the results obtained

31 January 2019…… ………………………………………………………………………

Date Authors signature

Review Summary

Introduction

Capsids (Heteroptera: Miridae) are a diverse group of plant bugs and include species that are important pests of soft fruit, tree fruit and protected edibles. Crop damage by capsids is difficult to predict, varying widely between farms and years. Feeding by these insects distorts developing plant parts including shoot growing points and developing fruits. . There are no known effective biological control agents available for UK capsid pests, and only very restricted availability of selective insecticides. Management of these pests currently relies on application of broad-spectrum insecticides, which can be effective at killing capsids but also reduces numbers of the naturally-occurring and released natural enemies helping to control other groups of pests within the crop production system. Growers therefore tend to intervene specifically for capsids as a last-resort option and at the risk of resurgence of other important crop pests. This review explores the nature and extent of capsid problems and the practices, products or innovations that may improve control of these pests. The primary aim is to identify capsid control options that may form the basis of further research as part of SCEPTREPlus or other projects.

Stakeholders with expertise in multiple horticultural sectors and crop protection activities were contacted and surveyed for information on capsids. Interview questions addressed multiple aspects of capsid control including: crops commonly affected; damage type, seasonal timing, impact and long-term trends; current control strategies used; efficacy and IPM compatibility of interventions; potential new leads; potential roles of natural enemies; future concerns. These interviews highlighted multiple issues, concerns and opportunities for further research, and were followed by more focused information gathering (through contacting individuals and internet-based searches) to identify promising new products or strategies for capsid control.

Summary

- Crops where growers regularly see significant capsid damage include strawberries, cherries, celery and cucumbers. Capsids are also observed as pests in raspberry, blackberry, blackcurrant, redcurrant and gooseberry.
- The economic impact of capsids is very difficult to estimate because, although they sometimes cause substantial direct crop losses, attempts to control them often reduce the efficacy of the biologicals that are released to control other, more damaging pests.
- A consistent message, based on observations by agronomists and growers with experience across multiple sectors, is that damage by capsids has become more frequent and of higher impact in recent years.
- The trend towards increased capsid damage is perceived to be linked to multiple factors but particularly: withdrawal of available products for control (particularly chlorpyrifos), the move towards increased reliance on biologicals for control of other pest groups and increases in average UK temperatures.
- Concerns were expressed regarding options for future capsid control, based on possible future withdrawal of the actives that are currently available and the compatibility of products with biological controls.

- The demand for a capsid control programme that is compatible with biologicals is particularly high in fruit crops such as strawberries and cherries, where growers risk the collapse of the IPM system and resurgence of thrips and mite damage if the currently-available insecticides are applied for capsid.

Cultural control

- There is widespread recognition that weeds act as alternative host plants for capsid pests and that these plants are often the source of crop invasions. Weed control is therefore carried out as standard good practice to minimise capsid risk.

Biological control

- Very little information is available on the importance of different groups of natural enemies in predation or parasitism of capsids in the UK. This was highlighted as an area where future research is required.
- There is a widely held (but not experimentally-validated) belief that the presence of *Orius* in crop areas helps to control capsids.

Chemical control (including biopesticides)

- Based on information from a variety of sources (technical advisors in pesticide companies in the UK and overseas, pesticide regulatory experts in the UK and crop protection experts advising on capsid control on arable crops in the USA and Australia), new leads with potential for use in the UK were identified. These include synthetic actives which have more specific activity against sap-feeding pests than the products that are currently approved for capsid control in many of the UK crops affected and biopesticides showing promising activity against capsids in previous studies.
- Australian researchers have discovered that mixing table salt (sodium chloride, e.g. at 7 g / L) with insecticide products can enhance the efficacy of active ingredients. This has become recommended practice for management of capsid pests in cotton, allowing insecticides to be applied at a lower rate, maintaining good efficacy against target pests while reducing negative impacts on beneficial insects. Salt additives may therefore have potential for improving capsid management in UK crops, but this remains to be tested.
- A German company (Katz Biotech AG) has recently patented a novel "attract-and kill" approach to capsid control based on microcapsules, consisting of a liquid core and dry, solid outer shell. The core contains an insecticide, while the shell incorporates chemicals that attract *Lygus* pests. The insects pierce the capsules with their mouthparts and take up the insecticide. These microcapsules can therefore be applied to crops without exposing beneficial natural enemies or pollinators to the killing agent. This technology is still in development, but laboratory and glasshouse trials have been encouraging. The company is interested in the possibility of providing such microcapsules for testing in the UK.
- A push-pull synthetic semiochemical strategy is currently in development for control of capsids in strawberry crops and has been demonstrated to reduce the frequency

of damage to fruit, increasing marketable yield. This novel technology has potential for further development and application to other capsid-damaged crops.

Next Steps

The review has identified six approaches that could be pursued in the short and longer terms:

1. Further research to investigate the roles of particular weed species as alternative hosts of capsids and sources of crop infestations. This should include comparisons with the plant species commonly included in seed mixes that are sown to enhance biodiversity in field margins and orchard alleyways, to address concerns that such mixes are exacerbating capsid problems in some crops.
2. Further research to investigate the roles of natural enemies in control of capsids. In particular, the widely held (but not experimentally validated) belief that the presence of *Orius* in crop areas helps to control capsids. It would also be valuable to explore the roles of other, naturally-occurring generalist predators such as spiders in suppressing populations of UK capsid pests.
3. Trials to evaluate “new” insecticide / bioinsecticide treatments to assess efficacy against capsid pests in comparison with the most effective currently-available products. It is essential that such trials include assessments of the impact of treatments on beneficial insects, particularly the biological control agents that are released to manage other pests as part of the IPM system but are heavily disrupted as a side effect of current capsid control measures.
4. Incorporation of salt additives to selected synthetic insecticides tested in (3) to explore whether such synergistic strategies improve capsid control / reduce impact on beneficial insects and are feasible with UK crops.
5. Incorporation of novel microencapsulated “attract-and-kill” formulations of insecticides in efficacy trials if possible.
6. Research to further refine and validate semiochemical-based approaches to capsid control, e.g. development of push-pull systems, improving trap designs and using pheromone-baited traps to monitor autumn populations (e.g. common green capsid in cherry) to inform the necessity and timing of clean-up sprays.

Take home messages

- Capsids remain sporadic secondary pests of numerous horticultural crops but the damage they cause has become more frequent and extensive in recent years. They have a particularly high impact on the production of strawberries, cherries, celery and cucumber.
- The few products available for capsid control are broad-spectrum insecticides which disrupt IPM of other key pest groups and are under threat of withdrawal.
- On a global scale, capsids are pests of large-scale arable crops such as cotton. Insecticides with more selective activity against sap-feeding pests, and lower impact

on beneficial natural enemies (e.g. sulfoxaflor and flonicamid) have become preferred interventions for capsids in Australia and the USA.

- Growers in the UK are permitted to apply an insecticide to a limited range of glasshouse crops (e.g. aubergines, peppers, cucumbers, tomatoes and protected ornamentals) and another insecticide can also be applied to some crops (e.g. apples and potatoes). The efficacy of these insecticdes against UK capsid pests and impact on natural enemies should be investigated.
- Additional novel insecticides with alternative modes of action are available for testing against capsid pests, including active ingredients currently under development by pesticide companies.
- Improved formulations of insecticides may be possible with enhanced efficacy against capsids and reduced impact on beneficials. Based on the results of international research, this may be achieved by mixing insecticides with salt or enclosing them in attractant-coated microcapsules.
- The entomopathogenic fungi *Beauveria bassiana* and *Metarhizium brunneum* are available as commercial formulations and should also be considered as candidates for inclusion in efficacy testing. *B. bassiana* has proven efficacy against some UK capsid pests. *M. brunneum* also has potential for capsid control (based on international research results) but has not been tested against UK pest capsids.
- Particular weeds (e.g. nettles) are assumed to be linked with capsids and control of these is recommended as good practice to minimise capsid risk. However, there is a lack of information on the relative importance of different weed species in harbouring capsid pest species and further research is needed.
- There is a lack of knowledge concerning the roles played by natural enemies in capsid outbreaks. In the longer term, this is also recommended as an area for future research
- Semiochemical-based approaches (including push-pull strategies and pheromone-based monitoring traps) have been developed for capsids as part of previous AHDB-funded projects and have potential for further refinement and optimisation to improve capsid management.

Review

Introduction

Capsids belong to a diverse group of insects called mirids (order Hemiptera; suborder Heteroptera; family Miridae). There are approximately 10,000 species of bugs in this insect family worldwide (Wheeler, 2000), and at least 230 species have been recorded in the UK (Bantock and Botting, 2018). Mirids have a wide variety of feeding habits. The group includes species that specialise as predators of other invertebrates or as plant feeders, but also many omnivorous species able to switch between roles as carnivores and herbivores (McGavin, 1993). Some species of predatory mirids may have beneficial effects by helping to reduce pest populations. The group includes predatory bugs (e.g. *Macrolophus* and *Nesidiocoris* species) that are released as biological control agents in glasshouses, although when populations of insect and mite prey are very low, these species are also capable of feeding on plants and causing damage (Jacobson, 2017). Overall, insects in the mirid family have much larger negative economic impacts, through feeding on plants and causing crop damage, than their positive effect as natural enemies. The crop pest mirids reviewed in this report are collectively known as capsids in the UK. Only a few capsid species damage UK crops but outbreaks may have significant impacts on crop yield and quality and on control of other pest groups.

