Project title:	Peppers and aubergines: A desk study to identify IPM compatible control measures for *Nezara viridula* and *Anthomonus eugenii*
Project number:	PE 014
Project leader:	Dr R J Jacobson, RJC Ltd
Report:	Final report: May 2013
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Key staff:	Dr R J Jacobson, RJC Ltd Dr A Cuthbertson, Fera Dr M Fountain, EMR Dr N Hassan, Russell IPM
Location of project:	RJC Ltd, Bramham, West Yorks Russell IPM, Third Ave, Deeside Industrial Park, Flintshire, CH5 2LA East Malling Research, New Road, East Malling, Kent, ME19 6BJ Libraries at Fera (Sand Hutton) and Lancaster, Leeds and York Universities
Industry Representative:	Mr G Taylor, (PTG Chairman) Valley Grown Salads, Paynes Lane, Nazeing, Essex, EN92EX
Date project commenced:	1 January 2013
Date project completed:	31 June 2013

DISCLAIMER

The results and conclusions in this report are based on an investigation conducted over a six month period. The conditions under which the investigation was carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

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

Dr R J Jacobson
Director
RJC Ltd

Signature .... Date ....

Report authorised by:

Dr R J Jacobson
Director
RJC Ltd

Signature .... Date ....

CONTENTS

GROWER SUMMARY

Headlines

- IPM compatible control measures identified for *Nezara viridula* and *Anthomonus eugenii* in pepper and aubergine crops.
- Candidate control measures for *N. viridula* require further evaluation in practical studies.
- Potential control measures for *A. eugenii* must be developed in liaison with Plant Health.

Background

Southern green shieldbug, *Nezara viridula*, is widely distributed across tropical and subtropical regions of the world where it is a serious pest of many important food crops. It has been imported into the UK on fruit and vegetable products for many years and is now considered to be established in London and the surrounding area. Breeding populations have most commonly been found in man-made habitats such as parks, gardens and allotments, where the pest is particularly fond of leguminous plants. *Nezara viridula* has found a niche in heated glasshouses growing peppers and aubergines in the Lea Valley.

In 2012, HDC commissioned a factsheet which provides an introduction to the biology and recognition of *N. viridula* and helps growers to distinguish it from less damaging native species of plant bugs (Factsheet 36/12). That factsheet will help to prevent unnecessary insecticidal treatments due to misidentification of the target organism. HDC have obtained an EAMU (Number 1994/12) enabling growers to use lambda-cyhalothrin (Hallmark with Zeon Technology) against *N. viridula* on pepper and aubergine crops. While effective, this product is extremely harmful to the biological control agents used against other pests in the IPM programmes for these crops. Most notably, applications of Hallmark could lead to secondary problems with western flower thrips (*Frankliniella occidentalis*) and associated infection with tomato spotted wilt virus. It is vitally important that UK growers have access to IPM compatible control measures against *N. viridula* as soon as possible.

Pepper weevil, *Anthomonus eugenii*, originates from Mexico and has spread throughout Central America, the Caribbean, southern USA and French Polynesia. *Anthomonus eugenii* has not yet been found in the UK but eradication measures were taken in four sweet pepper crops in the Netherlands during 2012. The main hosts of *A. eugenii* are cultivated and wild species of *Capsicum.* Feeding by adults extends to other Solanaceae, including tomatoes, tomatillo, aubergine and potatoes, as well as *Physalis, Datura, Petunia*, and *Nicotiana*.

Other wild Solanum species growing in the UK, such as nightshades, may potentially be alternative or intermediate hosts.

The most important damage and the main cause of yield loss is the destruction of blossom buds and immature fruits, which turn yellow and drop to the ground. Both adult and larval feeding causes bud drop. Adult *A. eugenii* also feed on leaves and blossoms and bore into fruits. Adult feeding punctures appear as small holes in immature fruits and small (2-5 mm) oval holes in leaves. Females chew a small hole into the fruit, deposit a single egg within the cavity and seal the hole with a clear anal secretion that hardens into an 'oviposition plug'. Larval feeding on seeds and other tissue in the developing fruits is very damaging, causing the core to become brown, and often mouldy. The stem of pods infested by larvae turn yellow and the pod turns yellow or red prematurely. Economic damage is reported to occur with adult populations of only 0.01 adult per plant.

UK Plant Health is currently (June 2013) reviewing the pest's status and issued a Rapid Pest Risk Analysis for industry consultation. In addition, The Food and Environment Research Agency (Fera) has recently produced a factsheet to increase UK growers awareness of the pest and to aid recognition should it arrive in this country**.** As described for *N. viridula*, it is vitally important that UK growers have knowledge of IPM compatible control measures that could be effective against *A. eugenii*.

In 2013, HDC commissioned this desk study to look at control measures being used against both *N. viridula* and *A. eugenii* in other parts of the world with particular emphasis on solutions that could be incorporated into existing IPM programmes in the UK. For each pest, potential control measures must be active against one or more life cycle stages and be compatible with the biological control agents already used within the existing IPM programmes. In addition, pesticides for use during cropping should have a harvest interval of three days or less to fit into the harvesting regimes.

