AHDB
AGRICULTURE & HORTICULTURE DEVELOPMENT BOARD

SCEPTREPLUS

Final Review Report

Trial code:	SP 24
Title:	**Southern green shieldbug (*Nezara viridula*): A review of control measures**
Crop	Protected Edibles / Solanaceae and Cucurbitaceae
Target	*Nezara viridula* (NEZAVI)
Lead researcher:	Dr Jennifer Banfield-Zanin
Organisation:	Stockbridge Technology Centre
Start date and duration	October 2018 / 6 months
Report date:	June 2019
Report author:	Dr Jennifer Banfield-Zanin, Dr David George, Dr Lauren Branfield
ORETO Number: (certificate should be attached)	N/A for a review

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

15.07.2019 J.A. Banfield-Zanin

Date Authors signature

Review Summary

Introduction

The southern green shieldbug (*Nezara viridula*) is already a significant pest of certain protected crops where it occurs in the UK, particularly on peppers. The insect can appear early in the season and has the potential to drive significant crop losses through the production period, both through direct feeding and the ability of this pest to spread crop disease and facilitate pathogen infection through plant parts damaged during feeding.

Though southern green shieldbug feed on all vegetative parts of the plant, the greatest impact is seen primarily in developing fruit and new growth. Feeding damage can distort and discolour fruit as it develops or, on larger fruit, resulting in hard brown spots and other surface damage. In addition to visual imperfections to the fruit, feeding on young fruits often leaves sticky regurgitated globules which require removal before point of sale.

Southern green shieldbug is easily confused with certain similar UK shield bug species, varying in appearance throughout its life-cycle. Positive identification is nevertheless possible in the field, aided by readily available hand-held or mobile-phone magnifiers and an AHDB Factsheet produced in 2012 to provide introductory information on pest biology and identification (Factsheet 36/12, Jacobson, 2012). Further details on separating this pest from similar species are provided in the Science Section of this review, though Factsheet 36/12 should be consulted as a more user-friendly guide to positive pest I.D.

While it is currently thought that the south-east presents the northern limit of southern green shieldbug in the UK, changing climate and a strong dispersal ability could facilitate movement to other parts of the country in the future. Southern green shieldbug can therefore be considered both an existing and emerging threat to UK protected edibles production, with a host range that could potentially expand this pest's significance into other sectors.

Given the above, the current review represents a timely update to our knowledge on possible control measures for this pest, with a view to informing further trials of promising plant protection products and IPM options. This work builds upon the previously published AHDB desk study, "PE 014: Peppers and aubergines: A desk study to identify IPM compatible control measures for *Nezara viridula* and *Anthomonus eugenii*" (Jacobson *et al*., 2013) and adopts a similar approach for continuity and ease of referencing between the two reviews. Though the current review does not aim to repeat the work undertaken in Factsheet 36/12 and PE 014, it refers to these documents throughout whilst updating our knowledge with information generated since 2012/2013 and incorporating industry input directly via a Grower Focus Group hosted by Gee Vee in April 2019.

In preparing the current review particular attention has been paid to biological control agents, biopesticides, chemical insecticides, basic substances, pheromones and semiochemicals for use in both monitoring and/or control, and other physical means of monitoring and/or control, such as the use of trap plants, barriers or light traps. Whilst maintaining a focus on southern green shieldbug, regular reference is made to closely-related pests, particularly the brown marmorated stink bug.

Summary

Monitoring

Visual observation appears to be the current norm for southern green shieldbug monitoring, based on crop walking with the addition of sweep-netting in more easily accessible and less fragile outdoor crops. Straight-forward, physical monitoring is labour-intensive, and not well-suited for use in high-wire glasshouse crops in the UK, particularly when mature. Though direct counting is currently being undertaken by growers, its effectiveness is dependent on factors including staff training and the stage of the pest/crop. The industry would therefore benefit from monitoring solutions that are easier to implement.

Use of light traps appears to hold promise for southern green shieldbug, and is commonly used for closely related pests, though trials would be needed to ascertain whether this approach is economical and compatible with modern production models. Use of pheromone traps is also a possibility, with commercially-available systems already on the global market for trapping similar species that could be of use for southern green shieldbug, particularly if modified to provide a light source and *N. viridula*-specific lures. Required trap densities would need to be investigated, however, to confirm whether this approach represents a cost-effective solution.

The efficacy of light and/or pheromone trapping could be improved through combination with trap plants. By drawing shieldbugs to certain areas of the glasshouse with highly attractive plants, it may be possible to increase the encounter rates of the shieldbugs with light or pheromone traps, improving the efficacy of monitoring by these means. Use of trap plants by themselves could also represent an interesting monitoring method, and potentially even a means of control, though work would be needed to identify appropriate trap plant species for use under glass, or to confirm the potential of those species that have been suggested to date (e.g. podding beans).

Behavioural and physical means of control

In addition to the possibility of using semiochemicals to attract and monitor southern green shieldbug, such products could also be useful in mating disruption. For southern green shieldbug, the possibility of disrupting mating through physical measures has also been suggested, using either physical barriers or plant-borne vibrational interference. Though it is difficult to envisage how physical barriers could be deployed within a glasshouse (above and beyond screening vents), it might be easier to distribute vibrational signals throughout a crop. This remains a highly novel technique, however, and further work would be required to demonstrate both effectiveness against southern green shieldbug and the plausibility of developing cost-effective engineering solutions to deliver this ‘treatment’. Best practice guidelines for cleaning down facilities after infestation with southern green shieldbug could also be beneficial to the industry, allowing overwintering forms of the pest to be better-targeted during periods when the glasshouse is empty.

Natural enemies

Though several species of natural enemies have been identified that hold potential for managing southern green shieldbug, including parasitoid wasps and flies, far fewer species are currently available to growers for release in UK glasshouses. Nevertheless, several generalist predators have been identified that may contribute to management of southern green shieldbug within integrated programmes, some of which are already readily available to UK growers. Though they would not be expected to target all pest stages, *Macrolophus* and *Orius* could potentially predate upon southern green shieldbug, with lacewings and ladybirds also warranting further investigation.

Basic substances

Overall, the literature suggests that physically acting 'biorational' products show mixed results in terms of demonstrating efficacy against large insects like southern green shieldbug, often being more effective against smaller-bodied pests. It is also worth noting that these products are typically relatively broad-spectrum and require short-interval repeated application to exert a meaningful effect on their targets, posing a potential risk to IPM programmes despite limited/zero residual activity, at least during high frequency application windows. Whilst their versatility and generally strong safety profiles support their further investigation as potential tools against southern green shieldbug, careful evaluation of these products should be undertaken within the context of overall glasshouse IPM programmes.

Biopesticides

When considering the different classes of biopesticides, it appears that microbial-based products may hold particular promise against southern green shieldbug, though work is still needed to confirm efficacies. Certain botanical products have also been shown to demonstrate efficacy against this and similar pests, and warrant further consideration on this basis, particularly given the increasing number of these products making their way onto the UK market. For both product types, care should be taken to ensure that trials are undertaken using commercially-relevant methodologies, where for many biopesticides the practicalities of field use (e.g. to ensure pest-product contact) may be more limiting to success than the activity of the product *per se*.

Chemical insecticides

Key literature pertaining to control of southern green shieldbug with chemical insecticides was reviewed by Jacobson *et al.* (2013), and since then there has not been significant work of note conducted on the subject. There nevertheless remain a number of potential actives that could, at least in theory, be useful in targeting southern green shieldbug. Several of these are already approved for use in protected edible crops, and some can be applied through irrigation systems (e.g. spinosad) and/or display systemic activity (e.g. acetamiprid). Such products should arguably be prioritised for testing against southern green shieldbug, ensuring levels of crop coverage and pest targeting that would be hard to achieve with non-systemic/non-translaminar products. In particular, products applied through the irrigation might be expected to cause minimal disruption to established biological control programmes that are already in place in most protected edible crops to manage other significant pests (e.g. thrips). Nevertheless, harvest intervals for such synthetic pesticides are often problematic in crops where fruit needs to be picked every few days.

Next Steps

- Though some IPM options identified through this review require further development and testing, use of, for example, pyrethroids and avermectins, as well as generalist biocontrol, vibratory disruption and physical barriers, all scored highly for industry interest. Trials to evaluate efficacy of near-market treatment options may be useful to industry.

- Support for other selected conventional pesticides, biopesticides and physically acting plant protection products was also evident. Certain interesting products that might control southern green shieldbug are already widely approved for use in protected edible crops, though validation of their full potential, particularly in full-scale glasshouse trials and in terms of IPM compatibility, is still required. A trial programme to screen these for efficacy, with consideration given to the role of appropriate application methods within high-wire cropping systems and to harvest intervals, may be of value.
- Further development of light/pheromone trapping, trap plants and use of barriers also garnered industry interest. Evaluation of these options as part of a monitoring and early exclusion approach may be of use to industry, as would investigations into what could be considered 'high risk' host plants that may be located in the vicinity of glasshouses, which may act as sources of the pest.
- Finally, exploration and evaluation of potential best practice guidelines for cleaning down facilities after infestation with southern green shieldbug could also be beneficial to the industry. Guidance on this aspect of control and how best to achieve it does not appear to be currently available.

Take home message(s)

- The southern green shieldbug can be a significant pest of certain protected crops, particularly peppers, where it occurs in south-east England. With its broad host range, good dispersal ability and against the backdrop of climate change, southern green shieldbug poses a risk to other crops throughout a broader geographic area.

- At present management options for southern green shieldbug are limited, though there is the potential to develop IPM programmes based on improved monitoring, chemical, biopesticidal and, potentially, biological control options.

- Protected edibles growers in the south-east should begin to monitor for southern green shieldbug early in the season, using information from AHDB Factsheets to identify the pest. Growers outside of the current UK range of southern green shieldbug, and in other sectors within its current range, should ensure that they are familiar with this pest, and be alert to the possibility of both host and range expansion.

- Growers wanting to explore novel IPM techniques to manage this pest could consider use of light traps and trap plants, as well as use of certain biological control organisms, although at present no firm recommendations can be made on the efficacy of these techniques against this pest.

Review

Introduction

Nezara viridula (L.) (Hemiptera: Pentatomidae), the southern green shieldbug, is a polyphagous pest, feeding on a wide range of plants of both agricultural and horticultural importance and presenting significant economic burden upon infestation in numerous crops. Also known under several synonyms (including *Cimex smaragdulus* Fab., *Cimex viridulus* L., *Nezara approximata* Reiche & Fairmaire and *Nezara aurantiaca* Costa), *N. viridula* is believed to be native to Ethiopia, though it is now widespread throughout tropical and subtropical regions. It had been imported into the UK on fruit and vegetable products for many years, and eventually was found in the wild in 2003. It has since become established in the south-east of England, finding a favourable environment in glasshouses in the north London and Lee Valley area. While it is currently thought that the south-east presents the northern limit of its potential outdoor range, thus confining the species, a changing climate is likely to expand this northward. Adult *N. viridula* are strong fliers, able to disperse naturally over large areas in warm weather, increasing the chance of range expansion. Furthermore, the likelihood that *N. viridula* could be transported further afield in the UK on either produce or packing materials, finding footholds elsewhere within heated, frost-protected glasshouse systems, is very high. These conditions would also allow the pest to overwinter successfully under glass.

In light of the serious impact that *N. viridula* can have on important food crops and the potential threat this pest represents for UK growers, AHDB (then HDC) commissioned several key pieces of work that precede this current review. A factsheet was developed to provide introductory information on pest biology and identification, to minimise unnecessary insecticide applications due to misidentification of the pest (Factsheet 36/12, Jacobson, 2012). In the same year an EAMU (Number 20121994) for lambda-cyhalothrin (Hallmark with Zeon Technology®) use against *N. viridula* in tomato, pepper and aubergine crops was also obtained, but while the product was effective it was also extremely harmful to biological control agents typically used as part of IPM programmes against other pests of these crops. Finally, also around this time, an extensive desk study and review was commissioned and published by AHDB (PE 014, Jacobson *et al*., 2013) to explore and identify control measures with potential for integration into IPM programmes for pepper and aubergine crops. The review encompassed a wide range of potential measures, from physical and cultural through biological and chemical control, across multiple life cycle stages and considering compatibility with IPM programmes and harvesting regimes.

It remains of critical, and mounting, importance that UK growers have access to IPM-compatible control measures against *N. viridula* in protected edible crop systems. Since the last review was published in 2013, further work by AHDB and others has been conducted on relatively closely-related pest species, such as other capsids and *Lygus*, in projects including FV 441 or the SCEPTRE programme. Much work has also been conducted on the increasingly prominent and invasive, closely-allied pentatomid pest, the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae). Such work is likely to provide insight into potential management strategies that may, or may not, be effective if deployed against *N. viridula*. The above in mind, the overall objective of this review is to build on the findings of PE 014 to explore understanding of current and potential control and monitoring options for *N. viridula*, with consideration of new literature published since 2013 and developing technologies.

Focus Group

An earlier draft of this review formed the basis of an industry focus group on *N. viridula*, which was held at Abbey View Produce Ltd on the 16th April 2019. The meeting was attended by a small but knowledgeable and highly informed group comprised of four growers/senior glasshouse managers, one consultant and one supply chain actor/distributor, as well as two STC staff and one AHDB representative. Attendees were asked to review the document draft and provide insights and feedback for incorporation into the final document presented here. These were gathered by means of open discussion and through completion of an input form by willing growers, in which they were asked to score various control options for industry interest, potential compatibility/feasibility in glasshouse crops, closeness to market and priority for further trials.

Target Description and Life-cycle

As temperature, day-length and light intensities increase in the spring, adult *N. viridula* emerge from overwintering sites and begin to mate (Todd, 1989). The barrel-shaped eggs are laid in the upper regions of crops on the undersides of leaves or pods as, usually, a polygonal 'egg mass', consisting of between 30 and 130 eggs firmly glued both together and to the plant material on which they were deposited (Todd, 1989; Jacobson, 2012), though larger masses have been reported (e.g. Waterhouse, 1998). Eggs have a conspicuous girdle of spines (Koppert Biological Systems, 2017), and as they develop change in colour from pale yellow at oviposition, through deep yellow, pinkish-yellow and then bright orange at hatching (Todd, 1989; Knight & Gurr, 2007). The hatched nymphs develop through five immature nymph stages before moulting into adults. The first instar tend to cluster on or near the egg mass and are not believed to feed until they moult into the second instar, at which point they also begin to disperse (Todd, 1989; Waterhouse, 1998). Instar duration depends on temperature and host food supplies, and multiple generations have been observed throughout a year, ranging from two to five depending on geographic region (Todd, 1989; Knight & Gurr, 2007).

Correct identification of *N. viridula* is important to distinguish the pest species from other native, non-pest pentatomid species, such as *Palomena prasina*, that sometimes stray into glasshouses but do not cause economic damage. Adult *N. viridula* are large shield-shaped bugs, typically green in colour with a characteristic series of dots along the front of the scutellum (the large, triangular-shaped plate) where it joins the pronotum: typically three, but sometimes up to five, pale dots with a black dot in each corner (Jacobson, 2012; Koppert Biological Systems, 2017). Small black dots can also be seen around the edge of the body, and the exposed wing membrane is pale in colour (Jacobson, 2012; Koppert Biological Systems, 2017). Antennal segments alternate between light and dark bands and eyes are typically dark red or black (Koppert Biological Systems, 2017). In contrast, adult *P. prasina* have darker exposed wing membranes and lack the distinctive series of dots. Adult *N. viridula* colouration can also change, as they become brownish in cooler temperatures. Colour variation is also observed across and within in the five nymphal stages. First instar nymphs are reddish in colour, with transparent legs and antennae and red eyes (Martin, 2016; Koppert Biological Systems, 2017). In the second instar, the nymphs become predominantly black, with a white or pale yellow spot on each side of the thorax, red bands between antennal segments and a reddish abdomen (Martin, 2016; Koppert Biological Systems, 2017). Third and fourth instar nymphs differ in colour and size, becoming increasingly greenish and developing a series of white or pale yellow patches near the middle and edge of the abdomen, with patches also along the top of the abdomen and some fourth instar nymphs showing the beginnings of a pinkish abdominal fringe (Martin, 2016; Koppert Biological Systems, 2017). Fifth instar nymphs are usually green with red spots down the median line on the abdomen, a pinkish abdominal fringe and obvious wing buds (Martin, 2016; Koppert Biological Systems, 2017). Dark-coloured nymphal variants start differentiating in the fourth instar – these remain relatively black in colour, and though they do shown the white to yellow spots and patches on the abdomen, the pink abdominal fringe is not particularly apparent (Martin, 2016; Koppert Biological Systems, 2017). Immature nymphal stages of *P. prasina*, by contrast, do not have the distinct white and yellow abdominal spots or patches, typically having black spots down the median line of the abdomen, as well as along the abdominal edge, with a dark head and thorax (though variants where these are green become observable around the third instar) (Jacobson, 2012).

Symptoms and Identification

As with all hemipteran pests, *N. viridula* has piercing, sucking mouthparts which are inserted into plant tissue to feed, at which point saliva is injected and the resulting liquid sucked back up into the insect and ingested. The insect can appear early in the season and has the potential to drive significant crop losses through the production period, with declines in marketable produce of 50% resulting from infestation in high pest pressure years. They typically feed on vegetative parts of the plant including leaves, pods and fruits, though the impact of their feeding is seen primarily in developing fruit and new growth. The main cause of damage to the plant is through injection of the saliva, which contains toxic substances and digestive enzymes such as serine proteases, and through direct damage of plant tissues (Bayer Crop Compendium, 2019). Feeding damage can render fruit unmarketable and includes distortion and discolouration of fruit as it develops or, where punctures are observed on larger fruit, the development of these feeding sites into hard brown spots and other surface damage (Koppert Biological Systems, 2017). Damaged areas of the plant may further wither and die, and feeding wounds may also facilitate infection by pathogens, some for which *N. viridula* is a vector. In addition to visual imperfections to the fruit, feeding on young fruits often leaves sticky regurgitated globules which require removal before point of sale.