Table 2. Notable UK capsid pest species and the crops commonly affected.

Capsid species	Common name (and abbreviation used in this review) if applicable	Crops affected	Previous name if applicable
Closterotomus norwegicus	Potato capsid	Potatoes, carrots, linseed and Asteraceae (e.g. chrysanthemums)	*Calocoris norwegicus*
Dicyphus errans	Slender grey capsid	Largely predatory but occasionally damages potato	-
Liocoris tripustulatus	Common nettle capsid	Protected pepper and aubergine, strawberry	-
Lygocoris pabulinus	Common green capsid (CGC)	All fruit crops particularly apple, pear, currant, gooseberry and strawberry. Also some arable crops (e.g. potato, beet).	*Lygus pabulinus*
Lygocoris rugicollis	Apple capsid	Apples, pears, currants and gooseberries	*Plesiocoris rugicollis*
Lygus rugulipennis	European tarnished plant bug (ETPB)	Strawberry, occasionally raspberry and other fruit crops, also brassicas, potato, beet, legumes and protected cucumber	-
Nesidiocoris tenuis	-	Tomato	*Cyrtopeltis tenuis*
Orthops campestris	-	Celery and other Apiaceae	-

In the UK, capsids are frequently pests of relatively high-value horticultural plants, particularly fruit crops. Some of the notable UK capsid pest species are listed in Table 2.

Target description and life-cycle

Capsids are small (usually less than 6 mm long as adults), active insects. Many species are approximately oval in body shape. They have a long feeding tube (rostrum) that is characteristic of the true bugs (order Hemiptera). The downward angle of the head tends to give their bodies a curved, hunched-over appearance when viewed from the side. Some species are brightly-coloured with distinctive patterns, whereas others are a more uniform green or brown colour. The adults have a triangular area (the scutellum) in the centre of their back, between the bases of the wings, and this is sometimes a distinctly different colour and may therefore stand out clearly against the rest of the dorsal surface.

Many species of mirids pass the winter as eggs, but some of the UK pest capsid species over-winter as adults, often sheltering in leaf litter or other dead outdoor vegetation, or feeding on weed species. In spring, responding to the increasing temperature and day length, the adults start to reproduce. The females insert their eggs into plants (often into stems and meristems), and these hatch into tiny nymphs (approximately 1 mm long). Mortality can be high for the over-wintering adults (Varis, 1972) and this first generation (with the nymphs often developing on weeds) therefore tends to be low numbers. Over-wintered adults may also enter glasshouses or attack outdoor flowering tree crops in April. The developing nymphs pass through five immature stages (instars) before becoming adult. Wing buds are present on the nymphs, becoming visible on the older instars. Although they are not able to fly, nymphs are very active and able to move rapidly over and between plants. Adults have wings and are therefore able to disperse over greater distances.

Although the adults and nymphs may damage crops during spring and early summer, capsids often have a higher impact in late summer, when a second generation and higher population levels appear. For example, in strawberry it is second-generation European tarnished plant bug (ETPB, *Lygus rugulipennis*) that causes the biggest capsid problems. ETPB often colonises strawberry crops having moved from weed species, where the first generation has developed. Some capsid pest species may have three generations in one year (Collier, 2017), while others (e.g. apple capsid, *Lygocoris rugicollis*) have just one generation. The common green capsid (CGC, *Lygocoris pabulinus*) has two generations per year, hatching from over-wintered eggs in spring and becoming adults in summer, but producing a second generation that reaches maturity in autumn.

Plant damage

Capsids damage a wide variety of crops, but infestations tend to be localised, sporadic and unpredictable. Agronomists and growers are likely to underestimate the importance of capsids as plant pests, as small populations of these insects may be inconspicuous yet inflict substantial damage to crops. Winged adults may be highly mobile, particularly on warm and sunny days. The immature stages (nymphs) may also disperse and feed on many different plants during their development, despite being unable to fly. For example, older nymphs of CGC that have developed on apple need to locate non-woody, herbaceous alternative host plants (e.g. potato) in order to complete their development to adult (Blommers et al., 1997). Individual insects may therefore cause damage to more than one crop type during their lifetime.

Capsids are sucking insects and tend to target the sites of new plant growth that are good sources of nitrogen, such as young leaves, meristems, shoots, flower buds and developing fruits and seeds. The insects use their flexible stylet mouthparts to macerate mesophyll cells and inject salivary enzymes, and then ingest the resultant partially-digested plant sap (Wheeler, 2001). Plant cells are damaged through mechanical stylet action and chemical digestion, aided by salivary enzymes (Wheeler, 2000). Damage to foliage may not be obvious immediately following feeding, but manifests later as necrotic lesions and torn patches with the continued growth and expansion of affected plant parts. Capsid damage to shoots may result in reduced growth, but the death of meristems following capsid feeding often also leads to increased branching, reducing the size of the entire plant (Hill, 1952). Developing flowers and fruitlets are also targeted for feeding, resulting in distorted, misshapen and rejected produce. There is likely to be a significant delay between capsid feeding and fruit damage symptoms. In strawberries, for example, there may be a 3-4 week interval between capsid feeding and detection of the damaged, distorted (“cat-faced”) fruit by growers (Cross, 2004).

Unlike other groups of sap-feeding bugs such as aphids and whiteflies, capsids do not regularly transmit plant viruses as a result of their feeding activity. However, although they are relatively unimportant as vectors of plant pathogens, examples of transmission of bacteria, fungi and occasionally viruses by mirids have been reported (Mitchell, 2004). Capsid feeding damage is more likely to be associated with pathogens that invade plants as secondary infections. Although not transmitted by the insects, such fungal and bacterial pathogens are able to enter plant parts (particularly fruit) through capsid feeding lesions. In addition to symptoms at sites of capsid feeding, systemic plant effects may also occur through the translocation of injected capsid saliva, leading to chlorosis, necrosis or distorted growth of plant parts that were not attacked directly.

The egg-laying behaviour of capsids is another source of potential injury to crop plants. Many insect species within the mirid family insert their eggs into the tissues of the host plant. This “endophytic oviposition” helps to protect the eggs from desiccation and natural enemies (Wheeler, 2001). The number of punctures made by the female’s ovipositor generally exceeds the number of eggs that she deposits, and this behaviour may cause significant damage to growing plant tissues. For example, the tarnished plant bug (*Lygus lineolaris*) is a widespread capsid pest in the USA, causing feeding damage to several important crops (Young, 1986), but can also cause apple tree stems to split following insertion of eggs (Howitt, 1993). Capsid oviposition injury to UK crops has also been recorded, for example damage to young apple fruit was reported to be caused by *L. pratensis* (Collinge, 1912). While insertion of the insect ovipositor contributes to such damage, the mouthparts of capsids are also involved in causing injury to plants during egg-laying (as a separate behaviour to feeding activity). Females of some species initially probe the plant tissue with their stylets before inserting the ovipositor into the same puncture site to lay an egg (Conti et al., 2012).

Capsids may cause significant damage to crops, even at low densities. One insect per 40 plants was estimated to be sufficient to cause losses in some soft fruit crops (Cross, 2004). Recent experiments with strawberries grown in tunnels indicated that, even in years with very low populations of capsids present (e.g. means of 0.02 adults and 0.02 nymphs of ETPB detected per plot of 50 plants using tap sampling in 2018), fruits developed substantial cat-faced damage during the sampling period (Fountain, 2019). Capsids are highly mobile and are therefore able to re-colonise crops quickly after control measures are applied. Their ability to react and disperse rapidly also means that they tend to escape predators / parasitoids and in the UK they have not been controlled effectively using biological methods. Their elusive habits and tendency to quickly drop to the ground or fly / run away when disturbed, means that capsids can be difficult to detect during crop inspections. By the time that plant damage becomes apparent, the insects may well have moved away from the crop. Although the prevalence of capsids tends to be sporadic and unpredictable, the damage they cause can be extensive. In late-season strawberry crops, for example, over 50% of fruit may be downgraded as a direct result of capsid feeding damage (Fitzgerald, 2010).

Capsids cause significant losses in several horticultural crops, but tend to be relatively minor pests of arable crops in Europe. For example, although the potato capsid *Closterotomus norwegicus* may become abundant in UK potato fields and damage crop foliage, it is a more common problem on chrysanthemums and carrots (Alford, 1999). Similarly, CGC may be abundant in crops such as beet, swede and potato, but has a larger economic impact on fruit crops and occasionally on protected ornamentals such as chrysanthemums (Alford, 1999).