Summary

Nezara viridula (Southern green shieldbug)

Monitoring systems

Sexually mature males of *N. viridula* have been shown to release a pheromone which is attractive in the field to females, males, and late-stage larvae of the same species. In parallel to the HDC desk study, the chemical components of the pheromone have been formulated into lures which can now be tested in traps in and around glasshouses in the north London area. Mercury vapour light traps have been used for monitoring adult *N. viridula* in Australian pecan crops. This technique could have potential as an alternative to pheromone traps and should be evaluated in UK glasshouses. If effective, the study could be extended to investigate alternative sources of light.

Trap plants

Plants which are more attractive to *N. viridula* than the crop have been used as traps in and around valuable broad acre crops in the USA, Australia and New Zealand. Sorghum and soybean appear to be particularly attractive to *N. viridula*. It is difficult to predict from the published work whether the plant species which have been shown to be more attractive than (say) cotton crops would also be more attractive than peppers or aubergines. Unpublished reports from allotments in the London area suggest that podding beans could be a useful alternative to soybean and sorghum in UK glasshouses. The size and growth habit of dwarf French beans could make them ideal candidates for use under the main crop canopy. Ideally, trap plants should be tested with and without insecticides to control the spread of offspring hatching from egg masses. Even pyrethroids could be used in this situation without impacting upon natural enemies operating within the main crop canopy.

Parasites

Over 60 species of parasitoids have been reported attacking *N. viridula*, with egg parasitoids the most important. The scelionid wasp, *Trissolcus basalis*, is the dominant egg parasitoid in the Americas, the Mediterranean Basin, the Middle East and Pakistan, and has been established in Hawaii, Australia, New Zealand, and other Pacific islands as part of biological control programs. However, it is not specific to this pest and it is unlikely that it could be introduced to the UK. Six species of tachinid flies are known to parasitise adult *N. viridula* and one, *Trichopoda giacomellii*, is reported to be specific for the pest. On that basis, it was introduced to control the pest at sites in western New South Wales and south-eastern Queensland. *Trichopoda giacomellii* is not indigenous to the UK but perhaps could be considered as a licensed biological control agent if further studies proved it to be specific to *N. viridula*. However, the cost of mass rearing the host bug in sufficient numbers to make the production system economically viable could be a limiting factor.

Predators

There are relatively few publications which specifically refer to predators of *N. viridula*. Several generalist predators feed on *N. viridula* egg masses but take relatively small numbers. The ability of *Orius* spp. and *Macrolophus pygmaeus* to feed on *N. viridula* eggs /

nymphs should be evaluated as both of these predators are already released in many UK pepper and aubergine crops and may make a contribution to the overall control of the pest.

Entomopathogenic fungi

Published information indicates that the entomopathogenic fungi, *Metarhizium anisopliae*, *Beauveria bassiana* and *Paecilomyces* spp., could all have the potential to contribute to an IPM programme against *N. viridula* and should be evaluated in greater depth. In the short term, crop-scale trials would be restricted to the only available product in the UK market; *i.e.* Naturalis-L. In the longer term, it would be sensible to screen a wider range of isolates from all three genera. Entomopathogenic fungi may be of particular interest to organic growers who have limited options for the use of conventional insecticides.

Chemical insecticides

Chemical insecticides have been used against *N. viridula* for over 50 years. The earliest reports described the efficacy of organochlorine, carbamate and organophosphate insecticides but the emphasis has gradually changed to the newer generations of synthetic pyrethroids. The latter are now the most commonly used products throughout the world. Although the majority of these chemicals have been reasonably effective against *N. viridula*, they are incompatible with IPM programmes in UK glasshouse crops. Of the chemical insecticides recently available to UK growers of protected edible crops, potentially useful products include:

- Pymetrozine (Chess) could be properly evaluated both as a high volume spray and via the irrigation in a commercial crop situation.
- The neonicotinoids, acetamiprid (Gazelle) and thiacloprid (Calypso, Reggae), may have a role in the IPM programme if they can be applied through the irrigation system to minimise their impact on biological control agents and pollination.
- The insect growth regulators, diflubenzuron (Dimilin Flo) and teflubenzuron (Nemolt) could be considered for evaluation against *N. viridula* in laboratory bioassays prior to being tested on a crop scale.

Spirotetramat (Movento) was released onto the UK market in 2010 for control of aphids on Brassicas and lettuce. It is registered for tomato in other parts of the world (*e.g.* Canada) and is said to be harmless to most beneficials. Unpublished information from Australia indicates that it may have had an incidental effect on *N. viridula* when applied against other pests. Spirotetramat has a unique two-way systemic mode of action which could allow it to be applied via the irrigation system. Although not currently available to UK pepper and aubergine growers, this could provide a good IPM compatible solution in the longer-term.

'Alternative' insecticides

Argentinian researchers have shown that plant essential oils (PEOs) from *Aloysia polystachya*, *Aloysia citriodora*, *Origanum vulgare*, *Thymus vulgaris* and *Schinus molle* var. *areira,* as well as N, N-diethyl-*m*-toluamide (DEET), have activity against various life stages of *N. viridula*. These PEOs are worthy of further evaluation.