Monitoring

Outside of the UK, physical monitoring of *N. viridula* in low level outdoor crops, such as soybean, sorghum and cotton, has typically been based on the use of net sweeping, where nets are used to sweep the crop canopy and the number of captured insects is then recorded. Another similar approach is to dislodge the insects from a plant by either shaking, ‘beating’ or otherwise agitating the plant material, then counting the number of insects that fall onto a light-coloured fabric or tarp surface; a useful technique where larger woody plants are involved, for example in systems such as orchards. Direct counting of insects on the host plants can also be undertaken, where the numbers of insects on a certain number of plants, or along a set distance within a crop row, are directly sighted and numbers recorded. These three methods, while simple, are labour-intensive, and are not well-suited for use in high-wire glasshouse crops in the UK, particularly when mature. Simultaneously, methods that may work well in monitoring of other pest species under glass seem not to work well for *N. viridula* – sticky traps, for example, appear to have limited ability to retain the pest.

Despite its pitfalls, direct observation remains the mainstay of *N. viridula* monitoring in UK glasshouse crops, with the success of this approach being dependant on staff training to recognise the pest in its various life stages (over which its physical appearance changes dramatically). Early detection of eggs and initial instars is particularly important to identify and address infestations before the pest becomes more mobile in later instars and spreads throughout the crop. These early stages are nevertheless hardest to monitor, with constant scouting needed on all plant parts, including the underside of leaves where eggs are often laid; adults tend to be easier to observe on smaller plants, though often favour lighter conditions found at the plant apex which are harder to observe in mature high-wire crops. As later (third plus) instars are also highly mobile, physically removing these during monitoring can be more difficult as the pest can rapidly move if disturbed.

Thus, though direct counting (and physical removal) is currently being undertaken by growers, the industry would benefit from monitoring solutions that are easier to implement. For any form of monitoring, including physical observation, guidance on standardised methods and associated thresholds would also be beneficial, and noted as a key area of industry interest going forward.

Light traps

Nezara viridula has been reported to show positive phototactic behaviour, where insects move towards a light source (Cantelo *et al.*, 1973, 1974; McPherson & Sites, 1989; Endo, 2016). Thus, light trapping has obvious potential to be used as a monitoring option to inform management strategies and decision-making processes on aspects such as planting, or deployment of insecticide applications and biological control agents. Trap design, however, may be key to the success of this approach. Pentatomids – the family group to which *N. viridula* belongs – are negatively geotactic (Čokl *et al*., 1999), meaning that they tend to move up towards the top of a plant, or to the top of a trap. This, combined with the observation that many stink bugs do not like to enter dark spaces and move around considerably once inside a trap, thus finding their way out, demonstrates why traps must be designed to limit or prevent post-capture escapees (Millar *et al.*, 2002).

Traditionally, mercury vapour light bulbs have been used for insect trapping. Coombs (2000), for example, successfully deployed four 400W traps to capture *N. viridula* in order to correlate trap catch data and climatic data, also noting that identification of population peaks was possible through light trapping. Endo (2016) successfully used a 100W mercury light trap to capture *N. viridula* specimens while investigating seasonal trends in capture rates. An investigation into the efficacy of different light trap types in West Java compared a 160W mercury light trap with a 20W solar trap for capture of rice pests, and found that while mercury light traps performed better overall, trap design was also important, with a 1m funnel size proving more efficient than a smaller 60cm one (Baehaki *et al.*, 2016).

While mercury vapour light trapping is clearly useful, large and relatively expensive mercury vapour-type traps are not necessarily well suited to use in a commercial high-wire crop. Nevertheless, advances in LED technology have led to the advent of more accessible, more manageable light trapping options (see below). LED lighting technology also offers an opportunity to take advantage of natural predispositions in insects for attractance to certain light wavelengths, allowing light traps to be optimised for use against particular pests. For example, the attraction of *H. halys* to various light stimuli was investigated in a recent behavioural study by Cambridge *et al.* (2017) in order to develop more effective trapping methods. They evaluated response to different colours using fixed-peak wavelength fluorescent bulbs (blue = 460nm, green = 560nm, yellow = 590nm, orange = 640nm, red = 750nm) and white incandescent bulbs, the latter of which were also used to evaluate the effect of different levels of light intensity (0.1, 10, 50, 75 and 155lx). The outcome of the study suggested a preference by *H. halys* towards 75lx intensity, with a stronger response to white light when compared to the other colour wavelengths. These findings are consistent with earlier work by Leskey *et al.* (2015b), who reported positive phototactic responses towards both full-spectrum and wavelength-restricted fluorescent bulb stimuli, with greatest attraction to white, blue and black (UV) stimuli under both laboratory and field conditions.

Attraction of *N. viridula* to high light areas of the crop/glasshouse (e.g. crop apexes and row ends) has been reported by growers, and the behavioural response of *N. viridula* to different light wavelengths has been specifically investigated using LEDs by Endo *et al.* (2014). This study evaluated visual responses to five different LED peak wavelengths (UV = 373nm, blue = 444nm and 464nm, green = 534nm, orange = 583nm) under the same photon flux density. The study suggested a preference towards shorter wavelengths in free-flying experiments, where male and female adults were found to have a strong preference towards the UV wavelength, followed by the two tested blue wavelengths, when compared to responses towards the green and orange wavelengths. Spectral sensitivity evaluations of *N. viridula* compound eyes showed a bimodal sensitivity pattern to all wavelengths between 300nm and 740nm, with a strong response at the 360nm peak, and a maximal response in the green region (520nm peak).

The findings of various studies on insect light wavelength preference suggest that it should be possible to optimise light traps for monitoring and control of *N. viridula* and pentatomid pests in general. A wide range of light traps are currently available commercially, including relatively inexpensive options that could lend themselves to being positioned at multiple points within a glasshouse. Some of these, designed specifically with *H. halys* in mind, combine attraction to light with the function of a sticky trap, though such designs tend to be ‘home made’ rather than commercially available. Evaluation of these designs under commercial growing conditions, with particular attention paid to the potential of LED-lit traps, should be undertaken to investigate whether, following optimisation, such traps might lend themselves as a partial control option as well as a monitoring strategy. Potential limitations of the technique do, however, exist; for example, light trap density may need to be too high to be cost-effective, and light trapping has been determined as being relatively ineffective at attracting pentatomid nymphal stages (Cambridge *et al.*, 2017).

Pheromone traps

Nezara viridula, and pentatomid bugs in general, are known to respond to sex and aggregation pheromones, and these behavioural responses can be useful as part of monitoring programmes through the use of pheromone-baited trapping. Successful field trapping of *N. viridula* has been undertaken using its known pheromone as a lure in baited pyramid traps (Tillman *et al.*, 2010). Specifics and control viability are described in a later section in this review (see: *Semiochemicals*). It is, however, important to note that the use of pheromone-baiting of, in particular, pyramid traps is an effective means of trapping a broad range of pentatomids and has been used to successfully monitor or evaluate pentatomid population numbers (Aldrich *et al*., 1991; Mizell & Tedders, 1995; Cottrell *et al.*, 2000; Johnson *et al.*, 2002; Leskey & Hogmire, 2005; Tillman *et al*., 2010; Nielsen *et al*., 2011; Leskey *et al.*, 2015a; Tillman & Cottrell, 2016). Combining pheromone lures with a synergist compound, such as methyl (2*E*,4*E*,6*Z*)-decatrienoate, has also been shown to increase attraction of such traps (Weber *et al.*, 2014; Leskey *et al.*, 2015a). The potential to further develop existing pheromone traps by incorporating lights, as described in the preceding section (e.g. Leskey *et al.*, 2015b; Cambridge *et al.*, 2017), could also amplify the attractive potential of these traps. Given that catch numbers have been reported in the literature as being potentially significant enough to represent some level of limited control (Tillman & Cottrell, 2016), this technique may hold potential for both monitoring and management of *N. viridula*, particularly if optimised.

A wide range of broad-capture pentatomid pheromone traps are available commercially. Pheromone trapping of pentatomids described in the literature included in this review typically consist of ground-based black pyramid traps (e.g. Nielsen *et al.*, 2011; Weber *et al.*, 2014; Leskey *et al.*, 2015a). This trap design has been shown to be more effective at capturing all stages of pentatomid bug life cycles when compared to others (e.g. bamboo poles), as it features a wider base for walking nymphs to approach and a wide platform on which flying adults can land (Tillman & Cottrell, 2016). Hanging designs are also available, such as the RESCUE!® Reusable Stink Bug Trap (Sterling Inc., USA). This particular product is a pheromone-baited trap that claims to catch all stages of the stink bug life-cycle with a 30-foot action radius, allowing insects to walk up the green ‘fins’ and through the cone to get trapped inside a clear chamber where they then dehydrate. Of particular interest, however, is that this trap is designed to allow a blue LED attachment to sit atop the trap for combined use.

Trap plants

Trap planting involves the strategic placement of plants preferable to an insect pest in comparison to an adjacent target crop of economic value. These trap plants are used to either prevent the pest from reaching the crop, or to concentrate the pest in a particular area to facilitate its management (through either mechanical or insecticidal means).

Jacobson *et al.* (2013) performed a thorough review of the literature evaluating trap planting to draw *N. viridula* away from target crops, herein summarised for reference. Most work has been undertaken to establish suitable trap plantings to draw the pest away from valuable broad-acre crops, with good success. McPherson & Newsom (1984) reported attraction of 70-85% of all *N. viridula* in a soybean crop to trap plant strips of more mature (podding) plants covering 1-10% of total crop area, in line with earlier findings by Newsom & Herzog (1977). Sorghum and soybean have both been identified as suitable trap plant species, with *N. viridula* exhibiting stronger preference for these crops when compared with cotton in trials in both the USA and Australia (Tillman, 2006a; Knight & Gurr, 2007), while both white and black mustard were reported as effective trap plants for use with sweet corn in a New Zealand trial (Rea *et al.*, 2002). Of particular note, podding soybean and soybean pods have been shown to strongly attract *N. viridula* (Velasco & Walter, 1992; Bundy & McPherson, 2000), with pod semiochemical methanol extractions also found to stimulate oviposition (Panizzi *et al.*, 2004). More recent research has further supported the efficacy of soybean as a trap plant for cotton and peanut (Tillman *et al.*, 2015b).

The 2013 review remains a good reflection on the subject of trap planting against *N. viridula* to date. As such, Jacobson *et al.* (2013)’s assertion on the difficulty of predicting whether the afore-mentioned plant species would be more attractive than peppers and aubergines still holds true. The observation that unpublished reports from London suggest attraction of *N. viridula* by podding beans remains a potentially important avenue for investigation, particularly when considered alongside the literature above that supports a preference for soybean in general, and podding soybean in particular. Jacobson *et al.* (2013) suggested that dwarf French beans could provide an ideal trap plant candidate for use within UK protected cropping systems, owing to their size and growth habit. The phenology and timing of, for example, podding, maturation, etc., must be considered when planting a trap crop, however, as these factors have been shown to affect the level of attraction of a trap crop to *N. viridula* (Todd & Schumann, 1988; Rea *et al.*, 2002).

Caution must also be taken to avoid potential negative impacts of trap planting, for example a build-up of pests on trap plants that can ‘spill-over’ onto the crop. The findings of Soergel *et al.* (2015) and Mathews *et al.* (2017), for example, highlight the potential of trap plants to act as a ‘sink’ for pests at critical times in the cropping cycle. Trap plant management should alleviate such risks, however, potentially allowing for insecticide applications on the sacrificial trap plants that would not be used in the main crop (this being in line with the suggestion of Jacobson et al. (2013) using dwarfing French beans as an example).

Recent research on *H. halys* could also suggest potential trap plants for evaluation of efficacy against *N. viridula*. Similarly to *N. viridula*, sorghum has also been identified as an effective potential trap plant for *H. halys* in field-based organic systems, with sunflower and okra also performing well (Nielsen *et al.*, 2016). Two further studies evaluated trap crops of *H. halys* in sweet peppers. Soergel *et al.* (2015) used sunflower as a trap plant to protect peppers, and observed higher numbers of *H. halys* nymphs and adults on the sunflowers than on the pepper across both trial years. Despite this, no reduction in damage to the fruit was observed in peppers surrounded by the sunflower trap plants when compared to the control pepper monocrop. Mathews *et al.* (2017) investigated the use of a combined sorghum and sunflower trap crop. The trap crop was found to be highly attractive, with between five and fifty times more *H. halys* per m^2 observed in the trap plants compared to the pepper crop. Though the trap crop was not effective at diverting adults away from the pepper crop during the early fruiting stages, it did reduce numbers in the later fruiting period, and the average density of nymphs was four times lower in trap plant-protected peppers five weeks after planting when compared to control peppers. Despite this, the resulting reduction in feeding-induced damage to the peppers was slight (reported as approximately 2%), and thus deemed insufficient to be economically viable.

It would be interesting to see whether a similar level of preference for sunflower was also exhibited by *N. viridula*, given that they have been shown to have preference for sorghum, and that modern dwarfing varieties of both exist. Even where direct reduction of pest damage is negligible, attractive and retentive trap plants could play a role in IPM as focused pest monitoring/trapping sites (see above), or areas for targeted chemical control or release/evaluation of biocontrol using natural enemies.

Sensing and robotics

Although currently relatively far from mainstream use, remote and robotic means of sensing for pest and disease presence are beginning to emerge in other sectors, and are currently the subject of R&D in the crop production industry. Given that *N. viridula* is known to utilise intra-specific pheromones, it follows that these could potentially represent targets for chemically-based remote monitoring systems, as could the chemicals produced by the crop in response to *N. viridula* attack. Remote imaging technology may similarly hold promise, where the relatively large size of the pest could help to facilitate its detection, and potentially even its mechanical removal, for example by some form of ‘robotic arm’. As methods such as automated harvesting progress, it would be logical to develop multi-functionality into the technology that will drive these systems, with the ability to monitor and treat the crop for pest and disease being a plausible ‘add on’.

Potential Cultural Control and Management

Physical barriers and hygiene

The use of physical barriers has been tested in south-eastern USA as a means to prevent *N. viridula* infestation into cotton. Tillman (2014) investigated whether strategic positioning of a physical barrier at the crop-edge interface would disrupt edge-mediated dispersal of adult *N. viridula*. The two-year study evaluated the use of a plant-based barrier (a sorghum sudangrass wall, with growth to over 2m height in both years) and a synthetic barrier (a 1.8m polypropylene wall) positioned between peanut and cotton, with an aim to supress movement of *N. viridula* into the cotton crop. Across both years, both wall types effectively disrupted the dispersal of *N. viridula* into the cotton crop, most likely due to the barriers, both of which were significantly taller than the cotton crop (1.3-1.4m height), interfering with the flight of *N. viridula* adults as they attempted to move from the low-growing peanut plants towards the cotton. Tillman *et al*. (2015b) further found use of a physical barrier to be the most effective management tactic in a study comparing trap cropping, pheromone trapping and physical barriers as suppressants for pentatomid numbers in cotton, also recording a lower cotton boll injury within the physical barrier plots.

Though it is not immediately apparent how this knowledge would be of benefit in management strategies within enclosed protected glasshouse systems, the findings do highlight that physical disruption of *N. viridula* behaviours could present useful options as part of a management strategy. Whilst use of mesh barriers could be employed under glass to separate different production areas, or contain hotspots of infestation, this would likely be prohibitively expensive with complete separation/containment hard to achieve.

Barrier-type methods as covered above could hold more promise if linked to biosecurity measures. Benefit is likely to be derived, for example, from ensuring that vents are covered and vent mesh maintained, and that other possible entry points are well sealed. Maintenance of positive air pressures and use of fans at entry points to provide temporary outward airflow upon entering facilities are also relatively common tools used to limit ingress of pest and disease in high-hygiene facilities. It may also be possible to scout and remove ‘high risk’ host plants from the immediate vicinity of the glasshouse exterior, limiting food sources nearby that might encourage *N. viridula* in the surrounding habitat. In a similar vein, it may be possible to introduce repellent plants to these areas, though more work would be needed to assess the probable benefit of either approach.

Finally, confirmed best practice for cleaning down facilities after infestation with *N. viridula* could also be beneficial to the industry. No current guidance appears available on how to best achieve this with *N. viridula* in mind, and/or which products to use for optimum results.

Vibratory disruption

Pentatomids are known to communicate through vibrational signals transmitted through host plant material. This appears to play a key role in mate location, where the sexual behaviour of *N. viridula* consists of long-range pheromone emission by males and short-range location, mate recognition and courtship by vibrational signals from the female (Todd, 1989; Čokl *et al*., 2000). As such, a potential avenue for the control of *N. viridula* is through the disruption of sexual signalling and communication by physical means.

Vibratory disturbance and ‘noise’ is known to alter the behaviour of *N. viridula* by disrupting this form of communication, as signal length and repetition rate are critical for mate recognition (Polajnar & Čokl, 2008a). Although studies have shown that *N. viridula* are, to some extent, able to compensate for and reduce noise interference, such that the time required for a male to locate a female is unchanged, they have also shown that experimentally introduced interference reduced the number of males responding to the signalling in the first place (Polajnar & Čokl, 2008b). In a recent study on another closely-allied pentatomid, *Euschistus heros*, Laumann *et al*. (2018) evaluated the potential of mechanically-transmitted pure tone vibrations as disruptors of *E. heros* mating behaviour. In a short-term, 24 hour experiment, the study suggested that vibrations at a frequency of 75-200Hz resulted in an increased proportion of females spontaneously emitting vibrational signals, while inhibiting the signalling and searching behaviour of males. Thus, copulation was reduced by 94-100% in comparison to an undisturbed control. In a longer-term trial, the use of background noise was less effective, reducing mating frequency to just 24.7%, though it was also observed that exposure to background noise reduced female fertility and fecundity.