Pest species and identification difficulties

The majority of UK crop invasions and damage by capsids are attributed to two species that are capable of feeding from a wide variety of plants: ETPB, *L. rugulipennis*, and CGC, *L. pabulinus*. ETPB is a relatively new pest in the UK, first reported damaging strawberry plants and fruit in the early 1990s, and has also become a pest of other outdoor and protected crops including glasshouse cucumbers. Adult ETPB are approximately 5-6 mm in length and variable in colour, from yellowish green to light or dark brown, with the scutellum distinctly visible as a lighter-coloured triangular or “V”-shaped area. Over-wintering adults of ETPB tend to be darker in colour than those of the summer generations. Adult CGC can be a little larger (5-7 mm) and most of the body is a uniform shiny green colour, with the exception of the hind end, where the membranous wing tips are visible as a dull brown area. The CGC has been established as a pest of UK crops for many years, particularly causing damage to apples and pears. These two species have different over-wintering strategies, with ETPB passing the winter as diapausing adults, but CGC surviving the colder months as diapausing eggs.

Despite the above general descriptions of these key UK pest species, identification of capsids to species is often extremely difficult. It is likely that even the most important pest species, including ETPB and CGC, are frequently misidentified and confused with similar species. For example, the identity of UK-collected specimens within the genus *Lygus* (which includes ETPB) can remain unresolved, even when examined by expert taxonomists (Nau, 2004). ETPB is extremely difficult to identify and discriminate from the four other British species in the genus: *L. pratensis*, *L. maritimus*, *L. punctatus* and *L. wagneri*. It is assumed that these other four British *Lygus* species have relatively localised distributions compared with ETPB and they are not currently considered as important pests, although *L. pratensis* has been reported as a pest of apples in the past (Collinge, 1912) and has expanded its range considerably in recent years (Bantock and Botting, 2018).

Similarly, capsid damage in apple and pear may be caused by either (or both) of two species in the genus *Lygocoris*: the widespread and relatively polyphagous CGC (*L. pabulinus*) and the apple capsid *L. rugicollis,* which has a more scattered distribution but can be abundant in some areas. Both species are relatively large, glossy green capsids and are very easily confused with each other and with additional, non-pest capsids (e.g. species in the genus *Orthotylus*) that may also be present in the crop production environment but do not feed on fruit crops (Bantock and Botting, 2018). While the above difficulties apply to the identification of adult forms of capsid pests, it is often the developing nymph stages that are responsible for crop damage, and identifying such immature stages to species level is likely to be even more problematic.

Monitoring and Insect Development Models

Capsid adults and nymphs readily drop from foliage when disturbed, and this can be used as the basis for sampling and monitoring. The foliage of plants can be brushed or shaken by hand to dislodge capsids at regular positions across the crop area (Cross, 2004). In crops where polythene mulches are used, dislodged insects can be easily spotted at ground level to allow counting and recording (Cross, 2004). In other crops and field margins, shaking or tapping plant parts with a large plastic tray held directly below is an effective method for the rapid detection and counting of insects (Xu et al., 2014). In celery crops, capsid pests are located in the centre of plants where they feed on and damage new growth. Sampling of such plants needs to be destructive and involves shaking whole uprooted plants inside a closed plastic bag (Collier, 2017).

Researchers at NIAB EMR and the Natural Resources Institute (University of Greenwich) collaborated on a series of projects to identify the sex pheromones of UK capsid pests and develop effective lures and traps for monitoring numbers. Components of the female-released ETPB pheromone were identified and were attractive to males under field conditions if released from glass microcapillary tubes (Innocenzi et al., 2005). Sex-pheromone-baited traps have subsequently been developed for both ETPB and CGC as part of AHDB Project SF 276 (Fountain and Jacobson, 2012). The traps and associated pheromone lures are commercially available to UK growers (supplied by Agralan Ltd). Traps placed in and around crops can provide an early warning of capsid invasion and damage, with a treatment threshold of 10 ETPB per trap recommended for insecticide sprays to outdoor and protected strawberry (Fountain and Jacobson, 2012).

The use of forecasting models for capsids can potentially improve understanding of when these pests are likely to arrive in crops and the likely timing for emergence of a second generation. As part of AHDB Project SF 114, a temperature-based phenological model was developed to predict the timing of development of ETPB. Capsid population patterns predicted by the model agreed well with observed data, suggesting that it could be used to assist growers in predicting the timing of arrival of first-generation ETPB in strawberry crops (Xu and Fitzgerald, 2013). Such forecasting approaches could therefore potentially help to inform the future deployment of pheromone traps or applications of insecticides (Xu et al., 2014).

Cultural Control and Management

As adult capsids often over-winter in leaf litter, removal of leaf debris and other dead plant material can help to reduce numbers in spring (Buczacki and Harris, 1998). Weed control is also important to remove alternative host plants that harbour capsids in and around the crop, so timely removal of weeds through mowing, mulching or herbicide application can be used to help keep capsid populations in check. However, removal of weeds when they support large populations of capsids (e.g. by strimming) may only encourage the pests to move away from these plants and invade neighbouring crops. The timing of weed removal can therefore be critical. Some apple rootstocks produce early-season sucker growth with leaves appearing before emergence of leaves from the main canopy. This early, low-level foliage has been observed to harbour capsids and other pests, and growers are advised to trim at an early stage as part of good practice to minimise capsid problems (AHDB Apple Best Practice Guide, 2018). Where possible, avoiding growing different capsid-susceptible crops in close proximity may be prudent. For example, nearby strawberry crops are suspected to be sources of capsids damaging cherries and top fruit when the trees are in close proximity to soft fruit production.

Trap crops have been explored as an approach to capsid management in some countries. In California, growers of organic strawberries have planted alfalfa trap crops close to the strawberry plants (Hagler et al., 2018), for example with the trap crop around the perimeter of smaller crop areas or inter-cropped in rows interspersed within larger crops (with the trap crop occupying approximately 2% of total crop area). *Lygus* pest species have a preference for alfalfa over strawberry plants, and growers can conveniently target the trap crop with their control measures, for example mechanically removing the pests using tractor-mounted vacuums (Swezey et al., 2007). In Australia, growers are also encouraged to plant strips of alfalfa (lucerne) as a trap crop, to reduce the movement of capsid pests into cotton crops (Cotton Pest Management Guide, 2018). In Italy, strips of alfalfa were also demonstrated to have potential as a trap crop, reducing damage by ETPB to some varieties of lettuce (Accinelli et al., 2005). The potential benefits of growing trap plants around strawberry plots were also investigated in the UK. Unfortunately, the presence of barrier strips of chamomile (*Matricaria recutita,* synonym *M. chamomilla*) or alfalfa (*Medicago sativa*) around strawberry plants had no significant impacts on numbers of ETPB within the crop (Easterbrook and Tooley, 1999).

There is a lack of reports of varietal resistance / susceptibility to capsids, probably because these pests are so highly mobile and opportunistic in their feeding habits. For example, all apple and pear varieties are susceptible to damage by CGC (AHDB Apple Best Practice Guide, 2018).

Physical removal of capsids from plants is possible using suction devices, and tractor-mounted vacuums have been used extensively in organic strawberry production in the USA (Swezey et al., 2007). On a smaller scale, growers have also used hand-held vacuums ("bug-vacs") to remove capsids and, for example, vacuuming of strawberry crops using these devices is recommended to help manage *Lygus* pests (Strawberry Pest Management Guidelines, 2018). However, this approach may also remove generalist naturally-occurring predators and released biocontrol agents. Vacuum-based removal of capsids from strawberry plants has also been trialled in the UK and had an impact on capsid numbers if carried out frequently, but was not found to be a cost-effective control method (J. Cross, pers. comm.).

Natural Enemies and Biological Substances

Predators

The contributions of natural predation to capsid mortality, and the main predator groups consuming these insects, are poorly understood. Wheeler (2001) discusses the roles of generalist predators, such as spiders and flower bugs (anthocorids) in predating mirids, and reviews the published information that is available on numerous groups of natural enemies gathered from several countries. In cotton production in the USA, where the Western tarnished plant bug (*Lygus hesperus*) may have a high economic impact, "big-eye bugs" in the genus *Geocoris* have a particularly high potential to suppress populations of the pest (Zink and Rosenheim, 2008). In Australia, lynx spiders (e.g. *Oxyopes molarius*) are prevalent predators in cotton crops and play important roles in reducing populations of green mirids (*Creontiades dilutus*) and damage to cotton bolls (Whitehouse et al., 2011). Such generalist predators therefore play important roles in suppressing populations of capsids. However, while capsid predator communities have been described and evaluated in overseas cropping systems (e.g. in organic strawberry in the USA; Hagler et al., 2018), there is very little information available on levels of predation of capsids in UK cropping systems, and the predators groups responsible.