Anthomonus eugenii (Pepper weevil)

Monitoring systems

Considerable literature relates to methods of monitoring the pest's population development as well as the use of action thresholds in field crop situations. While the techniques have little relevance to glasshouse crops in the UK, the studies clearly demonstrate that prompt action is required to avoid economic damage. Methods used in the field include:

- Inspection of terminal buds or bud clusters for adult weevils
- Making direct weevil counts using whole plant inspections
- Checking for feeding damage or egg laying in terminal bud clusters
- Use of sticky traps and pheromone baited traps

Adult *A. eugenii* are attracted to yellow sticky traps. One 375 cm^2 yellow sticky trap has been shown to capture as many adults as detected by inspecting 50 terminal pepper buds in field-grown peppers. As well as visual cues, adult *A. eugenii* are attracted to host plants by various semiochemicals. These include male-produced aggregation pheromones, host plant volatiles and feeding damage volatiles. The aggregation pheromone has been incorporated into monitoring traps but has not been exploited as a control measure. There is obvious scope to optimise the aggregation pheromone and to include Solanaceous plant volatiles and feeding damage volatiles in traps to make them more sensitive. These systems could be developed for mass trapping in UK glasshouse crops but approval would be required. In addition, volatiles believed to be present in the female's 'oviposition plug' would make an excellent candidate for repellent control strategies when the buds and young fruitlets are forming.

Cultural control

Several 'cultural' control measures have been employed against *A. eugenii* in the Americas but these relate to outdoor situations and have little relevance to the more intensively grown and continuously harvested pepper and aubergine crops in UK glasshouses. For example, cultural controls include avoiding fields with pepper weevil infestations when selecting sites for a new crop, crop-free periods and destruction of alternate wild solanaceous host plants. Differences reported in varietal susceptibility have been mainly due to the timing of ripening in outdoor crops. General hygiene has been shown to be of paramount importance; for example destroying crop residue avoids a carry-over of weevils to the next crop and removing fallen fruits results interrupts the pest's life cycle by destroying larvae and pupae.

Parasitoids and predators

Over 14 species of parasitoids which attack *A. eugenii* have been reported in the literature. The biology of the braconid wasps, *Triaspis eugenii* and *Urosigalphus* spp., would seem to make them well suited for biological control of pepper weevil due to their presumed host specificity and habit of attacking the host egg. They are not thought to be indigenous to the UK although this may be worthy of further investigation. *Catolaccus hunteri* is the most abundant and most studied of the parasitoids. It is an external parasitoid, attacking third instar larvae within flower buds and small fruit. However, it is known to be a generalist ectoparasitoid of at least 17 species of Curculionidae and two species of Bruchidae and as such it is unlikely that it could be released in the UK under licence as part of an IPM programme. There are very few reports of predators attacking *A. eugenii* and no reports have been found which refer to the possibility of biological control programmes.

Entomopathogenic fungi

Very little published material refers to the use of entomopathogenic fungi or other biopesticides against *A. eugenii*. This is perhaps because such products usually depend on contact action and a large proportion of the pest's life cycle stages are protected within the plant. *Beauveria bassiana* has been shown to infect adult *A. eugenii* in laboratory bioassays but no reliable data has been found to support its use in field situations. In the UK, Naturalis-L is the only product containing *B. bassiana* that is currently available to UK growers. It may be worth further investigating this product as part of a larger IPM strategy.

Chemical insecticides

Chemical insecticides have been used against *A. eugenii* since the early 1950s with the earliest studies focusing on organochlorines and organophosphates. Through the 1970s and 1980s, numerous carbamates, organophosphates and early generation synthetic pyrethroids showed potential against adult *A. eugenii* in the laboratory and were tested in the field. The control programmes consisted of intensive spray programmes with up to 15 sprays reported per crop. However, the results were variable; sometimes with significantly reduced numbers of weevils but continued damage to fruit. As early as 1954, researchers wrote that insufficient applications or failure to cover the plants thoroughly with DDT would allow survivors of each succeeding generation to lay enough eggs to cause considerable damage. The insecticides used may have changed over the years but that principle has remained true. New generations of synthetic pyrethroids and insecticides with novel modes of action have become available during the last decade. It has been difficult to find scientific papers which report their efficacy against *A. eugenii* but they have begun to appear in lists of products recommended by extension services throughout the USA. Typical programmes currently include oxamyl (Vydate), a broad range of synthetic pyrethroids and neonicotinoids, as well as cryolite (a fluoride-containing mineral). Potentially useful chemical insecticides which are or have been recently available to UK growers of protected edible crops include:

- Spinosad (Conserve) is known to be effective against some Coleoptera but we have no information about its efficacy against *A. eugenii*. It has been shown to have systemic activity and can be used through the irrigation system under the Extension of Authorisation 0325/2013. It therefore has the potential to control *A. eugenii* within plant material. This product should be tested against *A. eugenii* at the first opportunity.
- The neonicotinoids, acetamiprid (Gazelle) and thiacloprid (Calypso, Reggae), should be effective against *A. eugenii* but are not particularly IPM friendly. The adverse effects could be minimised if applied via the irrigation but this would require evaluation in a commercial crop situation.