The literature suggests that disruption of mating signals by means of mechanically-emitted vibrations could provide a novel potential component for *N. viridula* management within IPM systems, though this would require further evaluation for feasibility within commercial systems before more concrete recommendations could be made. Nevertheless, effective vibratory disruption could theoretically be easy to implement, and was highlighted as the most interesting avenue for further research at the Grower Focus Group conducted as part of this review.

Natural Enemies

Parasitoids

One of the most comprehensive studies of parasitoids noted as attacking *N. viridula* remains Jones (1988). As described by Jacobson *et al.* (2013), the review reports fifty-seven species of parasitoids among two families of Diptera (flies) and five families of Hymenoptera (wasps). A second review, Hokannen (1986), reported a further three species of *N. viridula* parasitoid. Jacobson *et al.* (2013) duly noted that these two reviews may well have incorporated some misidentified insects and that species specific names listed may have been synonyms given the extent and timespan of literature therein cited. Increased confidence can be assigned to subsequent work on the species identified as being of most importance, however, as these studies have been conducted in far greater depth since the publications of Jones (1988) and Hokannen (1986). Waterhouse (1998) further reviewed and extended the *N. viridula* parasitoid list, presenting some eighty species spread across two families of Diptera and six of Hymenoptera.

Wasps

The literature since 2013 continues to reflect the importance of egg parasitoids as biocontrol agents of *N. viridula*. These species remain the most numerous among *N. viridula* parasitoids, probably as the egg stage is an easier target for parasitism than later stages which are relatively well protected by a hard outer layer, and all species noted are Hymenoptera. Of those reported in Jacobson *et al.*’s 2013 review, the scelionid wasp *Trissolcus basalis* (Wollaston) continues to be of particular importance wherever present and has been well-studied. Although recorded from several pentatomid bug species, it is most closely associated with, and shows a preference for, *N. viridula* (Waterhouse, 1998). It is not only this pest's most important parasitoid species, but also the most widespread globally; although it was first found parasitising eggs of *N. viridula* in Brasil, it is now found across the Americas, Europe, and Asia as well as Africa, and has been introduced to Australia, New Zealand and many Pacific islands as a component of biological control programmes (reviewed by Jacobson *et al.*, 2013; CABI, 2019). The efficacy of *T. basalis* as a biocontrol agent appears positive. Ehler (2002), for example, reported from field studies that *T. basalis* typically parasitised 100% of an exploited mass of *N. viridula* eggs in northern California, and Corrêa-Ferreira & Moscardi (1996) observed *N. viridula* population density decreases of 54% and 58% in Brazilian trap/main crop following inundative release of *T. basalis*. In Australia, however, Knight & Gurr (2007) suggest that *T. basalis* may not be able to offer universally strong biocontrol potential. Though widespread and reasonable control has been achieved in Western Australia, *N. viridula* remains a significant pest in southeast Queensland and New South Wales despite sometimes high rates of parasitism by *T. basalis*.

Recently, the closely-allied *H. halys* has increased in prevalence and importance across Europe. As with *N. viridula*, it is a highly polyphagous pentatomid bug, feeding on many economically important crops and causing significant damages and losses in North America. In Europe, it is currently primarily a nuisance to humans, aggregating in dwellings and other man-made structures, but it's potential as a major pest to growers on the continent is being recognised and is reflected by an increasing body of literature. As a closely-related species to *N. viridula*, some of the findings of this growing body of work may translate into potential control measures worthy of investigation for UK growers. Haye *et al*. (2015) recently evaluated several native egg parasitoids of European pentatomid species for potential in controlling *H. halys*. Their trial in Switzerland yielded several European species of pentatomid egg parasitoid: four scelids, with three species in the *Trissolcus* genus (*T. semistriatus, T. scutellaris, T. culturatus*) along with *Telenomus chloropus*, and the eupelmid *Anastatus bifasciatus*. Of the four scelids, however, *T. chloropus* and *T. semistriatus* produced no offspring from fresh *H. halys* egg masses while *T. cultratus* and *T. scutellaris* only sporadically completed development. The eupelmid, *A. bifasciatus*, on the other hand, was capable of consistent, successful development on fresh *H. halys* eggs, although average parasitism rates were 34% at most. By contrast, an Asian egg parasitoid *Telenomus japonicus* and a Chinese strain of *T. cultratus* showed much higher rates of parasitism: 95% and 84% respectively. The findings of Haye *et al*. (2015) could suggest that native generalist egg parasitoids may exert some small parasitism pressure on *N. viridula*, but it is, in the grand scheme of things, unlikely to be at sufficient rates that it can be hoped to achieve reasonable control by itself at this time.

Flies

According to the parasitoid list presented by Waterhouse (1998), all nymphal and adult parasitoids of *N. viridula* are, with one exception, Diptera (flies), and of these, all but two species are in the family Tachinidae (the other two dipteran species belong to the family Sarcophagidae). Tachinid parasitoids oviposit on the abdomen of *N. viridula*. Larvae hatch from the eggs and then burrow into the host's tissue before continuing their life cycle and maturing into adults. Although tachinids are better adapted to parasitism of the adult stage of their host, some species have also been observed ovipositing on 4th- and 5th-instar nymphs. Success in this latter instance is dependent on whether the tachinid eggs hatch prior to moulting; if they do, then the larvae can successfully burrow into their host and mature into adults (Waterhouse, 1998), though successful parasitism rates have nonetheless been observed to be quite poor (Buschman & Whitcomb, 1980; Jacobson, 2013).

Of the species of tachinid known to parasitise *N. viridula*, a larger proportion are native to South America when compared to other localities and must have been dependent on other pentatomid species prior to the arrival of *N. viridula*. Despite this, in the Americas, several species have become well adapted to, and indeed show preference for, *N. viridula* (Waterhouse, 1998; Jacobson *et al.*, 2013). Jacobson *et al*. (2013) lists examples including *Trichopoda pennipes* in the U.S., *T. pilipes* in the West Indies, and *T. giacomellii*, *T. gustavoi*, *Eutrichopodopsis nitens* and *Ectophasiopsis arcuate* in South America. Several of these species have been established against *N. viridula* in other regions of the world. In addition to the examples presented by Jacobson *et al.* (2013), *T. pennipes* has been introduced to Southern Europe. In later work, Jacobson (2014) noted that a pheromone attractive to *T. pennipes* had been identified, and that though this species of tachinid was not reported as specific to *N. viridula*, and had not yet been reported in, nor was it indigenous to, the UK, it may warrant further investigation were *T. pennipes* found to be already present in the UK.

Trichopoda giacomellii was introduced to Queensland and New South Wales in Australia (Knight & Gurr, 2007), and though the species was able to establish, with reports of high rates of parasitism (Coombs and Sands, 2000), Knight & Gurr (2007) claim that biological control efforts with this species could not be considered fully successful. Nonetheless, considering the potential high parasitism rates of *T. giacomellii* combined with the host-specificity for *N. viridula* demonstrated by Sands & Coombs (1999), Jacobson (2013) suggested the species as warranting investigation as a potential licenced biological control agent for use in the UK, assuming additional work proved specificity. Literature since 2013 supports this view, and it remains a valid avenue for investigation.

Three species of tachinid are known from the natural Ethiopian range of *N. viridula*, and of these the species most consistently reported as having the greatest promise is *Bogosia antinorii* (Rondani) (Jones, 1988; Waterhouse, 1998; Jacobson *et al.*, 2013). This species is reportedly known only from *N. viridula* (van Emden, 1945; Barraclough, 1985), and although small release attempts in Australia seemingly failed to establish (Waterhouse & Sands, 2001) it may warrant further investigation as a potential licensed biological control agent under protected conditions if specificity against *N. viridula* is shown. At the very least, given the adaptive capabilities and potential preference shown towards *N. viridula* by tachinid parasitoids, tachinid species local and native to Europe should be screened against the pest for potential control capacity, with consideration for introduction into new areas if a viable commercial production system can be developed (Salerno *et al.*, 2002; de Groot *et al.*, 2007).

Jones (1988) stated that no hyperparasitoids were known to attack the parasitoids of *N. viridula*. Jacobson (2013) also could not find evidence of hyperparasitoids in the literature at the time of review. This current evaluation of the literature, however, has indicated that there are, in fact, known hyperparasitoids. For example, Waterhouse (1988) reports two hyperparasitoid species of *T. basalis* known from Australia (as reported in Clarke & Seymour, 1992), and one hyperparasitoid of the tachinid *T. pennipes* known from Hawaii (as reported in Davis & Krauss, 1965). Furthermore, the encrytid wasp *Ooencyrtus telenomicida*, in addition to competing against *T. bassalis* as a parasitoid of *N. viridula* in its own right, is also a known facultative hyperparasitoid of *T. basalis* (Cusumano *et al*., 2013).

To date, in the UK there are currently no parasitoids available from commercial suppliers that can be used specifically against *N. viridula*. A recent AHDB-commissioned study, FV 441 (Collier *et al*., 2017), noted that a short review of online literature highlighted several hymenopteran parasitoid species of interest for control against mirid bugs, a closely-allied family to Pentatomidae. *Anagrus atomus*, for example, is a parasitoid of leafhopper eggs that had been available commercially as Anagsure® through BCP Certis, though no longer appears available following the company's merger with Koppert (Collier *et al.*, 2017). They were unable to assess whether *A. atomus* would be able to parasitise and develop successfully on mirid target eggs as well, but were the species shown to do so it could well merit investigation against *N. viridula*, given that rearing the parasitoid ought to be commercially feasible and that it had been previously used in commercial settings. Furthermore, FV 441 also noted parasitoids in the *Peristenus* genus as being of interest. Indeed, the species *P. digoneutis* and *P. relictus* appear native to Europe, and though they are not available commercially are reported to be effective parasitoids against mirid nymphs. *Peristenus digoneutis*, for example, is noted as being effective across Europe against *Lygus rugulipennis* and has been released in the USA with success against *L. lineolaris* and other *Lygus* pests, although rearing of the parasitoid is difficult and may make commercial production unviable (Day, 2019).

Predators

A variety of generalist invertebrate predators have been shown to attack *N. viridula*, as well as other closely-allied hemipteran families. All three life stages of the pest (egg masses, nymphs and adults) have reported instances showing vulnerability to attack. Although predators are, at least under field conditions, unlikely to play the single leading role in suppressing pest population numbers, they can exert significant pressure on pest numbers and contribute in their population regulation. Ogburn *et al*. (2016), for example, suggested that predation on *H. halys* eggs accounted for some 80% of biological control activity. The potential of predation as part of an IPM strategy against *N. viridula* should thus not be underestimated, particularly in a 'closed' and controlled setting (i.e. under glass) and especially given the lack of parasitoids currently available commercially.

In an evaluation of predators under laboratory conditions, Ehler (2002) observed several species engaging in egg predation, and noted that these were typically characterised as having chewing mouthparts. Beetles in the family Malachiidae, lacewings, predatory bugs in the family Geocoridae (formerly a subfamily within Lygaeidae), earwigs and one isopod species were recorded as predating on eggs, though predation levels were typically less than 10% (Ehler, 2002). *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae), a pentatomid generalist predator used in European glasshouses for control of caterpillar outbreaks, has also been recorded feeding on *N. viridula* eggs, though again predation rates were low (De Clercq *et al*., 2002). Egg predation by generalist predators on pentatomid egg masses, however, can be quite high. In the U.S.A., for example, egg predation on the closely-related *H. halys* by chewing and sucking predators resulted in mortality of eggs reaching 40-70% in corn and soybean plots, 23% in ornamental nurseries, and approximately 25% in orchards (Rice *et al.*, 2014).

A broader range of predators has been observed attacking *N. viridula* adults and, in particular, nymphs. During laboratory screening, Ehler (2002) observed several species of predatory beetle, including Coccinellidae (ladybirds), Malachiidae, Anthicidae and Cantharidae (soldier-beetle) attacking *N. viridula* nymphs, along with lacewings, spiders and harvestmen, isopods and earwigs. Many species of predatory hemipterans in the families Geocoridae, Anthocoridae, Nabidae, Reduviidae and Miridae were also recorded feeding on *N. viridula* nymphs (Ehler, 2002). Similarly, Tillman *et al.* (2015a) recorded predation of stink bugs by generalist predators in the families Geocoridae, Anthocoridae, Pentatomidae, Reduviidae and Coccinellidae, as well as in spiders and ants. *Podisus maculiventris* has also been recorded as being able to attack and develop on *N. viridula* adults and nymphs, though these were recorded as being suboptimal prey for development, most likely due to their high mobility in comparison to this natural enemy's usual caterpillar prey (De Clercq *et al*., 2002).

In a recent review on the biology, ecology and management of the closely-allied pentatomid pest *H. halys*, Rice *et al*. (2014) listed 10 families of chewing and sucking predators that were, along with spiders, found attacking *H. halys* eggs, nymphs and adults. These included the aforementioned Anthocoridae, Geocoridae and Reduviidae hemipteran families, as well as Coccinellidae and lacewings. The predatory pentatomid *P. maculiventris* has also been recorded attacking *H. halys* (Lee, 2015).

In the recent AHDB-commissioned evaluation of natural enemies against mirid pests of outdoor celery, Collier *et al*. (2017) evaluated several commercially available predatory bugs, *Macrolophus pygmaeus* and *Orius strigicollis*, and a predatory rove beetle, *Atheta coriaria*, under laboratory conditions for their potential impact as biocontrol agents. Mortality rates of mirid pest nymphs ranged between 36% and 60%, showing significant differences to mortality seen under a control treatment. Percentage mortality of adults was not significant, however, suggesting a preference for, or at least a higher predation success rate on, nymphs (this not being unexpected given the relative body sizes of pest and predator, and the generally increased suitability of nymphs vs adults as prey, particularly directly after moulting and before hardening of the cuticle).

The findings outlined above provide further support to Jacobson *et al*. (2013)'s conclusion that the use of predators against *N. viridula* warrants further investigation for use in UK glasshouse protected edible crops. The same families of invertebrate appear as predators of *N. viridula*, as well as other closely-related hemipteran pest families, repeatedly. Several potential species, such as *Macrolophus* and *Orius*, are already released in the UK as part of IPM programmes in glasshouse protected edible crops, and these in particular should be assessed for predation impact against *N. viridula*. Investigation into lacewing and ladybird predation on *N. viridula* could likewise be recommended, these also being currently available within the UK.

Basic Substances

A number of biorational, physically acting 'insecticides' are available for use in a range of protected edible crops in the UK. Maltodextrin (e.g. Eradicoat®, Majestik®), fatty acid insecticidal soaps (e.g. Savona®, Flipper®) and dodecylphenol ethoxylate (Agri 50®) are approved for a number of protected edible crops, including tomato, pepper and aubergine crops. Typically, such products are targeted towards smaller soft-bodied pests, such as aphids and whiteflies, though some information has been recently made available on potential effects against pentatomid pests. In a laboratory study, Lee *et al*. (2014) evaluated the impact of a number of organically-approved insecticides against the closely-allied pentatomid *H. halys*, including potassium salts of fatty acids. In treated glass surface contact bioassays, the authors observed over 60% mortality of exposed nymphs and adults seven days after treatment with potassium salts of fatty acids (among others). Morehead & Kuhar (2017) found comparable mortality in submersion bioassays, with mortality somewhat reduced in bean dip bioassays. When the products were evaluated in the field, however, which included weekly applications, no significant reduction in stink bug feeding injury was observed when compared to an untreated control. Jacobson *et al*. (2013) reported that several soft soap products are marketed in the USA domestic market, though the most effective of these combined soap with an insecticide such as a pyrethrin or neem oil. Bergmann & Raupp (2014), however, only achieved limited control of *H. halys* adults using a range of such ready-to-use household insecticides, including ones with soaps as an active ingredient. Furthermore, Jacobson & Morley (2007) observed that weekly applications of soft soaps and maltodextrin suppressed *Macrolophus* spp. population growth in organic tomato, with damage caused to both plants and other biocontrol agents as a result of the intensive spray programmes often required for these products. Thus, such products may not be sufficiently effective for use as control against *N. viridula* when used in isolation, with risks to IPM programmes posed by these relatively broad-spectrum products when applied at high frequencies (even though residual toxicities to natural enemies after any single application may be very short).

Diatomaceous earth is a fine powder of diatomic fossils. When ground, the resulting microscopic skeletal pieces are extremely sharp and, upon contact with an invertebrate body, in either the digestive or respiratory system, cause irreparable damage, as well as triggering drying when in contact with a mucous membrane. This study was not able to locate literature on the efficacy of diatomaceous earth against pentatomid pests. More research is available, however, on the effects against coleopteran pests, particularly stored product pests. Trials testing diatomaceous earth against the chrysomelid beetle, *Callosobruchus maculatus*, achieved over 95% mortality of adults after five days (Kabir & Abdulrahman, 2018), for example. Vayias & Athanassiou (2004) evaluated SilicoSec®, a diatomaceous earth product available in Europe, for insecticidal efficacy against the tenebrionid beetle, *Tribolium confusum*, and observed around 80% adult mortality on different stored product substrates, although mortality rates are known to be affected by dose rate, temperature and humidity, as well as dose interval (Athanassiou *et al*., 2005). In the absence of literature on pentatomids, it is not possible to determine whether diatomaceous earth might provide a useful control option, and as such further research would be required. Consideration of potential crop safety and residue issues would also need to be addressed.

Kaolin, a naturally occurring clay with lethal and non-lethal activity against insects, has shown limited success when applied against pentatomid and mirid bugs. Direct mortality results from ingestion of the mineral particles, desiccation of the cuticle through abrasion or adsorption by cuticle waxes, whereas nonlethal effects include repellence and avoidance of treated plants, as well as discouragement of oviposition (Amalin *et al.*, 2015). In laboratory trials, Amalin *et al.* (2015) observed strong repellence and reduced feeding by the mirid, *Helopeltis collaris*, on kaolin-treated cacao pods. Marcotegui *et al*. (2015) tested the effect of kaolin against the lace bug, *Monosteira unicosta* (Hemiptera: Tingidae), in organic almond orchards, and observed a reduction in numbers of this insect by a half and a third across two years, with damage reduced by 26% and 11%, respectively. By contrast, however, many studies have shown limited to no significant reduction in feeding damage when crops were treated with kaolin products. Jaastad *et al*. (2009) observed reduced mirid pest numbers in apple crops treated with Surround®, for example, but did not find that this correlated with an acceptable or significant reduction in feeding damage. In trials on the tarnished plant bug, *Lygus campestris*, Lalancette *et al*. (2005) also concluded, based on damage at harvest, that kaolin had little effect. Beers & Himmel (2002) observed no reductions in either number of insects or feeding damage by *Campylomma verbasci*, another mirid pest, on apples. In their laboratory screening of organic insecticides, Lee *et al.* (2014) observed 80% mortality of the pentatomid *H. halys* seven days post-application with a kaolin and pyrethrin mixture, but did not appear to evaluate kaolin in isolation.