Collier (2017) investigated predation of adults and nymphs of the UK capsid pest species *Orthops campestris* by various groups of wild-caught generalist predators (including earwigs, spiders, ladybirds, lacewing larvae, damsel bugs and pirate bugs). Spiders and earwigs showed particularly good potential to feed on capsids, although these laboratory experiments did not give predators a choice of other prey types (they were confined in Petri dishes with high predator:capsid ratios) and replication was limited. The commercially-available predators *Orius*, *Atheta* and *Macrolophus* also showed some potential to consume and kill the capsids (Collier, 2017).

Parasitoids

Parasitism of UK capsid pest species has been reported, but rates appear to be low and variable between different host plants. For example, Solomon (1969) recorded 25% parasitism rates of CGC by parasitic wasps (*Leiophron* sp.) on nettles close to apple orchards, but found no parasitized capsids on apple host plants. The braconid wasp *Peristenus pallipes* has been recorded as a native UK nymphal parasite of ETPB, but unfortunately parasitism rates in the field have been very low (Cross, 2004). Studies carried out overseas suggest that classical biocontrol approaches have potential for management of capsids. The parasitoid species *Peristenus digoneutis,* for example, is an effective parasitoid of ETPB*,* although is not reported to be present in Britain. This species was discovered in northern Europe by staff of the USDA European Biological Control Laboratory and released against *L. lineolaris* in the north-eastern USA by the USDA Beneficial Insects Laboratory (Coutinot et al., 2005). The insect is able to parasitise *L. lineolaris* and *L. hesperus*, two closely-related North American pests of many crops which lack effective native parasites. A large-scale rearing method has been established for *P. digoneutis* (Whistlecraft et al. 2010) and releases have been linked with reduced tarnished plant bug numbers in New Jersey alfalfa by 75%. Researchers in New York and New Jersey demonstrated that this parasitoid will also fly into apples and strawberries and parasitize *Lygus* pests on those crops (Day, 2018). Releases of *P. digoneutis* and another introduced *Lygus*-specific parasitoid (*Peristenus relictus*) have, in combination with the deployment of alfalfa trap crops, been associated with a progressive decline in the prevalence of *Lygus* damage in Californian organic strawberry production since 2002 (Pickett et al., 2017).

Entomopathogens

Entomopathogenic fungi that are commercially developed as crop protection products tend to be strains that are originally isolated from widespread pest species such as whiteflies and aphids, rather than capsids. Strains of *Beauveria bassiana* were isolated from mirid samples collected in Ghana and reported to have relatively good efficacy against pests of cocoa (Padi et al., 2002). However, these mirid-targeted fungal strains have not been developed further for commercial use and pyrethroid and neonicotinoid insecticides remain widely used for control of mirids in Africa.

In the UK, bioassays have been carried out with capsid pests to investigate the potential of Naturalis-L and BotaniGard WP for control. These products contain spores of *B. bassiana* from strains originally selected for activity against whiteflies. A single application of Naturalis-L reduced numbers of *L. rugulipennis* adults by 60% compared to untreated controls (Jacobson, 2000). A sequence of three sprays, each of which contained larger numbers of spores than used previously, reduced numbers of capsids by 78% of untreated controls (similar results were recorded for both Naturalis-L and BotaniGard WP; Jacobson, 2000). Repeated applications of entomopathogen-based products therefore have potential for suppressing numbers of capsids.

Recent research in California has explored the potential of *B. bassiana* to become endophytic, and therefore remain potentially active within strawberry plants. The fungus colonised and persisted in plant tissue for up to 9 weeks after application (Dara, 2013; Dara et al., 2013). In laboratory bioassays, direct application of *B. bassiana* to *L. hesperus* adults resulted in high levels of mortality, but no effect of the pathogen on capsid numbers was observed in glasshouse or field studies (Dara et al., 2013). When investigating the potential application of entomopathogenic fungi for control of capsid pests, it is important to also consider their impact on beneficial arthropods. Portilla et al. (2017) demonstrated mortality of

L. lineolaris following spray applications of *B. bassiana* spores directly to the insects, but beneficial insects (including predatory lacewings, *Chrysoperla rufrilabis,* and honeybees *Apis mellifera*), were also killed by this treatment. However, it is important to note that insects would normally pick up spores through contact with treated foliage, so such direct-contact bioassays may over-estimate the impact of entomopathogenic fungi on pests and beneficials.

Botanical insecticides

Plant-derived insecticides have been tested against sap-feeding insects, particularly aphids, and have potential to control these pests (Pope, 2017). Limited information is available for UK capsid pests, but the neem-derived plant secondary metabolite azadiractin has shown potential for control of *Lygus* in the USA. In field trials, applications of neem-based products, containing azadiractin, gave effective control of *L. hesperus* and the beneficial effects were comparable with the protection offered by conventional synthetic insecticides (Dara, 2013).

Naturally-occurring insecticidal pyrethrins are available in the UK (e.g. as the products Pyrethrum 5 EC and Spruzit) and can be applied to crops (including by organic growers) to provide some control of numerous pests including capsids.

Synthetic Insecticides

Before 2016, when approvals were withdrawn for application of chlorpyrifos to UK crops, this organophosphate insecticide was relied on extensively to suppress pest numbers and damage in many of the horticultural crops affected by capsid. The particularly effective control of capsids provided by chlorpyrifos was demonstrated as part of previous SCEPTRE trials at NIAB EMR (O'Neil, 2015). When chlorpyrifos (applied to strawberry plants as the product Equity) was tested in comparison with other treatments, it was associated with larger reductions in numbers of ETPB nymphs (85%) than other insecticides tested including indoxacarb (40%) (O'Neil, 2015). In laboratory bioassays, Fitzgerald (2004) demonstrated that the neonicotinoid insecticides thiacloprid and acetamiprid showed some efficacy against ETPB, but the industry standard chlorpyrifos was much more effective than these treatments. Pymetrozine (applied as Chess) can give good control of ETPB in strawberry (O'Neil, 2015) and has been relied on extensively to reduce capsid damage to other crops (e.g. cucumbers) but will not be available beyond January 2020.

The most effective products currently available for reducing capsid numbers and crop damage are pyrethroids, but these insecticides are damaging to beneficial insects (Fitzgerald, 2010). Without viable alternatives, growers tend to rely on sprays of pyrethroids and other broad-spectrum insecticides for capsid control (see Appendix 2). For example, the neonicotinoid thiacloprid (Calypso) and the pyrethroid lambda-cyhalothrin are standard treatments for capsid in several crops (Fitzgerald, 2010; O'Neil, 2015). However, these broad-spectrum products are only partially effective at reducing capsid numbers and have a negative impact on the natural enemies of other important pests.

Broader perspectives based on arable crops and research overseas

Although capsids are most important as horticultural pests in the UK, on an international scale this group of insects plays significant roles as pests of arable field crops. Examples include cotton (Wilson et al., 2018) and forage legumes (Schroeder et al., 1998). In tropical regions, several species of capsid bugs cause significant economic damage to cocoa trees, particularly *Sahlbergella singularis* and *Distantiella theobroma* in Africa and *Monalonion* species in Central and South America (McGavin, 1993). Several species in the capsid genus *Helopeltus* are also important crop pests, for example causing damage to tea, cashew and cocoa crops in India (Srikumar and Shivarama Bhat, 2013).

In cotton production in the USA, reliance on pyrethroid insecticides has led to resistance to these products in a key cotton pest capsid, the tarnished plant bug *L. lineolaris* (Parys et al., 2018), and some strains of the pest have developed resistance to pyrethroids and other classes of insecticides (Snodgrass, 1996). The large-scale adoption of *Bt* transgenic cotton to successfully control insect pests with chewing mouthparts has led to reductions in the use of conventional insecticides in the USA and Australia, and progressive increases in the population sizes and pest status of mirid bugs (Lu et al., 2010; Men et al., 2005; Wilson et al., 2018). As a result of these problems and the large global market in cotton crop protection, agrochemical companies have become more interested in research and development of capsid-active products in recent years. Research on capsids in the USA has also been focused on fruit crops, particularly strawberry production in California, where 88% of the US-grown crop is produced. Capsid species in the genus *Lygus* are particularly damaging pests in this crop, and controlling these insects relies on applications of broad-spectrum insecticides (Dara, 2013). Although the pest species are different, their biology, type of damage and pest management issues are very similar to those of UK capsid pests, and the close parallels with UK fruit production mean that researchers investigating improved control of capsids in California are a further source of relevant information.

In addition, as sap feeders, capsids are likely to be suitable pest targets for some of the new systemic products that have been approved recently, or new actives that are being developed, for control of widespread sap-feeding pests such as whiteflies and aphids. Although capsids feed from mesophyll cells, rather than directly from plant vascular tissue like aphids and whiteflies, insecticides that are mobile within the phloem or xylem systems are also likely to be taken up by capsids when they ingest sap following their extensive cell damage. Few systemically-mobile actives have been tested directly on capsid pests of UK crops and this review has also included contacting researchers in crop protection manufacturing companies, seeking to highlight promising materials with potential for experimental trials.