Financial Benefits

The full economic implications of *N. viridula* and *A. eugenii* infestations have not yet been determined for UK growers. However, initial observations suggest that losses due to direct damage, secondary pest problems and the loss of goodwill with retail customers could be very substantial.

Action Points

This desk study has identified several monitoring and control measures that could be exploited by UK growers for the control of *N. viridula*. It should be possible to develop monitoring methods that can be used to accurately time IPM compatible treatments based on biological, physical and chemical techniques. However, it must be stressed that all these measures must be studied in greater depth before they can be recommended with any degree of confidence for use in UK crops.

Anthomonus eugenii in not indigenous to the UK and its status is currently being reviewed by Plant Health. Possible sightings of the pest must be immediately reported to Plant Health who will implement a programme of control measures. The development of IPM compatible strategies should be done in liaison with Plant Health.

SCIENCE SECTION

Introduction

Nezara viridula (Southern green shieldbug)

Nezara viridula is believed to be native to Ethiopia but is now widely distributed across tropical and subtropical regions of the world. It feeds on a wide range of plants and is a serious pest of many important food crops. *Nezara viridula* has been imported into the UK on fruit and vegetable products for many years but was not found in the wild until 2003. It is mainly confined to the south-east of England which is thought to be the northern limit of its outdoor range. It is now considered to be established in London and the surrounding area. Breeding populations have most commonly been found in man-made habitats such as parks, gardens and allotments, where it is seems particularly fond of runner beans. The adults are strong fliers and are capable of long-distance natural dispersal during warm weather. *Nezara viridula* has found a favourable niche in heated glasshouses in the north London area and it seems highly likely that it will eventually be transported to other parts of the country on produce and packing materials. It also seems likely that the pest would survive year round any where in the UK if it were within a glasshouse with frost protection between crops.

Nezara viridula has piercing-sucking mouthparts which are formed into a beak-like structure. Salivary fluid is pumped down one duct into the plant tissue and liquefied food is then sucked back into the insect. The insect probably feeds on all parts of the plants but the effects are most clearly seen in growing points and developing fruits. Damaged growing points usually wither and may die. Feeding on young fruit results in distortion and discolouration as the fruit swells. Feeding punctures on larger fruit cause hard brown spots and a variety of other imperfections, which render the fruit unmarketable. In addition, it is common for fruit to be contaminated with globules of sticky regurgitated food which must be removed before sale.

In 2012, HDC commissioned a factsheet which provides an introduction to the biology and recognition of the pest and helps growers to distinguish it from less damaging native species of plant bugs (Jacobson, 2012). That document will help to prevent unnecessary insecticidal treatments due to misidentification of the target organism.

HDC have obtained an EAMU (Number 1994/12) enabling growers to use lambda-cyhalothrin (Hallmark with Zeon Technology) against *N. viridula* on pepper and aubergine crops. While effective, this product is extremely harmful to the biological control agents used against other pests in the IPM programmes for these crops. Most notably, applications of Hallmark with Zeon Technology could lead to secondary problems with *Frankliniella occidentalis* (western flower thrips) and associated infection with tomato spotted wilt virus (Jacobson, 2009; O'Neill, 2009). It is vitally important that UK growers have access to IPM compatible control measures against *N. viridula* as soon as possible.

The overall objective of this project is to identify control measures that have potential to be incorporated into the IPM programmes for pepper and aubergine crops. This may include biological, physical, cultural and chemical control measures. In the absence of direct information about the effect of a pesticide on *N. viridula*, it is important to consider whether activity has been reported against related insects. *Nezara viridula* belongs to the Pentatomidae, a subdivision of Heteroptera which includes both plant feeding and predatory bugs (Figure 1). The Heteroptera is, in turn, a sub-division of the Order Hemiptera, which also includes aphids, whiteflies, leafhoppers and mealybugs. All the Hemiptera are considered to be 'true bugs' and have similarly adapted piercing and 'sucking' mouthparts. It is therefore possible, but not certain, that pesticides that are effective against other Hemipterous insects will also have an impact on populations of *N. viridula*.