Overall, the literature suggests that physically acting biorational products show mixed results in terms of demonstrating efficacy against pentatomids and allied pests. It is worth noting that although this product class shows great versatility, collectively these treatments are typically broad-spectrum, more suited to smaller, soft bodied pests, and require short-interval repeated application to exert a meaningful effect - posing a potential risk to IPM programmes despite limited/zero residual activity, at least during high frequency application windows. Furthermore, the most effective applications of these products in R&D trials have often utilised a combination of a physically acting compound and another insecticidal active, for example kaolin and pyrethrins (Lee *et al.*, 2014) or potassium salts and azadirachtin (Durmusoglu *et al.*, 2003), and only targeted immature nymphs rather than adults. Further careful evaluation of these products within the context of overall IPM programmes would therefore be required to assess their potential against *N. viridula*.

Conventional Insecticides

Chemical insecticides have long been utilised as a control strategy for pentatomids, including *N. viridula*. Both past and present products have typically been characterised by broad-spectrum activity, for example organophosphates, pyrethroids and neonicotinoids, and although a wide range of actives tested have shown efficacy in control they are often not compatible with UK glasshouse crop IPM strategies due to their toxicity to beneficial arthropods. Indeed, studies have observed that their use is often disruptive of IPM programmes, with subsequent outbreaks of previously well-controlled secondary pests (Leskey *et al.*, 2012b). For many synthetic products harvest intervals can also present an issue in crops that are continually harvested like pepper, limiting the potential of many to pre-fruiting phase application only (though effective synthetics are nevertheless of interest here to achieve maximum possible control ahead of fruit set, when pest management options then become more limited).

Key literature pertaining to control of *N. viridula* with chemical insecticides was reviewed by Jacobson *et al.* (2013), and there has been no further significant work of note on the subject since then. The findings of Jacobson *et al.* (2013) are summarised herein for reference, along with a review of any more recent studies and observations on active ingredients approval as at February 2019 (LIAISON database, Fera Science Ltd, 2019; EU Pesticides Database, EU Commission, 2019; BCPC, 2019; databases accessed February 2019). For any chemical insecticide, potential for use in crops where *N. viridula* currently poses a threat should be considered with harvest intervals in mind (i.e. these need to be very short during harvesting), though products with longer harvest intervals could potentially find a niche during the fruiting phase.

Pyrethroids

Pyrethroid insecticides have been shown to be effective in laboratory bioassays against *N. viridula*, with mortality rates of between 77% and 98% achieved following topical applications of bifenthrin, cypermethrin, zeta-cypermethrin and cyfluthrin (Greene *et al.*, 2001). Additional bioassays by Greene & Capps (2004) observed mortality rates of:

- 92-95% for cypermethrin – EU and UK approval;
- 92% for lambda-cyhalothrin – EU and UK approval, with a valid EAMU for targeting of *N. viridula*;

- 76-90% for bifenthrin – EU approval, not currently approved for use in UK;
- 63% for esfenvalerate – EU and UK approval;
- 87% for cyfluthrin – not approved for use in EU and UK;
- 87% for gamma-cyhalothrin – EU approval, not currently approved for use in UK.

The results of this study are in line with the findings of other studies, such as that of Rea *et al.* (2003) who observed 87% mortality of *N. viridula* in New Zealand sweet corn following application of lambda-cyhalothrin at a rate of 200ml Karate®/100L water per hectare, and several others reviewed by Jacobson *et al.* (2013) (e.g. Anderson & Teetes, 1995; Willrich *et al.*, 2003; Snodgrass *et al.*, 2005). More recently, bifenthrin treatment of egg masses has also been reported to reduce emergence, with egg mortality of 78% observed, with the same study finding mortality of 42.5% in egg masses treated with a beta-cyfluthrin and acephate mixture (Brown *et al.*, 2012).

Additional recent studies have provided yet further evidence on the efficacy of pyrethroids against *N. viridula*. In field evaluations of a range of pyrethroid products for efficacy against *N. viridula* and *Piezodorus guildinii* (another pentatomid pest) control in soybean, Temple *et al*. (2013) observed over 90% control of *N. viridula* by pyrethroid products, with gamma-cyhalothrin and cyfluthrin providing the greatest levels of control, at 99% and 97% respectively. López *et al.* (2013) tested a range of pyrethroid and organophosphates for toxicity against *N. viridula*, and similarly to other studies found gamma-cyhalothrin to have highest toxicity to this particular pest, followed by zeta-cypermethrin, then lambda-cyhalothrin and cypermethrin, with bifenthrin showing the lowest toxicity of the pyrethroids tested. Panza *et al*. (2015) compared lambda-cyhalothrin, alpha-cypermethrin and tau-fluvalinate in semi-field cage trials, and found the greatest toxicity to *N. viridula* with best on-plant persistence was given by alpha-cypermethrin, followed by lambda-cyhalothrin, which differed from the former by having intermediate persistence. Tau-fluvalinate, while highly persistent on plants, showed low toxicity under both laboratory and field cage conditions.

Recent work evaluating pyrethroid efficacy has also been conducted on the closely-allied pest, *H. halys*. Leskey *et al.* (2012a) tested nine pyrethroids against this pest: beta-cyfluthrin, bifenthrin, cyfluthrin, esfenvalate, fenpropathrin, gamma-cyhalothrin, lambda-cyhalothrin, permethrin, and zeta-cypermithrin. Although this class of insecticides were noted as having high initial efficacy (with pest mortality rates of 90% or over), with the exception of esfenvalerate (which was noted as having moderate efficacy), six of the nine actives tested decreased in efficacy over the course of the seven-day trial. These findings are corroborated by other studies. Leskey *et al.* (2014) observed highly variable efficacy with pyrethroid residues, for example, with mortality rates of between 40% and 94% depending on the active, and generally decreasing mortality as residues aged. This highlights the importance of complete spray coverage with these products in order to directly target pest populations, though this is not easily achieved in mature glasshouse edible crops. In a recent review on the literature pertaining to chemical control of *H. halys*, Kuhar & Kamminga (2017) evaluated research conducted in the USA between 2011 and 2016, and established a scale of mortality based on percentage mortalities published. The averages for pyrethroids ranged from less than 50% through to a 90-100% bracket. It is also of interest to note that substantial recovery of *H. halys* from a moribund state following application of pyrethroids has been recorded in several studies (Nielsen *et al.*, 2008; Leskey *et al.*, 2012a), though other pentatomids have not shown similar recoveries in condition.

Pyrethroids, while seemingly effective overall, are often considered a relatively poor fit in IPM programmes, so their use should likely be limited to situations where unacceptable economic damage is threatened and other IPM options have been exhausted. They could nevertheless be a useful product in this regard, and a programme to evaluate pyrethroids and determine effective application rates and treatment scenarios (particularly that minimise harm to IPM programmes) may well be of benefit to UK glasshouse growers.

Pyrethrins

Pyrethrins, extracted from *Chrysanthemum* pyrethrum, could have potential for use against *N. viridula*. In laboratory bioassays on the closely-allied *H. halys*, Lee *et al.* (2014) observed 73% mortality of adults seven days after being exposed to dried pyrethrin residues for 4.5 hours. Likewise, Morehead and Kuhar (2017) also observed high mortality, with rates of over 90% of both adults and nymphs, seen 48 hours after submersion in field rates of a pyrethrin product. In bean dip bioassays, where *H. halys* were exposed to bean pods that had been immersed in a field rate concentration of product, nymph mortality dropped to 40%, while adult mortality was still high at 80%. When tested under field conditions in outdoor peppers, however, pyrethrins were not found to reduce feeding-induced damage, although a combined pyrethrin and azadirachtin product did reduce damage in one year of the field trials (which were conducted across two years).

Pyrethrins are a fast-acting contact insecticide, and are typically more compatible with IPM and organic approaches than the synthetic pyrethroids, often with very short harvest intervals. Furthermore, a number of pyrethrin products are approved for use in the UK (Pyrethrum 5 EC, Agropharm; Spruzit, Certis). Evaluation for efficacy in high-wire glasshouse crops against *N. viridula* could, therefore, be of value.

Organophosphates

Organophosphates have also been found to be highly effective against *N. viridula*, with laboratory bioassays by Greene & Capps (2004) reporting the following mortality rates:

- 100% for methyl parathion – not approved for use in EU and UK;
- 96% for acephate – not approved for use in EU and UK.

Furthermore, Rea *et al.* (2003) observed 83% mortality following methamidophos application at a rate of 1L Tamaron™/100L water per hectare on New Zealand sweet corn. This active is also not approved for use in the EU or UK. Jacobson *et al.* (2013) reported comparable results with organophosphates in other reviewed literature, including Anderson & Teetes (1995), Willrich *et al.* (2003) and Snodgrass *et al.* (2005). Organophosphates have nevertheless been noted as being less effective than pyrethroids in reducing egg emergence, with Brown *et al.* (2012) reporting that egg masses treated with acephate showed mortality of 40%. More recently, López *et al.* (2013) found dicrotophos to be six times more toxic than acephate to *N. viridula*, with comparable toxicity of acephate and chlorpyrifos. Similarly to the Green & Capps (2004) laboratory evaluation, Tempe *et al.* (2013) observed 97% and 91% control of *N. viridula* by acephate and methyl parathion, respectively.

Recent research on *H. halys* also supports the potential efficacy of organophosphates, with typically moderate to high levels of initial efficacy (upwards of 60%) and stable or increasing efficacy over time (Leskey *et al.*, 2012a; Leskey *et al.*, 2014). This is supported by the review of Kuhar & Kamminga (2017); while three of the ten organophosphate actives considered averaged a score representing less than 50% mortality, the remaining averaged over 50% mortality, with five averaging above 70%.

Despite potential efficacy, the organophosphates tested in the studies listed in this section are not approved for use in the EU or the UK, with certain products belonging to this chemical class being phased out across Europe and not considered compatible with IPM approaces. Thus, they do not present a useful option for UK protected edible growers at this time.

Neonicotinoids

Screening of neonicotinoids has shown these products to be relatively effective at controlling *N. viridula*. Greene & Capps (2004), for example, observed 87% mortality following treatment with thiamethoxam in laboratory bioassays. Temple *et al*. (2013) recorded 80% mortality using thiamethoxam, and 71% mortality following imidacloprid application. While both are approved in Europe, this product is not approved for use in the UK at this time. Acetamiprid, however, is a neonicotinoid approved for use in the UK in a range of protected crops including tomato, pepper and aubergine. In oral toxicity bioassays, where *N. viridula* were fed on food covered with insecticide residue, this active was found to be moderately toxic to nymphs, with 45% mortality four days post-treatment, although it was not found to be effective against adults (Tillman, 2006b).

Evaluations of neonicotinoids against *H. halys* have also shown reasonable efficacy. Lower LC_{50} values have been reported than those for some organophosphates (Nielsen *et al.*, 2008), with moderate to high initial efficacy (Leskey *et al.*, 2012a). Kuhar & Kamminga (2017) scaled a range neonicotinoid products for efficacy against *H. halys*, with mortalities ranging between 50% and 90%. Leskey *et al.* (2012a) noted acetamiprid as having over 90% initial mortality, although efficacy decreased drastically over seven days (dropping to 10% over this period of time), while thiacloprid, despite having moderate initial effect, provided stable lethality over a period of seven days. Notably, efficacy appeared higher in studies where neonicotinoids were either applied topically and where the insects were allowed to feed on treated plant material, or when tested against immature nymph stages (Bergmann & Raupp, 2014; Kuhar & Kamminga, 2017). Despite some variability in studies such as these, Kuhar & Kamminga (2017) noted neonicotinoids as one of the active ingredient classes that had shown effective and consistent results against *H. halys* under field conditions. The class is also noted as one that is recommended for control in commercial management programs against *H. halys* in Asia, as supported by research conducted within this continent (Lee *et al.*, 2013).

The literature suggests a variable efficacy in neonicotinoid actives against *N. viridula*, dependent on a range of factors, although good levels of mortality have been achieved in certain studies. As a number of such products are approved for use in the UK on protected edible crops, often with relatively short harvest intervals, they should be evaluated for use by UK growers, with attention paid to minimising impact on IPM programmes and targeted timing of applications. A further benefit of this chemical class is its systemic nature, placing somewhat reduced emphasis on complete spray coverages required with other products that are hard (if not impossible) to achieve in glasshouse edibles, particularly in mature crops.

Avermectins

Avermectins are naturally occurring compounds, generated as fermentation products by *Streptomyces avermitilis*, which function by disrupting electrical activity in invertebrate cells. Thus far, the literature does not suggest strong efficacy of such products against pentatomid pests. Mortality of 42% in *N. viridula* has been reported four days post-application of emamectin benzoate (Green & Capps, 2004), but in more recent evaluations of abamectin on *H. halys*, mortality rates of less than 10% have been reported for adults in both dry residue and topical application studies (Leskey *et al.*, 2012a, Kuhar & Kamminga, 2017). While it is possible that nymphs may prove more susceptible, literature has not been identified that supports this specifically. As such, laboratory-based trials would likely be needed as a first step to evaluate efficacy against this life stage before potential usefulness for UK growers could be determined at a field scale in subsequent investigations. Nevertheless, abamectin-based pesticides are broadly available on- and off-label to target glasshouse pests, with relatively short harvest intervals, such that benefit may be derived from screening different formulations against different *N. viridula* stages.

Carbamates

In residue toxicity tests, Tillman (2006b) reported high toxicity of the carbamate oxamyl against *N. viridula* adults and nymphs exposed to residue-covered plastic Petri dishes, though in oral toxicity tests, where *N. viridula* were exposed to bean pods treated with oxamyl, no toxicity was observed. Recent work on *H. halys* has also shown a variable effect of carbamate application. Initial efficacy ranged from low (less than 10% for carbaryl), through to high (methomyl at over 90%), with compounds showing either stable or increasing efficacy over seven days (Leskey *et al.*, 2012a). Kuhar & Kamminga (2017) reported high mortality rates for methomyl, with adult mortalities consistently over 70% and nymph mortality of 50-69% in residue, topical application and bean dip bioassays.

A number of carbamates are approved for use in the UK, including oxamyl, and pirimicarb is approved for use in peppers via an EAMU with a three-day harvest interval. The literature suggests that carbamates could provide a potential active for inclusion in *N. viridula* management strategies, should crop safety and efficacy be shown in UK glasshouse crop systems.

Ryanoids

As with avermectins, the literature does not suggest that ryanoid class actives would have a strong impact as a control option against *N. viridula*. Both chlorantraniliprole and cyantraniliprole have caused less than 10% mortality when evaluated against closely-allied *H. halys* adults in both residue and topical application trials (Leskey *et al.*, 2012a, Kuhar & Kamminga, 2017), though higher toxicity to immature nymphs is not excluded as a possibility. Again, this would need to be evaluated, most likely in laboratory-based screening as an initial step preceding field trials.

Flonicamid

Flonicamid is a relatively selective active used against hemipteran and thysanopteran pests, operating as a feeding inhibitor. Despite this, investigations on efficacy against *H. halys* recorded mortality rates of less than 10% on dry residue (Leskey *et al.*, 2012a). Greene & Capps (2004) reported higher mortalities in another pentatomid pest, however, with 21% mortality 24 hours post-application, and 42% mortality four days post-application, in *Acrosternum hilare*.

Flupyradifurone

Flupyradifurone functions as a nicotinic acetylcholine receptor agonist, similarly to neonicotinoids. While very little literature is available at this time in terms of efficacy against pentatomids, a recent laboratory study investigating the toxicity of twelve insecticides against *H. halys* nymphs has suggested that application of formulated flypyradifurone at the Canadian label rate (750ml/ha) caused less than 15% mortality of nymphs 48 hours post-exposure to a topical application, with mortality increasing only to around 20% at twice the label rate (Gradish *et al.*, 2019). Given that the immature nymphs are, typically, most vulnerable to applications, it therefore seems unlikely that adults would suffer higher mortality rates. It therefore seems unlikely that this active would offer a significant *N. viridula* control option for UK growers.

Indoxacarb

This active is targeted at lepidopteran larvae, and as such good efficacy against pentatomid pests would not be expected. This is borne out in the literature, with Greene & Capps (2004) reporting only 16% mortality in *N. viridula* four days post-application, and Tillman (2006b) reporting no tarsal contact or direct ingestion toxicity, although a reduction in feeding time was observed. Similarly, recent studies on *H. halys* have reported less than 10% adult mortality in both dry residue and topical application studies (Leskey *et al.*, 2012a, Kuhar & Kamminga, 2017).

Pymetrozine

Jacobson *et al.* (2013) proposed that pymetrozine should be evaluated for use against *N. viridula*, given the possibility to apply the product both as a foliar spray and through irrigation systems. Whilst this statement still holds based on favourable application options and typically short (e.g. one day) harvest intervals, no further literature has been found at this time to suggest efficacy against pentatomids. Kuhar & Kamminga (2017) suggested that pymetrozine had not been found to be efficacious in controlling *H. halys*, despite efficacy against other soft-bodied hemipteran pests. Collier *et al.* (2017) reported a small reduction in the number of live mirid bugs captured six days following pymetrozine application in poly-tunnel potted celery, but this reduction was not found to be significant compared to that in an untreated control. Based on the scant literature, it seems unlikely that this active would present a useful control measure against *N. viridula*, but evaluation at laboratory and possibly field scales would be required to fully confirm efficacy, or lack thereof.