Identification of new opportunities for improved capsid control

Information was gathered from a variety of sources in order to produce a review of current capsid problems, available control measures and potential future leads. The following approaches were taken in order to access and collate relevant information:

1) Initial surveys: contact with agronomists and growers

In consultation with AHDB and NIAB EMR staff, an initial list of industry contacts was constructed as a starting point for information gathering. This was extended during the review process, through asking interviewees for further recommendations. The interviewees included agronomists / technical advisors and growers. However, under advice from AHDB, the list was biased towards agronomists and technical specialists, rather than growers, with the aim of interviewing key figures with experience spanning numerous sites of production and multiple crops.

Interviewees were contacted by telephone or e-mail, or visited in person whenever possible. Each person was asked the same set of questions (see Appendix 1), although some questions were more relevant than others, depending on each individual's role and experience. Interview questions, developed in consultation with colleagues at NIAB EMR and AHDB, were designed to cover:

- Crops commonly affected by capsid pest problems
- Type and impact of damage
- Capsid species responsible
- Timings and sources of pest infestation and damage
- Aspects of grower practice linked (positively or negatively) with capsid problems
- Current control strategies and their efficacy
- Issues with IPM compatibility
- Potential leads (novel products or approvals of existing products)
- Potential contributions of natural enemies (released or endemic) to capsid mortality
- Trends and patterns of capsid problems during last 5-10 years
- Future concerns

2) *Further surveys: contact with researchers and crop protection specialists*

Initial interviews were complemented by internet-based information searches, to identify further international experts to contact, particularly in the USA, Australia and Europe. These included pesticide regulatory experts, and researchers and technical advisors based at pesticide manufacturing companies, government agencies and universities. They were specifically asked to provide information on mirid crop pests, products currently used for control and any new products being developed.

Interview results

Responses of the agronomists and growers contacted are summarised according to crop (Appendix 2). However, some generic issues and priorities for further research emerging from this survey are highlighted here.

Trends towards increased capsid problems in recent years

In general, there was a tendency to report that, although capsids remain secondary pests with potentially high but sporadic impact, the insects have become more important pests in recent years (see Appendix 2). Interviewees were consistent in suggesting three main inter-connected reasons driving the increased impact of capsids:

- Withdrawals of available insecticides used to control them. Withdrawal of chlorpyrifos was the most commonly-cited factor associated with increased capsid problems, although it was recognised that this does not fully explain the trends (e.g. in cherry production, where chlorpyrifos was not previously available, growers have also seen capsid problems worsen).
- A trend towards increased reliance on biological control for management of other pest groups, particularly thrips, mites and aphids.

- A trend of increasing average temperatures.

Sources of capsids

Proximity to hedges and woodland were considered major risk factors for capsid damage by several interviewees. Common nettle (*Urtica dioica*) was universally highlighted as the main weed harbouring capsid pests (ETPB, CGC and nettle capsid). In addition, some interviewees mentioned other specific weed species that are abundant in headlands and other farmland habitats and provide food and shelter for capsids, including knotgrass (*Polygonum aviculare*), fat hen (*Chenopodium album*), docks (*Rumex* species), chamomile (*M. recutita*) and yellow cresses (*Rorippa* species). While these plant species were highlighted as likely candidate host weeds for the polyphagous pest species CGC and ETPB, these links have been made through field observations rather than evidence based on replicated sampling. The major capsid pest of celery crops (*O. campestris*) is a selective feeder and weed species within the celery (Apiaceae family) are targeted as part of management strategies, although it is not clear whether specific species of Apiaceae are favoured host plants of the pest. One interviewee raised concerns linked to the withdrawal of herbicides, limiting control options for weeds within polytunnels. However, other specialists advised that capsids tend to move into crops from weeds that are outside of tunnels (e.g. from headland areas where herbicides are not applied). Some interviewees had observed capsid adults overwintering in leaf litter and it was generally accepted that clearing away crop debris can help to alleviate *in situ* capsid problems.

Concern was expressed regarding the increased use of seed mixes to enhance biodiversity in orchard alleyways. The advantages of this approach, providing food sources and refuges for natural enemies and pollinators, may be offset to some extent by encouragement of capsids populations. However, it is not clear which (if any) of the plant species in the seed mixes sown to enhance the natural ecology of orchards may be acting as alternative hosts for capsid pests. In addition, the effects of biodiverse alleyway sowings are currently being tested as part of AHDB Project TF 223. This project includes assessments of capsid damage to apple and there is currently no evidence to support any (positive or negative) effects on capsids. However, this is a long-term trial and only 1 year of data has been collected so far.

Control options for capsids

Interviews highlighted the lack of availability of relatively selective insecticides for control, and the consequent reliance on broad-spectrum active ingredients, as the most important current capsid issues. Concerns were expressed regarding options for future capsid control, based on possible future withdrawal of the actives that are currently available and the limited compatibility of products with biological controls. The demand for a capsid control programme that is compatible with biologicals is particularly high in fruit crops such as strawberries and cherries, where growers risk the collapse of the IPM system and resurgence of thrips and mite damage if the currently-available insecticides are applied for capsid. In particular, July represents a crisis month for strawberry growers, when Western flower thrips numbers are high and maintenance of healthy populations of predators (mites and *Orius*) is vital for thrips control. This presents a “no win” situation for growers, as action taken against capsids to minimise losses through cat-facing of fruit leads to increased thrips numbers and bronzing losses instead. This period also coincides with build-up of spotted-wing drosophila (SWD), which is likely to trigger further IPM-disruptive applications of pesticides.

Calypso (thiacloprid) was the most widely cited insecticide product used against capsids, although some interviewees said that it has limited efficacy against capsid, only killing the pests if they are hit directly. Despite the general feeling that Calypso has limited efficacy, it is relied upon extensively for control of capsids and its likely withdrawal within the next two years is cause for serious concerns among growers. Additional concern was expressed that, although acetamiprid is available as an alternative neonicotinoid active, there is less confidence that this insecticide is effective against capsids.

In top fruit, flonicamid is available (e.g. as MainMan) and is used for aphid control (up to 3 treatments per crop). While the use of this active against capsids is untested, it is a relatively slow-acting insecticide and one agronomist expressed doubts that it will be fast enough to protect crops against capsids.

Natural enemies

The survey highlighted gaps in current knowledge regarding predation of capsids. Interviewees had not observed natural enemies predating capsids and were therefore not able to provide information on natural predation. However, there was a strong suspicion from several technical advisors that *Orius*, released for thrips control, may also be predating capsids in soft fruit. This was based on a perceived negative relationship between the abundance of *Orius* within crops and capsid numbers. When this was followed up through internet searches, it was found that anecdotal reports from Canada (Ferguson et al., 2012) suggest that *Lygus* bug populations are suppressed in glasshouse pepper crops when *Orius insidiousus* is well established in the crop environment. There are also reports of researchers observing *Orius* adults attacking *Lygus* nymphs (Ferguson et al., 2012).

Technical specialists advising on top fruit suspect that earwigs may play roles in predating capsids. A PCR-based approach has been used to amplify DNA from the gut contents of earwigs collected in UK apple orchards and demonstrated that earwigs consume apple leaf midge and rosy apple aphid (Fizgerald, 2009). However, targeted PCR primers based on capsid DNA sequences were not used in this previous study and trophic links between capsids and earwigs remain to be investigated.

Use of semiochemicals

The agronomists interviewed advised that they use beating methods and tray sampling to assess capsid numbers, rather than the pheromone traps that are commercially available. Such direct sampling of the crop was considered to be worth the extra effort and more reliable in terms of detecting pest presence and assessing population levels. In addition, tap sampling gives information on the immature stages of capsids that pheromone traps cannot provide. However, use of pheromone traps can give growers a 2-week warning of the occurrence of first capsid nymphs in strawberry, following an increase in adult trap catches (M. Fountain, pers. comm.). While pheromone traps are currently available for two UK capsid species (ETPB and CGC), further research will be needed in order to identify the pheromones of other capsid pests (e.g. *O. campestris* and *N. tenuis*) and develop effective traps for these species.

Opportunities to develop the use of pheromones were also discussed as part of possible future targeted control strategies. For example, in apple and cherry, where CGC causes particularly significant damage, pheromone traps could be used to monitor pest numbers in late summer / autumn (August/September), when adults are present and females insert their over-wintering eggs into soft shoots of the current season's growth and rootstock suckers. A clean-up application of insecticide at this time, informed by pheromone trap catches, could be beneficial in reducing capsid damage the following spring.