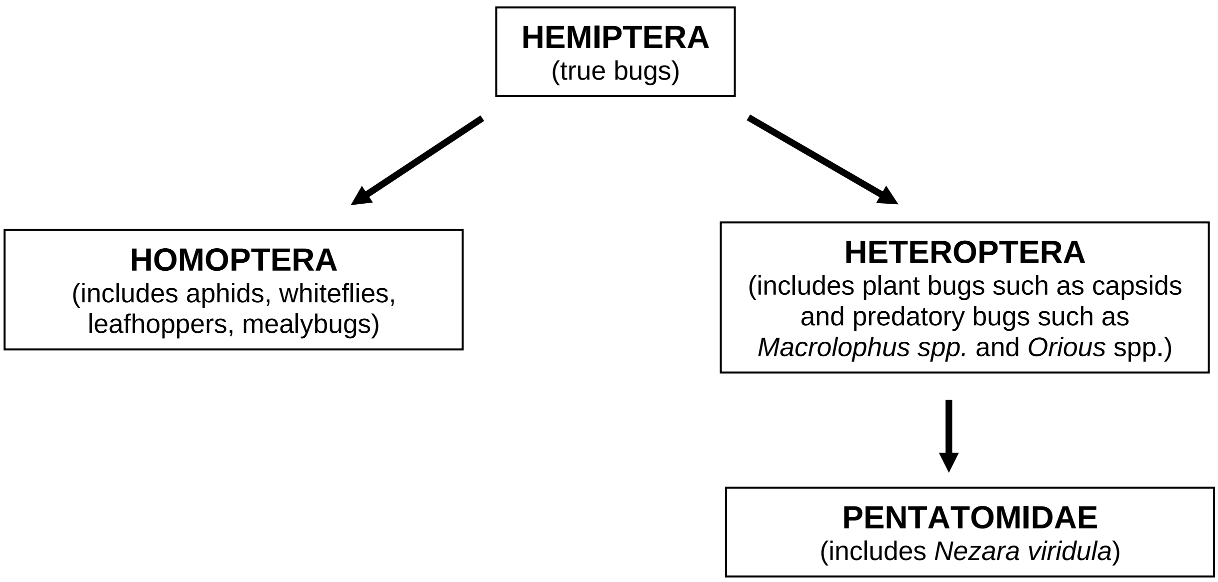

Figure 1. Close relatives of *Nezara viridula*

Anthomonus eugenii (Pepper weevil)

Anthomonus eugenii originates from Mexico (Laborde and Pozo, 1984; Rodriguez-Leyva *et al*., 2012) and has spread throughout Central America (Andrews *et al*., 1986), the

Caribbean (Abreu and Cruz, 1985), southern USA (Elmore *et al*., 1934; Goff and Wilson, 1937; Riley and Schuster, 1992) and French Polynesia (CABI, 2012). *Anthomonus eugenii* has not yet been found in the UK but eradication measures were taken in four sweet pepper crops in the Netherlands during 2012 (Baker *et al.*, 2012).

Over 30 species of *Anthonomus* are associated with Solanaceous plants (Clark and Burke, 1996). The main hosts of *A. eugenii* are cultivated and wild species of *Capsicum* (Acosta *et al*., 1987). Oviposition and larval development occurs on plants in the genera *Capsicum* and *Solanum*. Feeding by adults extends to other Solanaceae, including tomatoes (*Lycopersicon* spp.), tomatillo (*Physalis philadelphica*), aubergine (*Solanum melongena*) and potatoes (*Solanum tuberosum*), as well as *Physalis, Datura, Petunia*, and *Nicotiana* (Elmore *et al*., 1934; Patrock and Schuster, 1992; Rodriguez-Del-Bosque and Reyes-Rosas, 2003; Diaz *et al*., 2004; Capinera, 2008; Addesso and McAuslane, 2009). Other wild Solanum species growing in the UK, such as nightshades, may potentially be alternative or intermediate hosts (Aguilar and Servin, 2000).

The most important damage and the main cause of yield loss (Segarra-Carmona and Pantoja, 1988a) is the destruction of blossom buds and immature fruits, which turn yellow and drop to the ground (Elmore *et al*., 1934). Both adult and larval feeding causes bud drop. Adult *A. eugenii* also feed on leaves and blossoms and bore into fruits. Adult feeding punctures appear as dark specks or small holes in immature fruits and small (2-5 mm) circular or oval holes in leaves. Sometimes the fruit is deformed. Females chew a small hole into the fruit, deposit a single egg within the cavity and seal the hole with a clear anal secretion that hardens into an 'oviposition plug'. Larval feeding on seeds and other tissue in the developing fruits (Costello and Gillespie, 1993) is very damaging, causing the core to become brown, and often mouldy. The stem of pods infested by larvae turn yellow and the pod turns yellow or red prematurely. There is also a relationship between *A. eugenii* damage and internal mould due to *Alternaria alternata* (Bruton *et al*., 1989). Economic damage is reported to occur with adult populations of only 0.01 adult per plant (Segarra-Carmona and Pantoja, 1988b).

UK Plant Health is currently reviewing the pest's status and issued a Rapid Pest Risk Analysis for industry consultation (Baker *et al.*, 2013). In addition, The Food and Environment Research Agency (Fera) has recently produced a factsheet to increase UK growers awareness of the pest and to aid recognition should it arrive in this country (Ostojá-Starzewski, *et al.,* 2012**).**

Control measures taken in North and Central America are based on broad spectrum insecticides which would not be compatible with IPM programmes currently used by UK growers. This could lead to secondary problems with *F. occidentalis* and TSWV as described for *N. viridula*. As a contingency, it is vitally important that UK growers have knowledge of IPM compatible control measures that could be effective against *A. eugenii*.

As for *N. viridula*, the overall objective is to identify control measures that have the potential to be incorporated into the IPM programmes for pepper and aubergine crops. Candidates must be active against one or more life cycle stages of the pest under consideration and must be compatible with the biological control agents already used within the existing IPM programmes. In addition, pesticides for use during cropping should have a harvest interval of three days or less to fit into the harvesting regimes. It is perhaps inevitable that the candidates identified here will require further evaluation in practical studies.