Spinosad

Spinosad has been reported to have low efficacy against *N. viridula*. Greene & Capps (2004) observed 15% mortality in *N. viridula* four days post-application. Other studies have also suggested low toxicity when applied to egg masses, with only 10% pre-emergence nymph mortality recorded (Brown *et al.*, 2012). Bergmann & Raupp (2014) assessed the efficacy of spinosad against *H. halys* and recorded a slightly higher egg mortality following topical spray application, of around 25% eight days post-exposure. Furthermore, though mortality two days post-application of a topical spray was observed at less than 5% for adults, this increased to around 60% for nymphs following one hour exposure, and approximately 45% for adults and 75% for nymphs following 48 hours of exposure. Similarly, though dry residues were not found to be effective against adult *H. halys*, with less than 10% mortality following both one hour and 48 hours of exposure, mortality of nymphs in response to dry residues was much higher; up to 80% under the best treatment (Bergmann & Raupp, 2014). Cira *et al*. (2017) applied a spinosad product at a rate of 231g product per hectare to *H. halys*, and while they recorded very low mortality of eggs (only 3%) they also observed 96% mortality among those nymphs hatching from the eggs five days after hatch, with disruption to moulting into the second instar and a significant reduction in the number of feeding sites per individual, suggesting a potentially useful sublethal effect at these life stages (though no such effect on adult *H. halys* was observed). Furthermore, Collier *et al.* (2017) reported reductions in live mirid numbers three and six days following spinosad application in potted poly-tunnel celery that tended towards significance. These findings suggest that, while full control using spinosad is unlikely for *N. viridula*, the active could provide a useful component in management strategies. The fact that spinosad-based products are already widely improved in the UK, including for use in protected edible crops (with three day harvest intervals), and further approved for application via irrigation systems, further supports consideration of these products against *N. viridula*, as does the relatively strong IPM profile of this active.

Sulfoxaflor

Little evidence as to the potential efficacy of sulfoxaflor against *N. viridula* is available, though Cira *et al*. (2017) have reported a disruption in first instar *H. halys* nymphs moulting into the second instar, and significantly reduced feeding in adults, after exposure to this active. Further research would be needed to be in order to determine potential efficacy against *N. viridula*.

Lipid synthesis-disrupting actives

Jacobson *et al.* (2013) reported that unpublished information from an Australian contact suggested that the lipid biosynthesis inhibitor spirotetramat had been observed to have an incidental effect on *N. viridula*. Very little literature appears available on potential efficacy against *N. viridula*, but recent work on *H. halys* suggests low levels of efficacy against adults in residue trials, albeit with mortality increasing over time (Leskey *et al.*, 2012a, Kuhar & Kamminga, 2017). A number of such products are available in the UK, including spirotetramat and spirodiclofen (in protected tomato and pepper with a three day harvest interval), but further laboratory and field testing would be required before a sound evaluation against *N. viridula* could be made.

Biopesticides

Entomopathogenic fungi

Populations of *N. viridula* are naturally infected by entomopathogenic fungi, and their potential was reviewed by Jacobson *et al*. (2013). Literature continues to suggest that *Beauveria bassiana*, *Metarhizium anisopliae*, and *Paecilomyces* spp. could play a valuable role in IPM programmes against *N. viridula*, and thus still warrant further investigation. Although natural infection incidences are low, it has been suggested that greater potential is shown by entomopathogenic fungi as biopesticides of sucking pests, such as *N. viridula*, as they require contact rather than ingestion to infect a host (Sosa-Gómez & Moscardi, 1998).

Jacobson *et al*. (2013) described the outcomes of two studies on *N. viridula*. Sosa-Gómez & Moscardi (1998) evaluated isolates of both *M. anisopliae* and *B. bassiana* applied at a rate of 1.5x10^{13} conidia/Ha, with mycosis initially observed 7-15 days post-application and infection levels of up to 41% by 30 days post-application. El-Zoghby (2003) bioassayed *B. bassiana* against third-instar *N. viridula* nymphs, and observed a 23% population reduction 25 days post-application at a rate of 1x10^6 conidia/ml, as described by Jacobson *et al.* (2013). In a more recent study, Raafat *et al.* (2015) evaluated two *B. bassiana* isolates and one *Paecilomyces* isolate for effect against *N. viridula*. Key findings in this study include an observed difference in the ability of fungal isolates to infect *N. viridula*, as well as a spore concentration-dependent pattern in resulting insect mortality. Lethal concentrations of the two *B. bassiana* isolates and the *Paecilomyces* isolate were 323x10^6, 835x10^6 and 281x10^7 conidia/ml, but, dependent on the concentration, mortality rates could change from between 0-10% up to 25-37%. Rafaat *et al*. (2015) suggested that the difference in ability of fungal isolates to infect *N. viridula* targets was attributable to differences in hydrophobic properties of the fungal strains upon contact with host cuticle.

Entomopathogenic fungi have also been assessed for efficacy against a range of other, allied hempiteran pests, a number of which were reviewed by Jacobson *et al.* (2013). Good control of pests ranging from *H. halys*, to *Aelia rostrate* and *Plautia stali* is reported here, and other more recent literature has added further support to the usefulness of entomopathogenic fungi against problem Hemiptera. *Beauveria bassiana*, for example, has been found to have potential as a control measure against *Lygus lineolaris*; Sabbahi *et al*. (2008) reported a number of isolates that gave mortality rates of over 90% in screening tests, with some exerting this effect in fewer than 5 days post-application. Subsequent field trials on strawberry crops, where *B. bassiana* was applied weekly over a period of four weeks, triggered significant reductions in nymphal populations, with mean population densities of one insect per five plants in treated plots and four insects per five plants in untreated plots (Sabbahi *et al*., 2008). Furthermore, infective conidia were found to persist for up to six days after application, with multiple applications at 1x10^{13} conidia/Ha triggering a significant reduction in feeding-induced fruit injuries when compared to control plots.

Research on *H. halys* with existing, commercially available entomopathogenic fungi products has shown considerable promise. In evaluations of three *B. bassiana* and two *M. anisopliae* isolates, Gouli *et al*. (2012) observed good efficacy of *B. bassiana*, with one isolate resulting in between 85% and 100% mortality at nine and twelve days post-application. Somewhat poorer efficacy was seen with *M. anisopliae*, though mortalities of 40-88% were still achieved twelve days post-application. Of particular note is that the highly efficacious isolate of *B. bassiana* used here, *B. bassiana* (GHA), is the active ingredient in BotaniGard®. In more recent work, Parker *et al.* (2015) evaluated two different BotaniGard® formulations, the wettable powder and emulsifiable suspension, against second instar *H. halys*. Both were found to be effective, with applications of 1x10^7 conidia/ml causing 67-80% mortality nine days post-application and 95-100% mortality twelve days post-application, supporting the findings of Gouli *et al.* (2012).

Despite the promise of such studies, stink bugs, including *N. viridula*, have been shown to be naturally resistant to fungal infection due to aldehydes serving as antimycotic agents against certain entomopathogenic fungi as part of their defence secretions (Sosa-Gómez *et al*., 1997; Raafat *et al*, 2015). Furthermore, it is crucial to consider time to death as a critical factor in biopesticide use where *N. viridula* are present, particularly in low-tolerance crops, as it is the feeding which causes crop damage (Knight & Gurr, 2007). It may be possible to overcome these concerns, however, if immature nymphal stages are targeted rather than the adults (Sosa-Gómez & Moscardi, 1998), and if formulation and application is carefully considered to overcome problems of environmental sensitivity that can affect product performance. For example, Knight & Gurr (2007) suggested that the use of oil formulations decreased the impact of unfavourable abiotic conditions on fungal infection success rates, increasing the likelihood that such formulations could have a positive impact on *N. viridula* control, with a similar suggestion on the role of formulation additives also raised by Raafat *et al*. (2015). Further work on how to get the best from these, and other, biopesticides is underway, including through AHDB's AMBER project.

Currently, both *B. bassiana* and *M. anisopliae* are available commercially for use in the UK. *Beauveria bassiana* strain ATCC-74040 (Naturalis-L®) and *M. anisopliae* (Met52 OD®) have been approved for use in a wide range of protected edible crops, including tomato, pepper and aubergine. The findings of this review suggest that these continue to be good candidates for evaluation as part of an IPM approach to *N. viridula* management, warranting further investigation. *Beauveria bassiana* strain GHA is also available in the UK as BotaniGard® WP, and though it is only approved for use in protected ornamentals it may also warrant evaluation given the positive findings against *H. halys*.

Another entomopathogenic fungal product currently available commercially in the UK is *Lecanicillium muscarium* strain Ve6 (Mycotal®), for labelled use against whitefly larvae and noted as having significant impact against thrips and spidermite. There are few publications in the literature available assessing the potential impact of this entomopathogen on pentatomid bugs specifically, and so it is difficult to determine whether it may present a useful candidate for testing. Nevertheless, Erper *et al*. (2016) evaluated four isolates of *L. muscarium* against the green shield bug, *Palomena prasina* L. (Hemiptera: Pentatomidae), in a laboratory study and observed successful pathogenicity with mortality rates of 83-98% twelve days post-application. This suggests potential efficacy of *L. muscarium* against Hemiptera *per se*, although the isolates evaluated did not include the Ve6 strain. Another interesting study to note is Down *et al.* (2009), where the commercially available predatory bug, *O. laevigatus*, was used as an 'entomo-vector' to distribute *L. muscarium* through a crop to target thrips and whitefly. The authors surface dosed *O. laevigatus* individuals with *L. muscarium*, and while they did observe a higher mortality rate in these individuals than in untreated controls during leaf-disc bioassays, their findings during-whole plant bioassays suggested that infection of *O. laevigatus* by the entomopathogen would not have a large impact on the population of this natural enemy within the crop; although individuals were confirmed to have been infected, they were observed to increase in number post release, suggesting that the oviposition of viable *O. laevigatus* eggs had occurred (Down *et al*., 2009). Thus, based on the limited information available, although an evaluation of *L. muscarium* as a potential candidate for control of *N. viridula* in the UK may be of benefit, given pre-existing availability of a commercial product in the UK, the efficacy against *N. viridula* remains to be determined.

Viral pathogens

In trials on virus transmission in *N. viridula*, Williamson & von Wechmar (1992) observed that *N. viridula* from the South African region of Transvaal were more difficult to rear than others from the Western Cape, which they determined to be as a result of virus infection. They were able to isolate two viruses, NVV-1 and NVV-2, from individuals showing severe disease symptoms, which included dehydration, fluid retention, an abnormally large thorax and slow maturation rates. In diseased colonies, a reduction was seen in the number of eggs hatched, and most insects would not develop past the fourth instar. Only 23% of infected insects were able to mature to adulthood, with a reduction in mean life span of some 60% (Williamson & von Wechmar, 1995). Also of note: infection of virus-free *N. viridula* with a mixture of the two viruses resulted in disease symptoms; viruses were vertically transmissible through the eggs; and infection through surface contamination of the food source was also observed. Although NVV-1 and NVV-2 are not indigenous to the UK, they could perhaps be considered for further investigation if studies were able to evaluate specificity to *N. viridula*. It is unlikely that these viruses will be useful to UK growers in the short-term, however, owing to the body of work that would be required before their safe use could be evaluated.

Botanical products

Many plants produce natural chemicals as a defence against herbivorous pests, typically characterised as complex secondary metabolite compounds. These bioactive substances can be derived from these plants to produce insecticides of botanical origin which, while typically broad spectrum, are generally non-persistent in the environment due to rapid degradation (and thus are often highly compatible with integrated management systems).

Azadirachtin is a neem compound derived from *Azadirachta indica* A. Juss (Meliaceae) that has been screened for use against a range of pentatomid pests, including *N. viridula*. Neem extracts have insect growth regulatory activity, and cause, for example, mouthpart deformities in immature *N. viridula* nymphs leading to an inability to feed and subsequent death (Singha *et al*., 2007). Riba *et al*. (2003) observed significant mortality of *N. viridula* during moulting to the adult stage when azadirachtin was applied at 200-500ng per insect, ranging between 86-100%, with survivors often showing nymphal characteristics and dying soon after. Furthermore, applications of 20ng per insect, when applied to 5th instar nymphs, resulted in female adults developing from the treatment showing significantly reduced fecundity, depositing some 75% fewer eggs than under control treatments (Riba *et al*., 2003). Azadirachtin applications have also been shown to reduce the number of *N. viridula*-induced feeding scars on pecans under laboratory conditions, with reductions of between 60-86% observed (Seymour *et al*., 1995). It can also act as an antifeedant and oviposition repellent (Ascher, 1993).

Durmusoglu *et al.* (2003) assessed two different neem-based products against *N. viridula* (NeemAzal T/S®, Trifolio-M GmbH, Germany; and Neem Oil®, Organica Inc., USA) according to manufacturer recommendations, 0.5% and 2% respectively, under laboratory conditions. Neither product was observed to have a significant impact on adult mortality, nor on the mortality of freshly-deposited eggs. The products were, however, more effective against four-day-old egg mortality (61% and 35% for Neem Oil® and NeemAzal®, respectively, fourteen days post-application) and against immature nymphs (ranging between 45-60% and 19-32% for Neem Oil® and NeemAzal®, respectively, fourteen days post-application, with higher mortality of younger 1st instar nymphs and lower mortality for older 5th instar nymphs). Although Neem Oil® was found, in general, to be more effective against *N. viridula* in the trial, it is worth noting that this American product is a mixture containing fatty acids of neem seeds as 25% potassium salt, and this combined impact may well account for the difference in efficacy. NeemAzal® contains 1% azadirachtin, and is approved for use in Europe.

Field evaluations of commercial neem formulations have also suggested that azadirachtin may be a useful management tool for *N. viridula*. Repeated applications of Neemix® 4.5 EC (Certis USA, USA) at a rate of 210.4g azadirachtin per hectare (225ppm azadirachtin in 0.5% aqueous solution of product) were found to reduce densities of *N. viridula* in cowpea by 82-85% ten days after the first application, with adults with morphological deformities observed after a second application (Abudulai *et al.*, 2003). In addition to reduced densities, the same study observed reduced *N. viridula*-induced feeding damage to cowpea pods (by 49-61%) across two years of the trial, and reduced seed damage (by 24-53%) across three years of the trial (Abudulai *et al*., 2003).

Neem compounds have shown mixed results against other hemipteran pests. In an evaluation of domestic ready-to-use insecticides, Bergmann & Raupp (2014) observed over 80% mortality of *H. halys* nymphs following a neem oil extract product application, though mortality of adults was not significantly different from a control treatment. In submersion bioassays, the commercial azadirachtin formulation AzaDirect® (Gowan LLC, USA; 1.2% a.i.) was observed to cause a comparable 78% mortality of *H. halys* nymphs and 55% mortality of adults, but these mortality rates were not found to translate into reductions of feeding injuries when the same products were evaluated in field trials with weekly applications (Morehead & Kuhar, 2017). Lee *et al*. (2014), in laboratory assessments of the same formulation, were also unable to observe significant lethality towards adult *H. halys*. By contrast, in field trials against mirids, NeemAzal® was found to be effective at reducing pest numbers (ranging between 40% and 100% across three years) and feeding damage (ranging between 84% and 97% across three years) of two *Lygocoris* species on apples when compared with an untreated control, with reported values stated to be comparable to those of synthetic insecticides also evaluated (Jaastad *et al.*, 2009).

Although observations on the potential efficacy of neem compounds and azadirachtin appear to vary, certainly between laboratory and field trials, it seems plausible that azadirachtin-containing products could prove useful against *N. viridula*, particularly when targeted against immature nymphs. Such products should be considered for further evaluation and testing for usefulness to UK growers and possible integration into existing management strategies.

Plant essential oils and terpenes are complex volatile plant secondary metabolites, typically characterised by a strong odour, many of which are known to have either insecticidal or repellent properties. A number of these have been evaluated for action against *N. viridula*, and a number of these studies were reviewed by Jacobson *et al*. (2013). To summarise the findings of the review, Jacobson reported that essential oils extracted from the verbenas *Aloysia polystachya* (83.5% carvone) and *A. citriodora* (51.3% citronellal, 22.9% sabinene) reduced *N. viridula* egg hatch by 97% and 100%, respectively at 12.5µg/egg, with 100% 2nd instar nymph mortality recorded six hours after exposure to 88µg/ml *A. polystachya* and 97% 2nd instar nymph mortality recorded 48 hours after exposure to *A. citridora* at the same rate (Werdin González *et al.*, 2010). At doses as low as 2.6µg/ml, both extracts were found to be repellent (Werdin González *et al.*, 2010). Essential oils extracted from oregano (*Origanum vulgare*; 26% ρ-Cymene, 21.9% γ-Terpinene, 16.3% 1-Terpinen-4-ol) and thyme (*Thymus vulgaris*; 47.2% Thymol, 28.4% ρ-Cymene) were found to inhibit *N. viridula* egg hatch by 99.2% and 99.6%, respectively at doses of 12.5µg/egg, with strong fumigant and contact toxicity against both nymphs and adults (Werdin González, 2011b). Essential oils extracted from the peppercorn tree (*Schinus molle* var. *areira*), from both fruits and leaves, were found to be repellent from doses upwards and including 157.2µg/cm^2 after one hour exposure, and while this was still true for essential oils extracted from fruits after 24 hours of exposure, by this point the oils from the leaves had lost potency and therefore effect.