As part of a current AHDB project (SF 156), synthetic semiochemicals are being used to evaluate a "push-pull" approach to reducing damage by ETPB and CGC in strawberries, and this approach was also discussed during some interviews. Sachets releasing the repellent volatile hexyl butyrate are applied to the crop area to provide a "push" to the pest, while pheromone traps placed around the perimeter of plots release an attractant "pull" signal to lure capsids away from crops. Results collected in 2017 showed that the combined push-pull was associated with significantly reduced capsid damage scores from fruit picked from treated plots, compared with fruit from untreated control plots (Fountain et al. 2017; Fountain, 2018). This approach is being developed and tested further, although unfortunately the significant benefits of the push-pull treatments were not repeated during the 2018 field season under much lower pest pressure. In future, the push-pull approach could be extended to tree fruit, for example combining hexyl butyrate-releasing sachets positioned in trees with perimeter pheromone traps. With further improvements in trap design and lure efficacy, it may also be possible to develop mass trapping approaches for capsid control (Fountain et al., 2015).

Identification of new leads

Synthetic insecticides

Contact with technical experts and researchers internationally led to the identification of new leads with potential for use in the UK. These include actives in IRAC groups 4C, 4D, 22, 23, 28 and 29.

Further novel actives with potential for control of capsids were identified and reviewed through discussions with technical and development staff representing multiple agrochemical companies.

Manufacturers were contacted during the information-gathering phase of this review and agreed to provide material for experimental testing against capsid pests if these are taken forward as part of SCEPTREplus trials. In addition, some actives currently under development were highlighted as promising new leads by the technical staff at some companies. For confidentiality reasons, these insecticides cannot be identified in this review but they include actives from IRAC Groups 4, 22, 23, and 29. Such products / actives in development will need to be tested and reported as coded treatments in SCEPTREplus experimental trials for capsid control, although this precaution will also be applied to any products that do not have current UK approvals for the crops used in the trials.

An additional synthetic active was identified with potential for capsid control, but this is unlikely to become available in the UK. In field trials with Californian strawberries (Joseph and Bolda, 2016), the benzoylurea insect growth regulator (IGR) novaluron (IRAC group 15, applied as the product Rimon), performed very well in terms of *L. hesperus* control without significant impact on the beneficial insects that were also assessed. Based on these encouraging results, the manufacturers (Adama) were contacted to explore their interest in providing material for UK-based experimental trials. Unfortunately, based partially on difficulties with regulatory approval of IGR compounds within the EU, Adama has taken the decision not to develop novaluron as a product for sale in Europe.

Using salt additives to enhance efficacy of insecticides

Research by Australian entomologists has shown that salt can be mixed with a reduced rate of insecticide to provide a level of control of mirids that is similar to the full rate alone (Khan, 2003). The rationale behind this approach was based on reports from the USA (later published: Hagler and Blackmer, 2007) that, in laboratory experiments, feeding by *L. hesperus* was strong strongly inhibited if 0.5% potassium chloride was added to artificial diets. This was therefore investigated as part of a combined (insecticide plus salt) synergistic approach (Khan et al., 2002). When a reduced volume (40 ml / ha at 200 g / L) of the insecticide fipronil was applied to the cotton crop mixed with table salt (sodium chloride at 7 g / L), an increased mortality of mirid pests was recorded, compared with the insecticide applied at the same low rate without added salt (Khan, 2003). The impact of this reduced-rate insecticide combined with salt treatment was similar to the efficacy of the standard full rate (125 ml / ha at 200g / L) with no salt added. However, the reduced rate of insecticide allowed a reduction in the disruption of spiders and some other natural enemies of mirids within the crop.

Similar results were found with indoxacarb, with addition of sodium chloride again allowing effective mirid control at reduced rates, leading to a reduced impact of the insecticide on beneficials. The advantages of the addition of salt are therefore a substantial reduction in costs (with insecticides applied at less than 50% of normal recommended rates) combined with a reduced impact on beneficial natural enemies. Based on this research, application of indoxacarb plus salt (sodium chloride) has become a recommended standard treatment for control of green mirid in Australia (Cotton Pest Management Guide, 2018).

Synergistic combinations of insecticides and salt additives may also have potential for improving capsid control / reducing impact on beneficials in UK crops. However, if trials incorporating salt additives are carried out, it will be important to investigate the potential problems that could arise from this approach, particularly:

- possible phytotoxicity and plant water stress caused by addition of salt;
- potential post-harvest problems with salt residues contaminating fresh produce.

Attract-and-kill capsules

Recently-developed microencapsulation methods are showing potential as a new approach to the formulation and delivery of insecticides. Microencapsulation has the advantages of combining controlled release formulations with improved handling safety during application, and has therefore been of interest for the delivery of several pesticides (Tsuji, 2008). Spherical capsules can now be produced, containing insecticides as part of a liquid core. The capsule shells can also be coated with an outer layer incorporating attractants for the target pest.

This technology has been refined in Germany recently (Katz Biotech, 2019), and is described in a WIPA Patent Application (WO2017/097282A1) for microencapsulated insecticidal control of capsids (*Lygus* species). The microcapsules have a liquid aqueous core and a diffusion-inhibiting outer shell. The core comprises insecticide(s) and possibly a *Lygus* feeding stimulant, whereas the shell incorporates at least one volatile attractant for the pest. Pests are therefore attracted to the capsules, which imitate a food substrate and trigger piercing behaviour by the insects' mouthparts. Insects then ingest the liquid contents, including the pest control agent.

Examples of insecticides that may be incorporated in the core, and would be active via ingestion, include lambda-cyhalothrin, spinosad and thiacloprid. The outer shell has the required stability to protect the killing agent from environmental degradation, giving the microencapsulated insecticide a prolonged period of activity following application. In addition, insecticide application to the crop can take place at a substantially reduced rate per hectare and the highly-specific method of targeting the pest helps to protect beneficial natural enemies and pollinators. The liquid core capsules are sufficiently robust to enable application to cropping areas using a conventional seed spreader, or may be distributed within crops by hand, e.g. applied as arrays of capsules adhered to small cards.

This technology therefore provides a potential route for the delivery of insecticides to capsids in a highly-specific and contained manner. Contact has been made with Katz Biotech AG during the preparation of this review and the company are interested in providing materials for testing as part of future UK trials.

Bioinsecticides

Plant-derived insecticides have the potential to control capsids, and were therefore also researched through contact with international experts and internet searches.

Other areas of future research

This review has also highlighted a lack of information concerning the roles of natural enemies in controlling capsid pests in UK crops. Further studies investigating the suspected role of released *Orius* as capsid predators would provide valuable new information. In addition, the roles of particular naturally-occurring predator groups should be investigated. International research has demonstrated the value of DNA markers for revealing relationships between predators and capsids. For example, Hagler et al. (2018) used *Lygus*-specific PCR assays to make trophic links between particular predator taxa and capsid pests in Californian strawberry crops. As an alternative to such targeted DNA marker approaches, next-generation sequencing (NGS) methods can also be used to analyse the gut contents of suspected predators to reveal trophic relationships (Teide et al., 2016).

Improved knowledge of associations between UK capsid pests and particular weed species would also help to develop more informed control strategies. Demonstrating that weed species provide alternative feeding and reproductive sites for capsid pests is challenging, as it requires confident identification of capsid species on weed and crop plants, combined with evidence that individual insects are feeding on these different hosts. Insect identification may be aided by mitogenomic methods, which have been applied to the sequenced genomes of mirid species and show potential for species identification based on NGS (J. Wang et al., 2017). DNA-based methods can also be used to provide evidence that particular weed species are alternative host plants for capsid crop pests. In China, association of an important polyphagous mirid pest (*Apolygus lucorum*) with different host plants has been revealed using PCR primers specific to cotton or mungbean plants. DNA from both plant species could be detected in the guts of individual insects, providing new insights into the movement and feeding ecology of this pest (Q. Wang et al., 2017). Similar techniques could be applied to investigate movement of UK pest capsids to and from suspected wild weed host plants, relative to migration in to and out of susceptible crops.

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Disclaimer

Approvals for applications of plant protection products to particular UK crops mentioned in this review were based on the responses of interviewees supplemented by searches using Fera (https://secure.fera.defra.gov.uk/liaison/) and HSE (http://www.hse.gov.uk/pesticides/topics/databases.htm) databases. This information is assumed to be correct at the time of writing but is subject to change. The information presented in this review should not be used as the sole basis for crop protection decisions such as product choice, number of applications or harvest interval. Neither the author nor

NIAB EMR accept any liability for plant protection decisions based on the contents of this work.

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Appendix 1: Questionnaire used as a basis for initial interviews

Survey questions

Section 1: Participant details

1. Name
2. Company or organisation
3. (If applicable) Size of the farm (hectares under production)
4. Role within organisation
5. Specialisation (e.g. conventional or organic farm/agronomy/products)
6. Time in current position

Section 2: Crop

1. What are the primary crops grown at the farm? / What are the primary crops you advise on?
2. With regard to capsids, what are the crops that are most susceptible or experience the highest economic damage?
3. What is the reason for this susceptibility? (E.g. specific plant traits, growing conditions/system, difficulty achieving good coverage for PPPs, restrictions on PPPs)

Section 3: Pest

1. How frequently are capsids a problem (every year, most years, seldom)?
2. For this particular pest, what months does the problem usually occur? And, what stage of the season is that?
3. What damage is visible (description of symptoms)?
4. What pest monitoring methods are used?
5. Is it possible to estimate yield losses caused (£/ha, kg/ha, or % losses)?
6. Is it possible to highlight particular species of capsids having the greatest impact or are most difficult to control?
7. Why is this species more difficult to control or having higher economic impact?
8. What are the routes of the pests entering the farm/cropping area? (e.g. association with weeds?)