Materials and methods

A similar approach was taken for both *Nezra viridula* and *Anthomonus eugenii*. The two studies were done in sequence, starting with *N. viridula* because it was already established in UK crops and therefore of more immediate importance.

Information was collected and collated from various sources and by various methods including:

- Literature searches
- Insecticide databases
- Direct from suppliers of biological, chemical and other IPM-related products.
- Personal contacts in the 'International Organisation for Biological Control' and 'International Biocontrol Manufacturers' Association' who had first hand experience of controlling *N. viridula* and *A. eugenii* in other countries / other crops.

The study paid particular attention to the potential use of:

- Pheromones for monitoring and / or control
- Semiochemicals which may be used as attractants or repellants
- Biological control agents
- Biopesticides
- 'Trap plants' which are more attractive to the pests than the crop plants
- IPM compatible insecticides for use as high volume sprays and via the irrigation system
- Alternative insecticides (often referred to as 'soft chemicals')

Results and Discussion

Nezara viridula (Southern green shieldbug)

Invertebrate natural enemies:

Invertebrate natural enemies of *N. viridula* can be categorised as either parasitoids or predators. These two categories may be further sub-divided according to the life cycle stage of *N. viridula* that they attack; *i.e.* eggs, nymphs or adults.

Parasitoids

Jones (1988) published the most comprehensive single study of parasitoids that attack *N. viridula*. This worldwide review drew on published information from over 50 authors as well as his own previously unpublished data. The review reported 57 species of parasitoids among two families of Diptera (true flies) and five families of Hymenoptera (wasps). A second review (Hokkanen, 1986), which was published at about the same time, reported a further three species of parasitoids. With so many authors involved and with papers dating back over 100 years, it is perhaps inevitable that some of the insects included in these reviews were misidentified and some of the specific names may be synonyms. However, we can have greater confidence in the information provided about the most important species as these have been studied in more depth since 1988.

Egg parasitoids are the most important biocontrol agents of *N. viridula.* Over 40 species have been recorded emerging from *N. viridula* eggs. Several of these have been recorded only once and some are poorly adapted to *N. viridula.* Others are evidently well adapted; for example, several African and Asian egg parasitoids in the genera *Trissolcus, Telenomus* and *Gryon* have been identified as being suitable for biological control programs but have not yet been properly investigated. None of these species are believed to be indigenous to the UK.

The scelionid, *Trissolcus basalis,* is both the most important and the most widely distributed species. It has been frequently recorded from several other pentatomid bugs but seems to be most closely associated with *N. viiridula*. In fact, *T. basalis* is the dominant egg parasitoid of its primary host in the Americas, the Mediterranean Basin, the Middle East and Pakistan, and has been established in Australia, New Zealand, Hawaii and other Pacific islands as part of biological control programs (Lever, 1941a; Wilson, 1960; Davis, 1967; Rao *et al*. 1971). It is also believed to have been introduced into Taiwan, Chile and the U.S.S.R. Orr *et* *al.* (1985) studied the biology of *T. basalis*, including development and emergence at various temperatures and humidities. In field studies, Ehler (2002) reported that *T. basalis* typically parasitised 100% of the *N. viiridula* eggs in an exploited egg mass.

Tachinidae (Diptera) are the only known parasitoids that attack adult *N. viridula*. In the Americas, at least six tachinids have become well adapted to *N. viridula* since the pest became established; *i.e. Trichopoda pennipes* in the United States, *T. pilipes* in the West Indies, and *T. giacomellii, T. gustavoi, Eutrichopodopsis nitens* and *Ectophasiopsis arcuata* in South America. The biology of these tachinids is apparently similar and each species is closely associated with *N. viridula* within their respective geographic ranges. Both *T. pennipes* and *T. pilipes* have been successfully established against *N. viridula* in Hawaii, though *T. pilipes* is said to be the more effective species (Davis 1967). The role of *Bogosia antinorii* on *N. viridula* in Africa requires further investigation (Jones, 1988).

Sands and Coombs (1999) demonstrated that *T. giacomellii* was specific for *N. viridula* and on this basis the predator was introduced to control *N. viridula* at sites in western New South Wales and south-eastern Queensland (Coombs and Sands, 2000). Releases of adult *T. giacomellii* and of parasitised *N. viridula* were made either directly onto host plants or following temporary confinement in a field cage. Parasitism of *N. viridula* adults by *T. giacomellii* ranged from 9 to 72%, and was 42% of adults during diapause. The authors recommended release methodologies that limited immediate dispersal of the agent and / or their progeny.

Trichopoda giacomellii is not indigenous to the UK but could perhaps be considered as a licensed biological control agent for the UK if further studies proved that Sands and Coombs (1999) were correct in judging it to be specific *N. viridula*. However, the cost of mass rearing the host bug in sufficient numbers to make the production system economically viable could be a limiting factor (Dan Papacek, Bugs for Bugs, Australia, Pers. Comm., 2012).