A number of essential oils have also been evaluated as spatial repellents against *H. halys*. Essential oils extracted from pennyroyal (released at 55mg/day), lemongrass (25mg/day), spearmint (80mg/day), clove (14mg/day), wintergreen (63mg/day), rosemary (105mg/day), ylang-ylang (37mg/day), geranium (15mg/day), and a mixture of lemongrass, spearmint and clove at a 1:1:1 ratio, were combined with known pheromone attractants from commercially available stink bug traps (Rescue®), and all showed significant repellency to both *H. halys* nymphs and adults, with significantly fewer captured in the baited traps over the course of the trial (Zhang *et al.*, 2014). The oils extracted from lemongrass, spearmint, clove and ylang-ylang, and the mixture of three oils, reduced catch numbers by over 95%, while oils extracted from pennyroyal, wintergreen rosemary and geranium reduced catches by 60-85% (Zhang *et al.*, 2014). Synthetically generated compounds were also tested in the field with eugenol, *l*-carvone, *p*/*l*-menthone, pulegone, methyl salicylate, *trans*/*cis*-citralm methyl benzoate and β-caryophyllene reducing trap catches by 72-99%, and reasonably accounting for the repellency of their corresponding essential oils (Zhang *et al.*, 2014).

Garlic essential oils have also been evaluated against a number of pests. Though good mortality and repellency have been reported in many studies (e.g. Copping, 2004; Prowse *et al.*, 2006, Yang *et al.*, 2010; Mann *et al*., 2011; Attia *et al.*, 2012; Mobki *et al.*, 2014; Plata-Rueda *et al.*, 2017), other studies have not reported such effects. For example, mirid numbers and associated feeding damage were not found to be consistently reduced by application with a garlic extract product (ECOguard®, Ecospray Ltd, UK) in apple orchards (Jaastad *et al*., 2009), while laboratory studies of the toxicity and side effects of prepared garlic extracts on the beneficial pentatomid predator *Podisus maculiventris* have observed little effect on many biological life-history parameters (Mamduh *et al*., 2017, 2018). It is possible that, in enclosed spaces such as would be afforded by glasshouse growing, garlic may have a stronger impact, as any volatile impact and fumigant capacity should perhaps remain in place for longer than would be expected in the well-ventilated and more environmentally unstable conditions afforded by outdoor systems.

The studies outlined above, while providing variable evidence as to their potential efficacy, nonetheless support that plant essential oils and other botanical products should be further evaluated for potential use against *N. viridula*. While a number of compounds would require considerable further development, several products are already approved for use and available in the UK/EU, for example (but not limited to) 3AEY® (Eden Research), Requiem® (Bayer), Prev-Am® (Oro-Agri) and ECOguard® (Ecospray Ltd). Evaluation of these and other such products for efficacy against *N. viridula* under protected growing conditions would be required before sound conclusions could be drawn, however, and would be essential to determine whether EAMUs may be worth pursuing should efficacy and crop safety be proven. Potential issues around product tainting from certain botanical compounds should also be considered, especially for crops such as pepper which will be harvested every few days, as should the feasibility of achieving effective levels of crop coverage with certain products that rely strongly on product-pest contact, especially in mature crops where this is difficult to achieve.

Semiochemicals

Much research has been conducted on investigating sex and aggregation pheromones across a broad range on pentatomid bugs, and a number of key literature sources were reviewed by Jacobson *et al.* (2013). The identification and study of such pheromones can provide useful insights into pest behaviour, but also present potential management options by allowing either disruption of behaviour or the development of, for example, ‘lure and kill’ strategies. Nevertheless, the current focus of such research is often centred on monitoring (see earlier) rather than control.

Nezara viridula have been repeatedly and clearly shown to respond to pheromones, with adult males producing a sex pheromone that is attractive to females and other males, as well as late-instar nymphs (Harris & Todd, 1980; Aldrich *et al.*, 1987). Studies have confirmed variation across individuals and populations of the *trans* and *cis* epoxide ratios, but typically the pheromone blend consists of (*Z*)-α-bisabolene (17%), *trans*- and *cis*-1,2-epoxides of (*Z*)-α-bisabolene (44 and 15%, respectively), (*E*)-nerolidol (1.4%), and *n*-nonadecane (7.4%) (Aldrich *et al.*, 1987; Miklas *et al.*, 2000). Early instar nymphs are also known to utilise pheromones and chemical signalling to trigger aggregation behaviour (Lockwood & Story, 1985). Fucarino *et al.* (2004), for example, observed first instar *N. viridula* to form significant aggregations around beads treated with 4-Oxo-(*E*)-2-decenal.

Nezara viridula has successfully been trapped in the field using its reported pheromone, in a 3:1 *trans*- to *cis*-(Z)-α-bisabolene blend, with attraction increasing with pheromone dose (Tillman *et al.*, 2010). Indeed, pheromone baiting of pyramid traps has been shown to be effective as a means of capturing a broad range of pentatomid bugs (Aldrich *et al*., 1991; Mizell & Tedders, 1995; Cottrell *et al*., 2000; Johnson *et al.*, 2002; Leskey & Hogmire, 2005; Tillman *et al*., 2010; Nielsen *et al*., 2011; Leskey *et al.*, 2015a), with some studies reporting significant catch numbers (Tillman & Cottrell, 2016). Furthermore, attraction can be significantly increased where a suitable synergist is added. Both Weber *et al.* (2014) and Leskey *et al*. (2015a), for example, were able to significantly increase attraction of *H. halys* in pheromone-baited black pyramid traps with the addition of the synergist methyl (2*E*,4*E*,6*Z*)-decatrienoate.

Although semiochemical use is unlikely to present an efficient standalone control option against *N. viridula*, the use of such products is likely to form an important part of management strategies, particularly in terms of monitoring. Their use in combined ‘lure and kill’ systems is also likely to be an effective constituent part of a programme, but not if used in isolation.

Pentatomid aggregation-triggering pheromones have long been known to also attract their natural enemies (e.g. Harris & Todd, 1980), but much interesting work has more recently been conducted on the role of semiochemicals, kairomones, and other chemical volatile compounds in mediating egg parasitoid interactions with host targets. Peri *et al*. (2013), for example, observed that *Trissolcus* parasitoids showed longer searching behaviour once in contact with associated host chemical footprints, such as those belonging to *N. viridula*, when compared to those left by non-associated hosts, and furthermore that they spent longer on those traces left by female hosts. This supported previous work by Colazza *et al*. (2007), which showed *T. basilis* foraging response was mediated by an *N. viridula* contact kairomone, with traces from females eliciting a stronger response. Although interesting and perhaps useful in the future with further research and development, it is unlikely that this knowledge will be immediately useful in practical terms.

Summary of potential products and actives

A summary of some of the actives discussed as part of this review, with examples of products, is provided in Table 1 below. Where not approved for use in UK or, at least, Europe (LIAISON database, Fera Science Ltd, 2019; EU Pesticides Database, EU Commission, 2019; BCPC, 2019; databases accessed February 2019), classes/products have been excluded.

Table 1. Potential actives that could warrant further investigation/development for the control of *N. viridula* in UK glasshouses. Examples of products, approved crops and targets are not exhaustive and are provided for context. Targets are on-label unless specified. Key crops have been identified, where possible, as being of most relevance to protected edible crops in which *N. viridula* pose the greatest threat. Information accessed via LIAISON database (Fera Science Ltd., 2019), with non-UK EU approvals confirmed via EU Pesticides Database (EU Commission, 2019), in February 2019.

Insecticide type	Active	Example products	Approved for use in…	Target	Notes
Biopesticides					
Entomopathogenic fungi	*Beauveria bassiana*	Naturalis-L®	Protected edibles	Thrips, whitefly	
	Metarhizium anisopliae	Met52 OD®	Protected aubergine, cucumber, pepper, tomato	Pests (none specified)	
	Lecanicillium muscarium	Mycotal®	Protected aubergine, cucumber, tomato, pepper	Thrips, whitefly	
Neem extracts	Azadirachtin	Azatin®	Protected ornamentals	Thrips	
Plant extracts	Garlic	ECOguard®, NEMguard DE®	Protected carrots and parsnips, and some outdoor crops	Nematodes	
	Orange oil	Prev-Am®	EU - wide range of crops	Range of pests	
Terpenoids		3AEY®, Requiem EC®	EU (in progress for UK)	Aphids, whitefly, mites, thrips	
Chemical insecticides					
Pyrethroids	Lambda-cyhalothrin	Hallmark with Zeon Technology®	Wide range including protected aubergine, pepper, tomato	Wide range of insect pests	Off-label approval for use against *N. viridula*

Insecticide type	Active	Example products	Approved for use in…	Target	Notes
	Deltamethrin	Decis®	Wide range including protected aubergine, cucumber, pepper, tomato	Aphids, caterpillars, mealybugs, scale insects, whitefly	
	Cypermethrin	Cythrin 500 EC®	Wide range, including protected brassicas and edible podded peas	Wide range including aphids	
Pyrethrins		Pyrethrum 5 EC®, Spruzit®	Protected aubergine, cucumber, pepper, tomato	Pests (none specified)	
Neonicotinoids	Acetamiprid	Gazelle SG®	Protected aubergine, pepper, tomato	Aphids, whitefly	
	Thiacloprid	Calypso®	Protected aubergine, cucumber, pepper, tomato	Thrips, whitefly, leafminer	
Avermectins	Abamectin	Dynamec®	Protected aubergine, pepper, tomato	Mites, pests (none specified)	
Carbamates	Oxamyl	Vydate 10G®	Protected carrots and some outdoor crops	Nematodes	
	Pirimicarb	Aphox®	Protected peppers, courgette	Aphids	
Ryanoids	Chlorantraniliprole	Coragen®	Protected tomato (off-label)	*Tuta absoluta*	
	Cyantraniliprole	Verimark 20 SC®	Protected brassicas, strawberries	Pests (none specified)	
Other	Flonicamid	Mainman®	Protected aubergine, cucumber, tomato (off-label)	Aphids, whitefly, mealybugs	
	Flupyradifurone	Sivanto® prime	EU – wide range of crops	Range of primarily sucking pests (e.g. aphids, whitefly)	
	Indoxacarb	Rumo®, Steward®	Protected aubergine, cucumber, pepper and tomato	Pests (none specified)	

Insecticide type	Active	Example products	Approved for use in…	Target	Notes
	Pymetrozine	Chess WG®	Protected aubergine, cucumber, pepper, tomato	Aphids, whitefly	
	Spinosad	Spindle®	Protected aubergine, cucumber, pepper, tomato	Pests (none specified)	
	Sulfoxaflor	Sequoia®	Protected aubergine, cucumber, pepper, tomato	Pests (none specified)	
Lipid biosynthesis disruptors	Sirotetramat	Batavia®, Movento®	Protected salads, range of outdoor crops	Aphids, whitefly	
	Spirodiclofen	Envidor®	Protected cucumber, pepper, tomato	Spider mite	
Physically-acting/biorational					
	Maltodextrin	Eradicoat®, Majestik®	Protected edibles	Aphids, whitefly, spider mite	
	Fatty acid soaps	Flipper®	Protected tomatoes, cucumber, peppers, aubergine	Aphids, whitefly, spider mite	
	Dodecylphenol ethoxylate	Agri 50 E®	Edible crops	Aphids, leafhoppers, mealybug, whitefly, spider mite	
	Potassium salts of fatty acids	Jaboland®, Jabolim®, Nakar®	Protected tomatoes, peppers, aubergine	Pests (none specified)	
	Diatomaceous earth	SilicoSec®	EU – stored grains	Stored product pests	
	Kaolin (aluminium silicate)	Surround WP®	EU - orchards	Leafhopper, psyllid, moth	

Current Overseas Control Practices and Opportunities for Application in the UK

Current management practice overseas relies, most typically, on the application of broad-spectrum conventional chemical insecticides, particularly pyrethroids, organophosphates and neonicotinoids. There has not been significant new research evaluating efficacy of such actives against *N. viridula* since the Johnson *et al.* (2013) review, with much new research instead focusing on the closely-allied *H. halys*, against which, again, current management practice relies on broad-spectrum insecticides, with neonicotinoids recommended for control in Asia.

Certain organophosphate actives are being phased out across Europe, and certainly those actives evaluated in the studies cited in this review are not approved for use in the EU or the UK at this time, nor are they considered compatible with IPM and the approaches used in current glasshouse production. They do not, therefore, present a useful opportunity for application for UK growers, despite potential efficacy. Pyrethroids and neonicotinoids have been used overseas with relative success. Pyrethroids, while typically considered relatively incompatible with IPM programmes, could provide a useful 'last resort' in cases of likely unacceptable economic damage resulting from infestation. Neonicotinoids, in particular due to the class's systemic activity, could be especially helpful in high-wire glasshouse production, where complete coverage of a plant can be difficult to achieve.

There is also particular interest overseas on the role of biopesticides and plant-derived products, especially organically-approved ones, with a growing body of research to evaluate their efficacy. Although it would not appear that these have yet become the norm in terms of control practice, and varying results have been obtained in reported studies, such products would be more likely to present an opportunity for application in the UK as they are typically more compatible with IPM programmes.

Conclusions

The southern green shieldbug (*Nezara viridula*), is already a significant pest of certain protected crops where it occurs in the UK, particularly peppers, with potential to spread to other crops and regions of the country. Though *N. viridula* feeds on all vegetative parts of the plant, the greatest impact is seen in developing fruit and new growth. The insect can appear early in the season and has the potential to drive significant crop losses through the production period, both through direct feeding and the potential of this pest to spread crop disease and facilitate pathogen infection through plant parts damaged during feeding.

Given the above, the current review represents a timely update to our knowledge on possible control measures for this pest, with a view to informing further trials of promising plant protection products and IPM options. For the different management options considered, conclusions for each are provided below. Overall, it could be surmised that sufficient evidence exists to support that progress in IPM of *N. viridula* could be made through advances in multiple areas, with near-market gains achievable through validation of light/pheromone trapping, trap plants, selected plant protection products and (generalist) biological control. The latter, along with vibrational disruption and use of certain conventional pesticides (e.g. pyrethroids and avermectins) are of particular interest to the industry based on consultation undertaken as part of this review, and should be prioritised for further development on this basis.

Physical monitoring

Physical monitoring appears to be the current norm for southern green shieldbug, though it is labour-intensive and not well-suited for use in high-wire glasshouse crops in the UK. Light trapping, pheromone trapping and trap planting could all potentially assist in monitoring of this pest, though need to be validated within UK glasshouses for practicality, efficacy and cost-effectiveness.

Physical means of control

Whilst the literature suggests interesting and scientifically intriguing possibilities for using vibration to disrupt *N. viridula* mating, R&D effort would be needed to develop and validate such technology. Semiochemical mating disruption could be nearer-market, with other physical control measures noted as being effective (i.e. barriers), but probably impractical to implement within a glasshouse setting. Opportunity may exist for improving targeting of *N. viridula* infestations during empty periods, where in this instance guidance on optimal clean down procedures would be welcomed by the industry.

Natural enemies

Several species of pest natural enemies hold potential against *N. viridula*, though at present only generalist predators are accessible to growers. Although these would not be expected to target all *N. viridula* stages, *Macrolophus* and *Orius* could potentially predate southern green shieldbug, with lacewings and ladybirds also warranting further investigation.

Basic substances

Physically acting biorational products are highly versatile, generally with strong safety profiles, though they have shown mixed results in demonstrating efficacy, especially against larger-bodied pests like *N. viridula*. These products are also typically relatively broad-spectrum and require short-interval repeated application to exert a meaningful effect, potentially causing conflict with biological control programmes. Careful and considered evaluation of these products should therefore be undertaken within the context of overall glasshouse IPM programmes.

Chemical insecticides

Little work has been conducted on chemical insecticide use against *N. viridula* since the publication of the last AHDB review on this pest by Jacobson *et al*. (2013). There nevertheless remain a number of potential actives that could be useful in targeting this pest, several of which are already approved for use in protected edible crops, and some of which can be applied through irrigation systems and/or display systemic activity. Such products should arguably be prioritised for testing against *N. viridula*, ensuring levels of crop coverage and pest targeting that would be hard to achieve with non-systemic / non-translaminar products. Irrigation-applied products could be particularly useful, causing minimal disruption to established biological control programmes that are vital in protected edible systems to manage other key pest species. Harvest intervals will need to be carefully considered, however, to ensure that these are compatible with fruit picking timings; even a relatively modest three day interval may be problematic, though certain potentially interesting products operate to one day intervals, including in protected edible crops.

Biopesticides

It appears from the available literature that microbial-based products may hold particular promise against *N. viridula*, although certain botanical products have also been shown to demonstrate efficacy against this and similar pests. For both product types, care should be taken to ensure that trials are undertaken not only to confirm efficacy, but also to validate commercial applicability, where for many biopesticides the practicalities of field use (e.g. to ensure pest-product contact) may be more limiting to pest control potential, especially in high-wire crops with complex architectures, than the activity of the product *per se*.

Acknowledgements

The authors would like to thank AHDB for funding and supporting this project and for the financial and in-kind contributions from the crop protection manufactures and distributors involved with the SCEPTREplus programme as listed below:
Agrii, Alpha Biocontrol Ltd, Andermatt, Arysta Lifescience, BASF, Bayer, Belchim, Bionema Limited, Certis Europe, Dow, DuPont, Eden Research, Fargro Limited, FMC, Gowan, Interfarm, Lallemand Plant Care, Novozymes, Oro Agri, Russell IPM, Sumitomo Chemicals, Syngenta, UPL.

The authors would also like to thank the attendees at the Grower Focus Group for their very useful insight and feedback, including John Cappalonga (Focus Group organiser and project collaborator), Luke Hibberd and Alan Chambers, as well as other attendees who elected not to be named in this review report.

References

Abudulai, M., Shepard, B.M. & Salifu, A.B. (2003) Field evaluation of a neem (*Azadirachta indica* A. Juss)-based formulation Neemix® against *Nezara viridula* (L.) (Hemiptera: Pentatomidae) in cowpea. *International Journal of Pest Management*, **49**, 109-113.

Aldrich, J.R., Oliver, J.E., Lusby, W.R., Kochansky, J.P. & Lockwood, J.A. (1987) Pheromone strains of the cosmopolitan pest, *Nezara viridula* (Heteroptera: Pentatomidae). *Journal of Experimental Zoology*, **244**, 171-175.

Aldrich, J.R., Hoffman, M.P., Kochansky, J.P., Lusby, W.R., Eger, J.E. & Payne, J.A. (1991) Identification and attractiveness of a major component for Nearctic *Euschistus* spp. stink bugs (Heteroptera: Pentatomidae). *Environmental Entomology*, **20**, 477-483.