Section 4: Control questions

1. What are the management strategies currently used? Biological only, conventional chemistry only, IPM strategies, etc.
2. What products are currently used? What rates are they used at? How often?
3. How well do the current control strategies work?
4. Are there any concerns about them continuing to work? Resistance, loss of registration, other issues?
5. What other management strategies and products have been tried in the past?
6. Why are they no longer used? Are they no longer available, were not successful, too expensive, unsafe, etc.?
7. Are any new products expected in the next 18 months? Conventional chemistry, new actives in development, biological, nets/barriers, other?
8. How important is IPM compatibility?
9. How important is crop hygiene for controlling the pest?

Appendix 2: Questionnaire responses summarised according to crop

Many crops are affected by capsids in the UK. It was not possible to thoroughly research every crop susceptible to damage by this group of pests within the limited resources and time available for this review. However, interviewees contacted were able to provide information on crops in a variety of sectors, including soft fruit, top fruit, field vegetables and protected edibles.

Soft fruit

Several of the technical advisors interviewed identified soft fruit (particularly strawberries) as the crops that are most susceptible to regular capsid damage.

Strawberries

- Capsids continue to present large and regular problems for strawberry growers, both for crops protected under tunnels and grown in open field situations.
- June bearer crops may be attacked by capsids but everbearers are more susceptible and can be written off completely following late season damage.
- Capsids have become a bigger problem in recent years, since growers have switched to relying more on biological controls for other pest groups (particularly thrips) and applications of broad-spectrum insecticides have been reduced.
- Common green capsid may be present but European tarnished plant bug is recognised as continuing to be linked with most capsid damage (misshapen fruits). One agronomist highlighted nettle capsid damage to strawberries, recognising that this species is a more minor problem compared with ETPB.
- July is the peak in terms of capsid numbers and can be a crisis point for growers. Western flower thrips numbers are also high at this time, so maintenance of good populations of predators (mites and *Orius*) is vital for thrips control. This presents a "no win" situation for growers, as action taken against capsids to minimise losses through cat-facing of fruit leads to increased thrips numbers and bronzing losses instead.
- Capsid damage varies widely between different farms and years. Several interviewees highlighted a link between the nature of the local habitat and risk of capsid damage (e.g. proximity of woodland and hedgerows, weeds close to or inside tunnels).
- There is a trend for fewer everbearer crops to be kept for a second year, which is one factor that is tending reduce capsid pest damage.
- Thiacloprid (e.g. Calypso) was widely cited as the preferred insecticide applied for capsid when action becomes necessary, and a current EAMU allows for its use against capsid in protected and outdoor strawberry. Lambda-cyhalothrin (e.g. Hallmark) and deltamethrin (e.g. Decis) are also applied for these pests, although their approvals do not specify capsid. All these actives were reported to achieve effective knock-down of capsids, but several interviewees considered thiacloprid to be more effective, based on its systemic activity within the plant and a less damaging impact on biological controls than the pyrethroids.
- Although thiacloprid may continue to be available until 31/10/2021 (when EAMU expires for protected and outdoor strawberry), interviewees emphasised the urgent need for insecticides that have less impact on biocontrols to help alleviate the current "cat-faced *vs.* bronzed" July dilemma.

Cherries

Technical specialists with expertise on several tree fruit crops advised that cherries represent the tree crop with highest susceptibility to capsid damage.

- Cherries are regularly damaged by capsids, with losses in the 10-20% range possible.
- Several interviewees with expertise in this crop reported that capsid damage has become worse in the last 2-3 years. It was reported that all cherry growers now have some degree of capsid damage every year.
- The reasons for the higher impact of capsids in recent years were not clear as, unlike in several other crops, it cannot be linked to loss of chlorpyrifos (this active was not previously approved for cherries). The increasing impact of capsids may be linked to climatic factors and / or the trend towards increased protection of cherry crops, although unprotected cherry crops are also affected.
- Cherries are particularly susceptible to capsids from the end of flowering until the start of fruit set (dependent on flowering time but generally towards the end of April).
- Feeding damage becomes visible on fruit, leading to distortion. Misshapen fruit is the biggest problem, and 5-10% losses are seen regularly.
- Damage also occurs later to new growth (meristems and emerging leaves), leading to holes in expanded leaves and potentially very large reductions in leaf area for photosynthesis. The impact of this foliar damage on yield is difficult to quantify, but one grower described the appearance of the crop in late summer as looking like "someone has been through the trees with a shotgun".
- CGC is highlighted as the capsid species responsible (detected through beat / tray or sweep net sampling at the time of damage).
- Ideally, insecticides would be applied at the start of capsid arrival and damage, but in practice they are often applied too late, once damage is detected.
- It would be feasible to apply insecticides in the autumn, when CGC adults are laying eggs on cherry. This could be combined with monitoring using pheromone traps in order to optimise the timing of such autumnal clean-up sprays. This approach has been discussed with growers and researchers, but has not yet been tried or evaluated through trials.
- Hallmark is considered to be effective against capsids if it can be applied with appropriate timing. Two applications per season are available, but growers may be reluctant to use it to target capsids due to the impact on beneficial natural enemies and pollinators, and the need to keep applications in reserve for later use against SWD.
- Calypso and Gazelle (acetamiprid) are currently available but were considered to be less effective against capsids in this crop.
- Batavia (spirotetramat) is approved for the crop but is limited to application after flowering and therefore cannot be deployed at the critical period to prevent capsid damage to fruit.
- The potential for exclusion netting (for SWD) also providing protection against capsids was discussed. However, some growers of protected cherry already deploy SWD netting early in the season (April) and these are not providing protection

against capsid. This is likely to be because spring damage is being caused by CGC nymphs that have hatched from eggs laid in the crop the previous autumn.

- There is high demand from cherry growers for products that could be deployed for capsid control without compromising the biological control of two spotted spider mite and western flower thrips.
- The widespread reliance on biologicals for thrips and mites, and the costs of increased damage by these pests following sprays targeted at capsids, makes decisions to intervene or tolerate capsids very difficult to judge. More evidence-based decision support is needed to help growers make these judgements.

Cane fruit

- Interviewees providing information on raspberry and blackberry also covered a variety of other fruit crops and tended to report more serious capsid damage on strawberry, cherry and top fruit, with capsids mentioned as relatively minor pests of cane fruit.
- However, CGC damage to primocane raspberries in July and August (with the second crop affected) was reported.
- CGC also occasionally damages blackberry crops, but ETPB was reported to be more damaging to blackberries.
- Capsid damage to high-value dessert blackberry cultivars can be a particular problem.
- In blackberry, capsids attack flowers and developing fruit, leading to distorted fruit at harvest, but do more damage through feeding on new vegetative growth.
- This damage to meristems can substantially reduce and delay next year's crop but also leads to excessive branching of plants (and loss of plant structure and accessibility for picking).
- Hallmark, deltamethrin and Calypso were specified to be the only effective insecticides available for control of capsids in cane fruit.
- One advisor with a cane fruit specialism highlighted the more effective and persistent activity of Calypso compared to other products available. Pyrethrum 5 EC is sometimes used and is more compatible with biologicals but has very limited persistence.
- Compatibility with effective controls of other pests was highlighted as a continued concern in cane fruit. In particular, applications of insecticides for capsids (and SWD) can disrupt control of mite pests (particularly twospotted spider mite) by naturally-occurring beneficials and the predators that are introduced by growers (e.g. *Phytoseiulus persimilis*).

Bush fruit

- Agronomists with blackcurrant expertise advised that some capsid damage can be observed in most years.
- Damage particularly coincides with a few weeks during and immediately after the flowering stage (from April through to May), is visible as feeding marks on the growing points, and may lead to stunting of the whole plant.

- Feeding damage to the young leaves of blackcurrants results in a lace-like “net curtain” appearance as the leaves expand and holes appear between veins. The species responsible is assumed to be CGC.
- However, capsids rarely have significant impact on yield because there is good incidental control as a result of the products that are applied for other, more important pests of blackcurrant (particularly aphids and winter moth). One technical advisor commented that when growers have tried avoiding insecticide applications targeting these other pests, capsid numbers and damage have been notably worse (with up to 5% crop loss).
- Calypso or Hallmark are applied as standard practice and give effective pest control within this crop.
- IPM compatibility may be an issue with these products (e.g. possible impact on earwigs, which may be providing good predation of sawflies) but this requires further research.
- There is concern that Calypso could be at risk as a result of current scrutiny of neonicotinoids.