The nymphal stages of Pentatomidae are generally free from significant attack by parasitoids. Some of the tachinids will deposit eggs on the larger *N. viridula* nymphs but they are better adapted to the adult stage of their hosts and rates of parasitism are poor (*eg* Buschman & Whitcomb 1980).

It is interesting to note that Jones (1988) categorically stated that no hyperparasitoids were known to attack the various parasitoids of *N. viridula* and no such reports have been found in the subsequent literature. It would therefore seem that these beneficial species are free of their own natural enemies.

Predators

There are relatively few publications which specifically refer to predators of *N. viridula*. Ehler (2002) investigated predators associated with eggs of *N. viridula* by placing egg masses in weeds, cultivated tomato and bean crops in northern California. Egg predation was generally less than 10% and normally involved predators with chewing mouth parts. He noted that predators seldom destroyed an entire egg mass, typically eating about 40 eggs per exploited mass. Laboratory evaluation of 25 species of potential arthropod predators revealed that few fed on *N. viridula* eggs to any extent but several species fed on *N. viridula* nymphs.

The use of predators against *N. viridula* could be worthy of further investigation in the UK. In particular, we should evaluate the ability of *Orius* spp. and *Macrolophus pygmaeus* to feed on *N. viridula* eggs / nymphs as both of these predators are already released in many UK pepper and aubergine crops.

Biopesticides:

There have been mixed reports about the efficacy against *N. viridula* of fungal entomopathogens of the genera *Metarhizium*, *Beauveria and Paecilomyces.*

Sosa-Gomez *et al.* (1988) tested isolates of *Metarhizium anisopliae* (CNPSo-Ma12) and *Beauveria bassiana* (CNPSo-Bb56) under field conditions as biological control agents of *N. viridula* and two other shield bugs which attack soybean plants. Kaolin-based powder formulations of *M. anisopliae* or *B. bassiana* were applied to soybean plots at a rate of 1.5 x 10^{13} conidia per ha. After treatment, cages were placed in plots and shieldbug adults were introduced into the cages. Mycosis was initially observed 7-15 days post application and infection levels of up to 41% were achieved at day 30. Field results were confirmed through laboratory bioassays. El-Zoghby (2003) cultured an isolate of *B. bassiana* and bioassayed it against third instar nymphs of *N. viridula*. Field application of $1x10^6$ conidia / ml decreased the bug population by 23% after 25 days. Four successive applications at intervals of about one week resulted in 18.1 - 23.4% reduction in the pest population.

In addition, entomopathogens of the genera *Metarhizium*, *Beauveria and Paecilomyces* have been evaluated against a range of other plant bugs. Gouli *et al.* (2012) recently bioassayed three isolates of *B. bassiana* and two of *M. anispoliae* isolates against

Halyomorpha halys (brown marmorated stink bug). One *B. bassiana* isolate was the active ingredient in BotaniGard which produced 85% and 100% mortality 9 and 12 days post treatment, respectively. Experimental isolates ERL1170 and ERL1540 were also reported to be efficacious. *Metarhizium anispoliae* isolates produced lower mortalities of 40-88% at 12 days. Mustu *et al.* (2011) investigated the effects of isolates of *B. bassiana* against the adult stages of *Aelia rostrata* (wheat stink bug) under 70% and 95% relative humidity and with $1x10^6$ and $1x10^8$ conidia per ml. The result of experiments showed the entomopathogen to be more effective at 95% R.H. and at $1x10^8$ conidia per ml causing 100% mortality in the 9th day of incubation. Ihara *et al.* (2001) selected entomopathogenic fungi with high pathogenicity against adult *Plautia stali* (brown-winged green bug) from among 711 isolates in laboratory culture collections including *Beauveria, Metarhizium* and *Paecilomyces* genera. Thirty one isolates of *B. bassiana* and 20 isolates of *M. anisopliae* were selected for the first screening in which the bugs contacted conidia on developing culture plates. For the second selection, the bugs were dipped into a conidial suspension and LC_{50} values were estimated from data collected on the seventh day after treatments. The results showed that *M. anisopliae* isolates were relatively more virulent than *B. bassiana* isolates. The minimum LC50 value was obtained from *M. anisopliae* isolate FRM515 and Ihara *et al.* (2001) suggested that it could be a potential candidate as a microbial control agent for *P. stali*.

In the UK, *B. bassiana* (Naturalis-L) has been approved for pepper, aubergine, tomato, cucumber. Previous formulations of this entomopathogen provided useful levels of control of *Lygus rugulipennis* (European tarnished plant bug) on cucumber. In the first trials, single high volume (HV) and ultra low volume (ULV) applications of Naturalis-L provided similar reductions (mean approx 60%) in numbers of adult bugs (Jacobson, 1999). In subsequent trials, both Naturalis-L and BotaniGard WP were applied as high volume and ultra low volume sprays on three occasions. There were no differences between these treatments and overall they reduced numbers of adult bugs by 78% (Jacobson, 2002). The frequency of sprays used in the second set of trials would suggest that only the ULV treatment would be acceptable in a commercial crop. More recent results against other pests in the UK have been inconsistent (Jacobson, 2011).