Amalin, D.M., Averion, L., Bihis, D., Legaspi, J.C. & David, E.F. (2015) Effectiveness of kaolin clay particle film in managing *Helopeltis collaris* (Hemiptera: Miridae), a major pest of cacao in The Philippines. *The Florida Entomologist*, **98**, 354-355.

Anderson, R.M. & Teetes, G.L. (1995) Evaluation of insecticides for suppression of stink bugs on sorghum. *Arthropod Management Tests*, **21**, 295.

Ascher, K.R.S. (1993) Nonconventional insecticidal effects of pesticides available from the Neem tree, *Azadirachta indica*. *Insect Biochemistry and Physiology*, **22**, 433-449.

Athanassiou, C.G., Vayias, B.J., Dimizas, C.B., Kavallieratos, N.G., Papagregoriou, A.S. & Buchelos, C.Th. (2005) Insecticidal efficacy of diatomaceous earth against *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) and

Tribolium confusum du Val (Coleoptera: Tenebrionidae) on stored wheat: influence of dose rate, temperature and exposure interval. *Journal of Stored Products Research*, **41**, 47-55.

Attia, S., Grissa, K.L., Mailleux, A.C., Lognay, G., Heuskin, S., Mayoufi, S. & Hance, T. (2012) Effective concentrations of garlic distillate (*Allium sativum*) for the control of *Tetranychus urticae* (Tetranychidae). *Journal of Applied Entomology*, **136**, 302-312.

Barraclough, D.A. (1985) The Afrotropical genus *Bogosia* Rondani, 1873 (Diptera: Tachinidae). *Annals of the Natal Museum*, **26**, 339–376.

Baehaki, S.E., Iswanto, E.H., Munawar, D. & Sumaryono, N. (2016) Light traps abilities of mercury (ML-160 watt) BSE models and light traps of solar cell (CFL-20 Watt) to capture pests in the rice field. *American Journal of Engineering Research*, **5**, 138-144.

Bayer Crop Science (2019) *Crop Compendium:* Nezara viridula. Accessed 25th January 2019. <https://www.cropscience.bayer.com/en/crop-compendium/pests-diseases-weeds/pests/nezara-viridula>

British Crop Protection Council (BCPC) (2019) The UK Pesticide Guide 2019. Lainsbury, M.A. (ed). Hobbs the Printers Ltd, Totton (UK).

Beers, E.H. & Himmel, P.D. (2002) 'Control of *Camplyomma verbasci* with registrated and unregistrated pesticides'. In: *Proceedings of the 76th Annual Western Orchard Pest and Disease Management Conference*; Portland (OR, USA), January 2002.

Bergmann, E.J. & Raupp, M.J. (2014) Efficacies of common ready to use insecticides against *Halyomorpha halys* (Hemiptera: Pentatomidae). *The Florida Entomologist*, **97**, 791-800.

Brown, S.A., Davis, J.A. & Richter, A.R. (2012) Efficacy of foliar insecticides on eggs of *Nezara viridula* (Hemiptera: Pentatomidae). *The Florida Entomologist*, **95**, 1182-1186.

Bundy, C.S. & McPherson, R.M. (2000) Dynamics and seasonal abundance of stink bugs (Heteroptera: Pentatomidae) in a cotton-soybean ecosystem. *Journal of Economic Entomology*, **93**, 697-706.

Buschman, L.L. & Whitcomb, W.H. (1980) Parasites of *Nezara viridula* (Hemiptera: Pentatomidae) and other Hemiptera in Florida. *The Florida Entomologist*, **63**, 154-167.

CABI (2018) *Invasive Species Compendium: Datasheet* – Trissolcus basalis. Accessed 25th January 2019. < https://www.cabi.org/isc/datasheet/54843>

Cambridge, J.E., Francoeur, L. & Hamilton, G.C. (2017) Brown marmorated stink bug (Hemiptera: Pentatomidae) attraction to various light stimuli. *The Florida Entomologist*, **100**, 583-588.

Cantelo, W.W., Smith, J.S. Jr, Baumhover, A.H., Stanley, J.M., Henneberry, T.J. & Peace, M.B. (1973) Changes in the population levels of 17 insect species during a $3^1/_2$-year blacklight trapping program. *Environmental Entomology*, **2**, 1033-1038.

Cantelo, W.W., Goodenough, J.L., Baumhover, A.H., Smith, J.S. Jr, Stanley, J.M. & Henneberry T.J. (1974) Mass trapping with blacklights: effects on isolated populations of insects. *Environmental Entomology*, **3**, 389-395.

Cira, T.M., Burkness, E.C., Koch, R.L. & Hutchison, W.D. (2017) *Halyomorpha halys* mortality and sublethal feeding effects following insecticide exposure. *Journal of Pest Science*, **90**, 1257-1268.

Clarke, A.R. & Seymour, J.E. (1992) Two species of *Acroclissoides* Girault and Dodd (Hymenoptera: Pteromalidae) parasitic on *Trissolcus basalis* (Wollaston) (Hymenoptera: Scelionidae), a parasitoid of *Nezara viridula* (L.) (Hemiptera: Pentatomidae). *Journal of the Australian Entomological Society*, **31**, 299–300.

Čokl, A., Virant-Doberlet, M. & McDowell, A. (1999) Vibrational directionality in the southern green stink bug, *Nezara viridula* (L.), is mediated by female song. *Animal Behaviour*, **58**, 1277-1283.

Čokl, A., Virant-Doberlet, M. & Stritih, N. (2000) The structure and function of songs emitted by southern green stink bugs from Brazil, Florida, Italy and Slovenia. *Physiological Entomology*, **25**, 196-205.

Colazza, S., Aquila, G., De Pasquale, C., Peri, E. & Millar, J.G. (2007) The egg parasitoid *Trissolcus basalis* uses *n*-nonadecane, a cuticular hydrocarbon from its stink bug host *Nezara viridula*, to discriminate between female and male hosts. *Journal of Chemical Ecology*, **33**, 1405-1420.

Collier, R., Norman, D., George, D., Jukes, A. & Elliott, M. (2017) *Celery: Investigations of strategies to control mirid bugs in outdoor crops.* AHDB Final Project Report. AHDB, U.K.

Coombs, M.T. (2000) Seasonal phenology, parasitism, and evaluation of mowing as a control measure for *Nezara viridula* (Hemiptera: Pentatomidae) in Australian pecan. *Environmental Entomology*, **29**, 1027-1033.

Coombs, M. & Sands, D.P.A. (2000) Establishment in Australia of *Trichopoda giacomellii* (Blanchard) (Diptera: Tachinidae), a biological control agent for *Nezara viridula* (L.) (Hemiptera: Pentatomidae). *Australian Journal of Entomology*, **39**, 219-222.

Copping, L.G. (2004) *The Manual of Biocontrol Agents*. 3rd ed. BCPC, Hampshire (UK).

Corrêa-Ferreira, B.S. & Moscardi, F. (1996) Biological control of soybean stink bugs by inoculative releases of *Trissolcus basalis*. *Entomologia Experimentalis et Applicata*, **79**, 1-7.

Cottrell, T.E., Yonce, C.E. & Wood, B.W. (2000) Seasonal occurrence and vertical distribution of *Euschistus servus* (Say) and *Euschistus tristigmus* (Say) (Hemiptera: Pentatomidae) in pecan orchards. *Journal of Entomological Science*, **35**, 421-431.

Cusumano, A., Peri, E., Amodeo, V., McNeil, J.N. & Colazza, S. (2013) Intraguild interactions between egg parasitoids: window of opportunity and fitness costs for a facultative hyperparasitoid. *PLoS One*, **8**, e64768.

Davis, C.J. & Krauss, N.L.H. (1965) Recent introductions for biological control in Hawaii – X. *Proceedings of the Hawaiian Entomological Society*, **18**, 87–90.

Day, W.H. (2019) *Peristenus digoneutis*. In: Shelton, A. (ed) *Biological Control: A Guide to Natural Enemies in North America.* Accessed 30th January 2019. <https://biocontrol.entomology.cornell.edu/parasitoids/peristenus.php#>

De Clercq, P., Wyckhuys, K., De Oliveira, H. & Klapwijk, J. (2002) Predation by *Podisus maculiventris* on different life stages of *Nezara viridula*. *The Florida Entomologist*, **85**, 197-202.

De Groot, M., Virant-Doberlet, M. & Žunič, A. (2007) *Trichopoda pennipes* F. (Diptera, Tachinidae): a new natural enemy of *Nezara viridula* (L.) in Slovenia - short communication. *Agricultura (Slovenia)*, **5**, 25-26.

Down, R.E., Cuthbertson, A.G.S., Methers, J.J. & Walters, K.F.A. (2009) Dissemination of the entomopathogenic fungi, *Lecanicillium longisporum* and *L. muscarium*, by the predatory bug, *Orius laevigatus*, to provide concurrent control of *Myzus persicae*, *Frankliniella occidentalis* and *Bemisia tabaci*. *Biological Control*, **50**, 172-178.

Durmusoglu, E., Karsavuran, Y., Ozgen, I. & Guncan, A. (2003) Effects of two different neem products on different stages of *Nezara viridula* (L.) (Heteroptera, Pentatomidae). *Journal of Pest Science*, **76**, 151-154.

Ehler, L.E. (2002) An evaluation of some natural enemies of *Nezara viridula* in northern California. *BioControl*, **47**, 309-325.

El-Zoghby, A.A. (2003) Studies for using *Beauveria bassiana* (Bals.) Vuillemin on controlling the green stink bug *Nezara viridula* L. (Heteroptera: Pentatomidae) in sugar beet plantations in Egypt. *Egyptian Journal of Biological Pest Control*, **13**, 47-49.

Endo, N. (2016) Effective monitoring of the population dynamics of *Nezara viridula* and *Nezara antennata* (Heteroptera: Pentatomidae) using a light trap in Japan. *Applied Entomology and Zoology*, **51**, 341-346.

Endo, N., Wakakuwa, M., Arikawa, K., Hironaka, M. (2014) Spectral preference in a free-flying condition of the southern green stink bug, *Nezara viridula* (Heteroptera: Pentatomidae). *Japanese Journal of Applied Entomology and Zoology*, **58**, 23-38.

Erper, I., Saruhan, I., Akca, I., Aksoy, H.M. & Turner, C. (2016) Evaluation of some entomopathogenic fungi for controlling the green shield bug, *Palemena prasina* L. (Heteroptera: Pentatomidae). *Egyptian Journal of Biological Pest Control*, **26**, 573-578.

European Union Commission (2019) EU Pesticides Database. Accessed February 2019. <http://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/public/>

Fera Science Ltd. (2019) LIAISON. Accessed February 2019. <https://secure.fera.defra.gov.uk/liaison/>

Fucarino, A., Miller, J.G., McElfresh, J.S. & Colazza, S. (2004) Chemical and physical signals mediating conspecific and heterospecific aggregation behavior of first instar stink bugs. *Journal of Chemical Ecology*, **30**, 1257-1269.

Gradish, A.E., Fraser, H. & Scott-Dupree, C.D. (2019) Direct and residual contact toxicity of insecticides to *Halyomorpha halys* (Hemiptera: Pentatomidae). *The Canadian Entomologist*, **00**, e1-10. Online First View, doi:10.4039/tce.2018.62

Greene, J.K., Herzog, G.A., Roberts, P.M. (2001) Management decisions for stink bugs. In: *Proceedings of the 2001 Beltwide Cotton Conference*; Anaheim (CA, USA), January 2001; Cotton Council of America, TN (USA).

Greene, J.K. & Capps, C.D. (2004) Efficacy of selected insecticides for control of stink bugs. In: *Summaries of Arkansas Cotton Research 2004 – Arkansas*

Agricultural Experiment Station Research Series 533; University of Arkansas System, Arkansas (USA), pp. 177-185.

Gouli, V., Gouli, S., Skinner, M., Hamilton, G.H., Kim, J.S. & Parker, B.L. (2012) Virulence of select entomopathogenic fungi to the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae). *Pest Management Science*, **68**, 155-157.

Harris, V.E. & Todd, J.W. (1980) Male-mediated aggregation of male, female and 5th-instar southern green stink bugs and concomitant attraction of a tachinid parasite, *Trichopoda pennipes*. *Entomologia Experimentalis et Applicata*, **27**, 117-126.

Haye, T., Fischer, S., Zhang, J. & Gariepy, T. (2015) Can native egg parasitoids adopt the invasive brown marmorated stink bug, *Halyomorpha halys* (Heteroptera: Pentatomidae), in Europe? *Journal of Pest Science*, **88**, 693-705.

Hokkanen, H. (1986) Polymorphism, parasites, and the native area of *Nezara viridula* (Hemiptera: Pentatomidae). *Annales Entomologici Fennici*, **52**, 28-31.

Jaastad, G., Trandem, N., Hovland, B. & Mogan, S. (2009) Effect of botanically derived pesticides on mirid pests and beneficials in apple. *Crop Protection*, **28**, 309-313.

Jacobson, R.J. (2012) *Southern Green Shieldbug*. HDC Factsheet 36/12. AHDB, U.K.

Jacobson, R.J. (2014) *Potential controls for Southern Green Shieldbug in UK glasshouses*. HDC Briefing Note: Protected Edibles. AHDB, U.K.

Jacobson, R.J. & Morley, P. (2007) *Organic tomato: Development and implementation of a robust pesticide-free IPM programme*. HDC Final Project Report. AHDB, U.K.

Jacobson, R.J., Cuthbertson, A., Fountain, M. & Hassan, N. (2013) *Peppers and aubergine: A desk study to identify IPM compatible control measures for* Nezara viridula *and* Anthomonus eugenii*.* AHDB Final Project Report. AHDB, U.K.

Johnson, D.T., Lewis, B.A. & Mizell III, R.F. (2002) Trapping brown stink bugs in peach. *Horticultural Studies 2001: Arkansas Agricultural Experiment Station Research Serial*, **494**, 19-23.

Jones, W.A. (1988) World review of the parasitoids of the Southern Green Stink Bug, *Nezara viridula* (L.) (Heteroptera: Pentatomidae). *Annals of the Entomological Society of America*, **81**, 262-273.

Kabir, B.G.J. & Abdulrahman, H.T. (2018) 'Evaluation of insecticidal efficacy and persistence of Nigerian raw diatomaceous earth against *Callosobruchus maculatus* (F.) on stored cowpea'. *12th International Working Conference on Stored Product Protection (IWCSPP)*; Berlin (Germany), 7th-11th October 2018.

Knight, K.M.M. & Gurr, G.M. (2007) Review of *Nezara viridula* (L.) management strategies and potential for IPM in field crops with emphasis on Australia. *Crop Protection*, **26**, 1-10.

Koppert Biological Systems (2017) '*Nezara viridula*'. In: *Knowing and Recognising: The biology of pests, diseases and their natural enemies*. Koppert B.V., Berkel en Rodenrijs (The Netherlands), pp. 309-310.

Kuhar, T.P. & Kamminga, K. (2017) Review of the chemical control research on *Halyomorpha halys* in the USA. *Journal of Pest Science*, **90**, 1021-1031.

Lalancette, N., Belding, R.D., Shearer, P.W., Frecon, J.L. & Tietjen, W.H. (2005) Evaluation of hydrophobic and hydrophilic kaolin particle films for peach crop, arthropod and disease management. *Pest Management Science*, **61**, 25-39.

Laumann, R.A., Maccagnan, D.H.B., Čokl, A., Blassioli-Moraes, M.C. & Borges, M. (2018) Substrate-borne vibrations disrupt the mating behaviors of the neotropical brown stink bug, *Euschistus heros*: implications for pest management. *Journal of Pest Science*, **91**, 995-1004.

Lee, D.-H. (2015) Current status of research progress on the biology and management of *Halyomorpha halys* (Hemiptera: Pentatomidae) as an invasive species. *Applied Entomology and Zoology*, **50**, 277-290.

Lee, D.-H., Short, B.D., Joseph, S.V., Bergh, J.C. & Leskey, T.C. (2013) Review of the biology, ecology, and management of *Halyomorpha halys* (Hemiptera: Pentatomidae) in China, Japan, and the Republic of Korea. *Environmental Entomology*, **42**, 627-641.

Lee, D.H., Short, B.D., Nielsen, A.L. & Leskey, T.C. (2014) Impact of organic insecticides on the survivorship and mobility of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) in the laboratory. *The Florida Entomologist*, **97**, 414-421.

Leskey, T.C. & Hogmire, H.W. (2005) Monitoring stink bugs (Hemiptera: Pentatomidae) in mid-Atlantic apple and peach orchards. *Journal of Economic Entomology*, **98**, 143-153.

Leskey, T.C., Lee, D.-H., Short, B.D., Wright, S.E. (2012a) Impact of insecticides on the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae): analysis of insecticide lethality. *Journal of Economic Entomology*, **105**, 1726-1735.

Leskey, T.C., Short, B.D., Butler, B.R. & Wright, S.E. (2012b) Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae) in mid-Atlantic tree fruit orchards in the United States: case studies of commercial management. *Psyche*, **2012**, e1-14.

Leskey, T.C., Short, B.D. & Lee, D.-H. (2014) Efficacy of insecticide residues on adult *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) mortality and injury in apple and peach orchards. *Pest Management Science*, **70**, 1097-1104.

Leskey, T.C., Agnello, A., Bergh, J.C., Videly, G.P., Hamilton, G.C., Jentsch, P., Khrimian, A., Krawczyk, G., Kuhar, T.P., Lee, D.-L., Morrison III, W.R., Polk, D.F., Rodriguez-Saona, C., Shearer, P.W., Short, B.D., Shrewsbury, P.M., Walgenbach, J.F., Weber D.C., Welty, C., Whalen, J., Wiman, N. & Zaman, F. (2015a) Attraction of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) to traps baited with semiochemical stimuli across the United States. *Environmental Entomology*, **44**, 746-756.