Top fruit

- Apples are regularly damaged by capsids, with losses commonly within the 10-20% range.
- Capsids may also attack pears. Generally, they have not been such a big problem in this crop, although one top fruit specialist reported seeing increased capsid damage in pears during the last 2-3 years.
- Loss of chlorpyrifos had a clear impact in top fruit, with increased capsid problems since its withdrawal.
- The increased use of seed mixes to increase biodiversity in alleyways between tree rows may also have played a role in encouraging capsids in recent years. Growers tend to sow these mixes every 10-20 alleys, and it is notable that the trees bordering these alleys suffer more capsid damage. The mixes comprise a blend of annual and perennial plants designed to increase biodiversity, encouraging beneficial natural enemies and nesting bees. Such sympathetic plantings have been adopted increasingly over the last 10 years, but the potential roles of particular plant species in the mixes as alternative hosts for capsids are not known.
- Trees along the edges of orchards may be heavily damaged, particularly if they are close to areas acting as sources of capsids, such as woodland. Other crops close to orchards may also be a source of capsids, for example one grower advised that orchards close to hop gardens often suffer particularly heavy capsid damage.
- Green capsid species are associated with the damage. These are assumed to be CGC and apple capsid but are not examined and identified to species by those interviewed.
- As in cherries, damage to fruit occurs during a narrow interval (immediately after flowering for top fruit), usually a three-week period during May. This coincides with the period between petal fall and fruit reaching 12 mm diameter.
- The main problems are distorted and scarred fruit, and associated loss of crop and cost of thinning.

- Losses can be up to 50% from individual trees, especially those around the edges of orchards.
- Some growers may apply acetamiprid (e.g. as Gazelle). Calypso was reported to be particularly effective as a control for capsids in top fruit. However, only two applications per season are available in apples and pears, and growers are likely to have already needed to apply the product for other pests (e.g. apple blossom weevil or Rhynchites weevil) or may prefer to withhold its use for pest outbreaks (e.g. mussel scale) that may follow capsids later in the season. Pyrethroids are approved but some agronomists advise growers never to apply these in top fruit, such is their extreme impact on IPM.
- Batavia (sprirotetramat) was approved in 2018 for the control of sucking insect pests of top fruit. It may have some activity against CGC but this is not yet established. It can only be applied after flowering, but as this coincides with periods of post-blossom capsid damage, this product may prove to have some use against capsids in apple. However, growers are likely to want to reserve its use for control of aphids (e.g. rosy apple aphid and woolly apple aphid) later in the season.
- Flonicamid (e.g. Mainman) is another recently-approved insecticide with activity against sap feeders that is available for use in apples. The target pests are aphids and efficacy against capsids is not known. One agronomists expressed a lack of confidence in the use of flonicamid for capsid control, as it may not be fast-acting enough to protect crops against these mobile pests.

Stone fruit

Several of the advisors giving responses on fruit crops included plums and apricots in their remit, but none reported capsid problems on these crops.

Grapevine

The vineyard managers and advisors contacted did not report extensive capsid problems. The UK crop tends to receive comparatively low insecticide inputs in general, as it currently tends to escape heavy insect and mite damage. This may change in the future as the total area under production continues to increase in the UK. Capsids are present and cause some foliar damage, but the total leaf area lost is a tiny proportion of the crop. Hallmark is available for use and is occasionally applied for capsid, with good efficacy. The roles of natural enemies in reducing pest populations in UK grapevine is currently poorly understood, and it is difficult to assess what impact Hallmark applications may be having on natural biological control.

Dwarf hops

One agronomist highlighted dwarf hop production as an additional area where capsids cause regular pest problems. The pest is rarely a problem in tall hops, which have a more open canopy. The architecture of dwarf hops appears to suit the pest better, and capsids possibly benefit from the refuges provided by the over-wintering stems that are left *in situ* for dwarf varieties. The species responsible is CGC. The first generation of the pest causes some feeding damage to leaves (in April and May), but this does not have a high impact on the crop. However, in July / August the second generation feeds on flower buds. This stops the development of cones and is therefore much more damaging, with up to 50% of crop loss possible. Hallmark can be applied and is effective against capsids, but can only be used once per season in hops.

Glasshouse crops

Cucumbers

- Capsids (ETPB and CGC) are regular problems in cucumber production and have a particularly high impact on early growth.
- The crop is particularly susceptible when the young plants are growing up to the wire (at a plant height of approximately 1.5 – 2.0 m), when they have a single growing point.
- Capsids feed on the stem and growing point, leading to the death of the growing tip and cessation of growth. This can therefore be devastating when the young plants have a single growing point.
- After plants have reached 2.2 m and developed more growing points, they are less vulnerable, but capsids can still damage growing points and reduce yield.
- Feeding and oviposition damage also occurs to the young developing fruits, causing distorted growth and rejections.
- Growers produce three crops per year under glass. It is the second and third crops (in May and July respectively) that are damaged by capsids.
- Damage is caused by adults that have entered through vents. Netting is an available option but requires expensive modifications of glasshouse ventilation systems and is not deployed.
- Pheromone traps have been investigated as a method for trapping the adults and monitoring numbers, but these have not been adopted by growers, as capsids tend to be already damaging plants by the time they are detected in the traps.
- In the past, no effective IPM-compatible control measures were available for capsids and growers could only deal with the problem by applying broad-spectrum insecticides that disrupted the IPM programme.
- Since 2000, pymetrozine (e.g. Chess) has become the standard treatment and is very effective with repeated applications.
- Pymetrozine gives very good compatibility with the biological controls that are deployed for other pest groups (*Encarsia* wasps for whitefly and *Orius* / predatory mites for thrips).
- The imminent withdrawal of pymetrozine is therefore a major concern to cucumber growers, as they no longer have what are considered to be IPM-compatible control measures for capsids.
- Although Sequoia (sulfoxaflor) was recently approved for use in cucumber and may prove to have activity against capsids, it is limited to a maximum of two treatments per crop. Some growers perceive this active as a “neonic in disguise” and are reluctant to use it and put biologicals at risk.

Peppers

European tarnished plant bug and common nettle capsid are occasionally observed causing damage in protected pepper crops. Although capsid feeding at the meristem can be devastating to an individual plant, with the loss of the growing point and consequent failure to produce any fruit, this damage was described as rare and sporadic by the technical advisors interviewed. Interviewees advised that capsids do not cause direct damage to the fruit in this crop. One advisor, overseeing relatively large areas of peppers and cucumber under glass, said that capsid damage in pepper was insignificant compared with cucumber. When damage does occur in pepper, it tends to be very patchy within the glasshouse and only affected hotspots are then treated, which allows preservation of the biological control agents released for aphids and thrips. Insecticides, including acetemiprid and deltamethrin, may be used but growers rarely apply products specifically for capsid control. One grower had to go back “more than a decade” to recall the last time that insecticides were applied for capsids in the protected pepper crop.

Other glasshouse salad crops (lettuce, endives, spinach, pak choi, tomatoes)

Growers and advisors with expertise on the above crops were also contacted, but no capsid problems were reported.

Field vegetables

Celery

The susceptibility of celery crops in eastern England to capsid pests and the impact of control measures has recently been investigated (AHDB Project FV 441) and the main findings summarised (Collier and Norman, 2018). The capsid species *O. campestris* was confirmed as the pest causing brown scarring of stems and foliage through feeding damage and, in severe cases, destroying the celery heart

The R&D Coordinator of a large consortium of UK outdoor celery growers (including organic and conventional production) provided an update on capsid damage in the 2018 season and commented on overall trends over the last four years:

- In 2018, capsid damage to celery crops reached higher levels than previously recorded, with 30% crop damage recorded at the end of July and 75% damage expected by the end of the season. 100% losses are experienced by some growers in some fields.
- Numbers of capsid adults and nymphs are monitored regularly in the crop and have increased three-fold over the last 4 years (mean number of insects per square meter: adults = 2.4 in 2014, 7.4 in 2018; nymphs = 4.6 in 2014, 14.0 in 2018).
- In organic crops, covers made of fine netting are used, combined with applications of spinosad (Tracer).
- In conventional crops, lambda-cyhalothrin (Hallmark) remains the preferred insecticide, based on recent trials, and remains effective. Spinosad (Tracer) and deltamethrin (Decis) are also applied. Multiple applications of these insecticides are available (four of Hallmark and three each of Tracer/Decis) but these are insufficient to achieve effective control when pest pressure is high.
- Coragen (chlorantraniliprole) is approved for use in celery but not tested for efficacy against capsids.

- Capsids damage the crop for several months of each year. Pest problems start in June each year and continue until October.
- The abundance of host weeds around cropping areas provides alternative plants for capsid numbers to build up on. It is recognised that populations of *O. campestris* build up on “umbelliferous” weeds in the celery family (Apiaceae), although interviewees were unable to comment on particular species associated with capsids.

Hardy nursery stock

Industry representatives and technical advisors with experience of this sector were also contacted, but did not report capsid problems.