Leskey, T.C, Lee, D.-H., Glenn, D.M., Morrison III, W.R. (2015b) Behavioural responses of the invasive *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) to light-based stimuli in the laboratory and field. *Journal of Insect Behaviour*, **28**, 674-692.

Lockwood, J.A. & Story, R.N. (1985) Bifunctional pheromone in the first instar of the southern green stink bug, *Nezara viridula* (L.) (Hemiptera: Pentatomidae): its characterization and interaction with other stimuli. *Annals of the Entomological Society of America*, **78**, 474-479.

López, J.D. Jr, Latheef, M.A. & Hoffmann, W.C. (2013) Toxicity of selected insecticides and insecticide mixtures in glass-vial bioassay of southern green stink bug (Hemiptera: Pentatomidae) from Central Texas. *Southwestern Entomologist*, **38**, 571-578.

Mamduh, Z., Hosseininaveh, V., Allahyari, H. & Talebi-Jahromi, K. (2017) Side effects of garlic extract on the life history parameters of the predatory bug, *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae). *Crop Protection*, **100**, 65-72.

Mamduh, Z., Hosseininaveh, V., Fazeli, M.M., Talebi-Jahromi, K. (2018) Toxicity of garlic extract on spined soldier bug, *Podisus maculiventris* (Hemiptera: Pentatomidae) in comparison to its two hosts. *Journal of Crop Protection*, **7**, 93-107.

Mathews, C.R., Blaauw, B., Dively, G., Kotcon, J., Moore, J., Ogburn, E., Pfeiffer, D.G., Trope, T., Walgenbach, J.F., Welty, C., Zinati, G. & Nielsen, A.L. (2017) Evaluating a polyculture trap crop for organic management of *Halyomorpha halys* and native stink bugs in peppers. *Journal of Pest Science*, **90**, 1245-1255.

Mann, R.S., Rouseff, R.L., Smoot, J.M., Castle, W.S. & Stelinski, L.L. (2011) Sulfur volatiles from *Allium* spp. affect Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae), response to citrus volatiles. *Bulletin of Entomological Research*, **101**, 89-97.

Marcotegui, A., Sánchez-Ramos, I., Pascual, S., Fernández, C.E., Cobos, G., Armendáriz, I., Cobo, A. & González-Núñez, M. (2015) Kaolin and potassium soap with thyme essential oil to control *Monosteira unicostata* and other phytophagous arthropods of almond trees in organic orchards. *Journal of Pest Science*, **88**, 753-765.

Martin, N.A. (2016, revised 2018) Green vegetable bug - *Nezara viridula*. In: *Interesting Insects and other Invertebrates: New Zealand Arthropod Factsheet Series Number 47*. Accessed 4th March 2019. <http://nzacfactsheets.landcareresearch.co.nz/Index.html> ISSN 1179-643X.

McPherson, R.M. & Newsom, L.D. (1984) Trap crops for control of stink bugs in soybean. *Journal of the Georgia Entomological Society*, **19**, 470-480.

McPherson, J.E. & Sites, R.W. (1989) Annotated records of species of Pentatomidae (Hemiptera) collected at lights. *The Great Lakes Entomologist*, **22**, 95-98.

Miklas, N., Renou, M., Malosse, I. & Malosse, C. (2000) Repeatability of pheromone blend composition in individual males of the southern green stink bug, *Nezara viridula*. *Journal of Chemical Ecology*, **26**, 2473-2485.

Millar, G., McBrien, J.H.L., Ho, Y., Rice, R.R., Cullen, E., Zalom, F.G. (2002) Pentatomid bug pheromones in IPM: possible applications and limitations. *IOBC wprs Bulletin*, **25**, e1-11.

Mizell III, R.F. & Tedders, W.L. (1995) A new monitoring method for detection of the stink bug complex in pecan orchards. *Proceedings of the Southeastern Pecan Growers Association*, **88**, 36-40.

Mobki, M., Safavi, S.A., Safaralizadeh, M.H. & Panahi, O. (2014) Toxicity and repellency of garlic (*Allium sativum* L.) extract grown in Iran against *Tribolium castaneum* (Herbst) larvae and adults. *Archives of Phytopathology and Plant Protection*, **47**, 59-68.

Morehead, J.A. & Kuhar, T.P. (2017) Efficacy of organically approved insecticides against brown marmorated stink bug, *Halyomorpha halys* and other stink bugs. *Journal of Pest Science*, **90**, 1277-1285.

Newsom, L.D. & Herzog, D.C. (1977) Trap crops for control of soybean pests. *Louisiana Agriculture*, **20**, 14-15.

Nielsen, A.L., Shearer, P.W., Hamilton, G.C. (2008) Toxicity of insecticides to *Halyomorpha halys* (Hemiptera: Pentatomidae) using glass-vial bioassays. *Journal of Economic Entomology*, **101**, 1439-1442.

Nielsen, A.L., Hamilton, G.C. & Shearer, P.W. (2011) Seasonal phenology and monitoring of the non-native *Halyomorpha halys* (Hemiptera: Pentatomidae) in soybean. *Environmental Entomology*, **40**, 231-238.

Nielsen, A.L., Dively, G., Pote, J.M., Zinati, G. & Mathews, C. (2016) Identifying a potential trap crop for a novel insect pest, *Halyomorpha halys* (Hemiptera: Pentatomidae), in organic farms. *Environmental Entomology*, **45**, 472-478.

Ogburn, E.C., Bessin, R., Dieckhoff, C., Dobson, R., Grieshop, M., Hoelmer, K.A., Mathews, C., Moore, J., Nielsen, A.L., Poley, K., Pote, J.M., Rogers, M., Welty, C. & Walgenbach, J.F. (2016) Natural enemy impact on eggs of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in organic agroecosystems: a regional assessment. *Biological Control*, **101**, 39-51.

Panizzi, A.R., Berhow, M. & Bartelt, R.J. (2004) Artificial substrate bioassay for testing oviposition of southern green stink bug conditioned by soybean plant chemical extracts. *Environmental Entomology*, **33**, 1217-1222.

Pansa, M.G., Blandino, M., Ingegno, B.L., Ferrari, E., Reyneri, A. & Tavella, L. (2015) Toxicity and persistence of three pyrethroids for the control of cereal bugs on common wheat. *Journal of Pest Science*, **88**, 201-208.

Parker, B.L., Skinner, M., Gouli, S., Gouli, V. & Kim, J.S. (2015) Virulence of BotaniGard® to second instar brown marmorated stink bug, *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae). *Insects*, **6**, 319-324.

Peri, E., Frati, F., Salerno, G., Conti, E. & Colazza, S. (2013) Host chemical footprints induce host sex discrimination ability in egg parasitoids. *PLoS One*, **8**, e79054.

Plata-Rueda, M., Martínez, L.C., Santos, M.H.D., Fernandes, F.L., Wilcken, C.F., Soares, M.A., Serrão, J.E. & Zanuncio, J.C. (2017) Insecticidal activity of garlic essential oil and their constituents against the mealworm beetle, *Tenebrio molitor* Linnaeus (Coleoptera: Tenebrionidae). *Scientific Reports*, **7**, 46406.

Polajnar, J. & Čokl, A. (2008a) The effect of noise on sexual behaviour of the southern green stink bug *Nezara viridula*. *Bulletin of Insectology*, **61**, 181-182.

Polajnar, J. & Čokl, A. (2008b) The effect of vibratory disturbance on sexual behaviour of the southern green stink bug *Nezara viridula* (Heteroptera, Pentatomidae). *Central European Journal of Biology*, **3**, 189-197.

Prowse, G.M, Galloway, T.S. & Foggo, A. (2006) Insecticidal activity of garlic juice in two dipteran pests. *Agricultural and Forest Entomology*, **8**, 1-6.

Raafat, I., Meshrif, W.S., El Husseiny, E.L., El-Hariry, M. & Seif, A.I. (2015) *Nezara viridula* (Hemiptera: Pentatomidae) cuticle as a barrier for *Beauveria bassiana* and *Paecilomyces* sp. infection. *African Entomology*, **23**, 75-87.

Rea, J.H., Wratten, S.D., Sedcole, R., Cameron, P.J. & Davis, S.I. (2002) Trap cropping to manage green vegetable bug *Nezara viridula* (L.) (Heteroptera: Pentatomidae) in sweet corn in New Zealand. *Agricultural and Forest Entomology*, **4**, 101-107.

Rea, J.H., Cameron, P.J., Wratten, S.D., Davis, S.I., Sedcole, J.R. & Chapman, R.B. (2003) Evaluation of insecticides for the control of the green vegetable bug, *Nezara viridula* (L.) (Hemiptera: Pentatomidae), on sweet corn, *Zea mays* (L.), in New Zealand. *International Journal of Pest Management*, **49**, 105-108.

Riba, M., Martí, J. & Sans, A. (2003) Influence of azadirachtin on development and reproduction of *Nezara viridula* L. (Het., Pentatomidae). *Journal of Applied Entomology*, **127**, 37-41.

Rice, K.B., Bergh, C.J., Bergmann, E.J., Biddinger, D.J., Dieckhoff, C., Dively, G., Fraser, H., Gariepy, T., Hamilton, G., Haye, T., Herbert, A., Hoelmer, K., Hooks, C.R., Jones, A., Krawczyk, G., Kuhar, T., Martinson, H., Mitchell, W., Nielsen, A.L., Pfeiffer, D.G., Raupp, M.J., Rodriguez-Saona, C., Shearer, P., Shrewsbury, P., Venugopal, P.D., Whalen, J., Wiman, N.G., Leskey, T.C. & Tooker, J.F. (2014) Biology, ecology, and management of brown marmorated stink bug (Hemiptera: Pentatomidae). *Journal of Integrated Pest Management*, **5**, a1-a13.

Salerno, G., Colazza, S. & Bin, F. (2002) *Nezara viridula* parasitism by the tachinid fly *Trichopoda pennipes* ten years after its accidental introduction into Italy from the New World. *BioControl*, **47**, 617-624.

Sands, D.P.A. & Coombs, M.T. (1999) Evaluation of the Argentinian parasitoid, *Trichopoda giacomellii* (Diptera: Tachinidae) for biological control of *Nezara viridula* (Hemiptera: Pentatomidae) in Australia. *Biological Control*, **15**, 19-24.

Seymour, J., Bowman, G. & Crouch, M. (1995) Effects of neem seed extract on feeding frequency of *Nezara viridula* L. (Hemiptera: Pentatomidae) on pecan nuts. *Austral Entomology*, **34**, 221-223.

Singha, A., Thareja, V. & Singh, A.K. (2007) Application of neem seed kernel extracts result in mouthpart deformities and subsequent mortality in *Nezara viridula* (L.) (Hem: Pentatomidae). *Journal of Applied Entomology*, **131**, 197-201.

Snodgrass, G.L., Adamczyk, J.J. Jr, Gore, J. (2005) Toxicity of insecticides in a glass-vial bioassay to adult brown, green, and southern green stink bugs (Heteroptera: Pentatomidae). *Journal of Economic Entomology*, **98**, 177-181.

Soergel, D.C., Ostiguy, N., Fleischer, S.J., Troyer, R.R., Rajotte, E.G. & Krawczyk, G. (2015) Sunflower as a potential trap crop of *Halyomorpha halys* (Hemiptera: Pentatomidae) in pepper fields. *Environmental Entomology*, **44**, 1581-1589.

Sosa-Gómez, D.R. & Moscardi, F. (1998) Laboratory and field studies on the infection of stink bugs, *Nezara viridula*, *Piezodorus guildinii*, and *Euschistos heros* (Hemiptera: Pentatomidae) with *Metarhizium anisopliae* and *Beauveria bassiana* in Brazil. *Journal of Invertebrate Pathology*, **71**, 115-120.

Sosa-Gómez, D.R., Boucias, D.G. & Nation, J.L. (1997) Attachment of *Metarhizium anisopliae* to the southern green stink bug *Nezara viridula* cuticle and fungistatic effect of cuticular lipids and aldehydes. *Journal of Invertebrate Pathology*, **69**, 31.39.

Temple, J.H., Davis, J.A., Hardke, J., Moore, J. & Leonard, B.R. (2013) Susceptibility of southern green stink bug and redbanded stink bug to insecticides in soybean field experiments and laboratory bioassays. *Southwestern Entomologist*, **38**, 393-406.

Tillman, P.G. (2006a) Sorghum as a trap crop for *Nezara viridula* (L.) (Heteroptera: Pentatomidae) in cotton. *Environmental Entomology*, **35**, 771-783.

Tillman, P.G. (2006b) Susceptibility of pest *Nezara viridula* (Heteroptera: Pentatomidae) and parasitoid *Trichopoda pennipes* (Diptera: Tachinidae) to selected insecticides. *Journal of Economic Entomology*, **99**, 648-657.

Tillman, P.G. (2014) Physical barriers for suppression of movement of adult stink bugs into cotton. *Journal of Pest Science*, **87**, 419-427.

Tillman, P.G. & Mullinix, B.G. Jr (2004) Comparison of susceptibility of pest *Euschistus servus* and predator *Podisus maculiventris* (Heteroptera: Pentatomidae) to selected insecticides. *Journal of Economic Entomology*, **97**, 800-806.

Tillman, P.G. & Cottrell, T.E. (2016) Stink bugs (Hemiptera: Pentatomidae) in pheromone-baited traps near crop field edges in Georgia, USA. *The Florida Entomologist*, **99**, 363-370.

Tillman, P.G., Aldrich, J.R., Khrimian, A. & Cottrell, T.E. (2010) Pheromone attraction and cross-attraction of *Nezara*, *Acrosternum*, and *Euschistus* spp. stink bugs (Heteroptera: Pentatomidae) in the field. *Environmental Entomology*, **39**, 610-617.

Tillman, P.G., Greenstone, M.H. & Hu, J.S. (2015a) Predation of stink bugs (Hemiptera: Pentatomidae) by a complex of predators in cotton and adjoining soybean habitats in Georgia, USA. *The Florida Entomologist*, **98**, 1114-1126.

Tillman, P.G., Khrimian, A., Cottrell, T.E., Lou, X., Mizell III, R.F. & Johnson, C.J. (2015b) Trap cropping systems and a physical barrier for suppression of stink bugs (Hemiptera: Pentatomidae) in cotton. *Journal of Economic Entomology*, **108**, 2324-2334.

Todd, J.W. (1989) Ecology and behaviour of *Nezara viridula*. *Annual Review of Entomology*, **34**, 273-292.

Todd, J.W. & Schumann, F.W. (1988) Combination of insecticide applications with trap crops for early maturing soybean and southern peas for population management of *Nezara viridula* in soybean (Hemiptera: Pentatomidae). *Journal of Entomological Science*, **23**, 192-199.

van Emden, F.I. (1945) Keys to Ethiopian Tachinidae. 1. Phasiinae. *Proceedings of the Zoological Society of London*, **114**, 389–436.

Vayias, B.J. & Athanassiou, C.G. (2004) Factors affecting the insecticidal efficacy of the diatomaceous earth formulation SilicoSec against adults and larvae of the confused flour beetle, *Tribolium confusum* Du Val (Coleoptera: Tenebrionidae). *Crop Protection*, **23**, 565-573.

Waterhouse, D.F. (1988) *Biological Control of Insect Pests: Southeast Asian Prospects*. Australian Centre for International Agricultural Research Monograph No. 51, ACIAR, Canberra (Australia).

Waterhouse, D.F. & Sands, D.P.A. (2001) *Classical Biological Control of Arthropods in Australia*. Australian Centre for International Agricultural Research Monograph No. 77, CSIRO Publishing, Melbourne (Australia).

Weber, D.C., Leskey, T.C., Walsh, G.C. & Khrimian, A. (2014) Synergy of aggregation pheromone with methyl (*E,E,Z*)-2,4,6-Decatrienoate in attraction of *Halyomorpha halys* (Hemiptera: Pentatomidae). *Journal of Economic Entomology*, **107**, 1061-1068.

Werdin González, J., Gutiérrez, M.M., Murray, A.P. & Ferrero, A.A. (2010) Biological activity of essential oils from *Aloysia polystachya* and *Aloysia citriodora* (Verbenaceae) against the soybean pest *Nezara viridula* (Hemiptera: Pentatomidae). *Natural Product Communications*, **5**, 301-306.

Werdin González, J., Gutiérrez, M.M. & Ferrero, A.A. (2011a) Repellency assays with plant extracts and essential oils from *Schinus molle* var. *areira* (L) (Anacardiaceae) and DEET against *Nezara viridula* L. (Hemiptera: Pentatomidae). *BioAssay*, **6**, 8.

Werdin González, J., Gutiérrez, M.M., Murray, A.P. & Ferrero, A.A. (2011b) Composition and biological activity of essential oils from Labiatae against *Nezara viridula* (Hemiptera: Pentatomidae) soybean pest. *Pest Management Science*, **67**, 948-955.

Williamson, C. & von Wechmar, M.B. (1992) Two novel viruses associated with severe disease symptoms of the green stinkbug *Nezara viridula*. *Journal of General Virology*, **73**, 2467-2471.

Williamson, C. & von Wechmar, M.B. (1995) The effects of two viruses on the metamorphosis, fecundity, and longevity of the green stinkbug, *Nezara viridula*. *Journal of Invertebrate Pathology*, **65**, 174-178.

Willrich, M.M., Leonard, B.R. & Cook, D.R. (2003) Laboratory and field evaluations of insecticide toxicity to stink bugs (Heteroptera: Pentatomidae). *The Journal of Cotton Science*, **7**, 156-163.

Yang, F.L., Zhu, F. & Lei, C.-L. (2010) Garlic essential oil and its major component as fumigants for controlling *Tribolium castaneum* (Herbst) in chambers filled with stored grain. *Journal of Pest Science*, **83**, 311-317.

Zhang, Q.-H., Schneidmiller, R.G., Hoover, D.R., Zhou, G., Margaryan, A. & Bryant, P. (2014) Essential oils as spatial repellents for the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae). *Journal of Applied Entomology*, **138**, 490-499.