In Australia, a strain of *M. anisopliae* has been isolated from soil which is said to have good activity against *N. viridula* (Stephen Goodwin, Biological Solutions, Australia, Pers. Comm., 2013). This strain is being developed as a commercial product and details are currently confidential. Other unpublished information about a different *Metarhizium*-based product under development did not give reason for optimism. This report indicated that the defence compounds produced by 'stink bugs' have antifungal properties (Hugh Frost, Novozymes, UK, Pers. Comm., 2013).

No attempt has been made to list the above mentioned entomopathogens in order of efficacy because the tests have used different methodology and have been done under varying conditions. In particular, the researchers have used different isolates of fungi and applied them against various life cycle stages of the pests. Nonetheless, there is sufficient available information to indicate that *M. anisopliae*, *B. bassiana* and *Paecilomyces* spp all could have the potential to contribute towards an IPM programme against *N. viridula* in UK glasshouse crops and should be evaluated in greater depth. In the short term, trials should be restricted to the only available product in the UK market, *i.e. B. bassiana* (Naturalis-L). However, in the longer term, it would be sensible to screen a wider range of isolates from all three genera.

Chemical insecticides:

Published information on the use of chemical insecticides against *N. viridula* dates back over 50 years. One of the earliest reports described the efficacy of DDT and endrin (organochlorines), carbaryl (carbamate), and methyl parathion, phosmet and dicoptophos (organophosphates), against various stink bugs affecting cotton in Arizona (Wene and Sheets, 1964). Since then the emphasis has gradually changed to newer generation insecticides. For example, Hoffmann *et al*. (1987) completed several trials in processing tomatoes in California using methomyl (carbamate), fenvalarate (early synthetic pyrethroid) and endosulfan (organochlorine) as well as methyl parathion. Some work continued on organophosphous insecticides during the 1990s and early 2000s but in general the research became more focused on the newer generations of synthetic pyrethroids. The majority of these chemicals were reasonably effective. However, there is little value in reviewing all the studies in this report as the chemicals used would be incompatible with the IPM programmes in UK glasshouse crops. Examples of a few key studies from this period are summarised below.

Greene *et al*. (2001) obtained 77% to 98% mortality of *N. viridula* when using topical applications of the pyrethroid insecticides bifenthrin, cypermethrin, *z*-cypermethrin, and cyfluthrin in laboratory bioassays. Greene & Capps (2004) summarised laboratory bioassays carried out between 1999 and 2004 on a total of 21 products applied at various rates in laboratory bioassays. As expected, organophosphorus and pyrethroid insecticides provided highest mortality. For the pyrethroids, esfenvalerate (Asana) gave 63% mortality, bifenthrin (Capture) 76%, cyfluthrin (Baythroid) 87%, gamma cyhalothrin (Prolex) 87%, bifenthrin (Discipline) 90%, cypermenthrin (Ammo) 92%, lamda-cyhalothrin (Karate) 92%, cypermenthrin (Fury) 95%, and zeta-cypermethrin (Mustang Max) 99%. For the organophosphates, acephate (Orthene 97) gave 96% mortality and methyl parathion 100%. These results are broadly consistent with other published data from USA and New Zealand during the same period [*eg* McPherson *et al.*, (1995); Anderson and Teetes, (1995); Rea *et al*., (2003); Willrich *et al*. (2003a and b); Snodgrass *et al*., (2005)].

Brown *et al.* (2012) investigated the effect of eight formulate insecticides on *N. viridula* eggs. Differences in nymphal pre-emergence mortality were recorded. The lowest instances of bug emergence (and highest mortality) were observed in egg masses treated with bifenthrin (78.7%) followed by beta-cyfluthrin + acephate (42.5%) and acephate (40.9%). The highest emergence (and lowest mortality) occurred in egg masses treated with spinosad (10.4%). Results indicate that insecticides used to control *N. viridula* nymphs and adults can impact on nymphal pre-emergence mortality and control *N. viridula* before emergence.

Since the mid-2000s, several publications have included reference to the neonicotinoids. In general, they have been slightly less effective against *N. viridula* than the better synthetic pyrethroid and organophosphate insecticides. For example, thiamethoxam (Centric) gave 87% in laboratory bioassays (Greene & Capps, 2004).

Other non-pyrethroid and organophosphate insecticides have been less effective; *eg* spinosad (Tracer) 15%; indoxacarb (Steward) 16%; emamectin benzoate (Denim) 42%; novaluron (Diamond) 67% (Greene & Capps, 2004).

Tillman (2006a) considered the efficacy of several insecticides when presented to *N*. *viridula* in different ways. In residual toxicity tests, cyfluthrin, dicrotophos, and oxamyl (carbamate) were highly toxic. In oral toxicity tests, where *N*. *viridula* fed on food covered with insecticide residues, none of the insecticides were toxic to adults of *N. viridula* but acetamiprid and thiamethoxam (neonicotinoids) were moderately toxic to nymphs. In the oral toxicity test, where *N*. *viridula* fed on a gel-food containing insecticides, cyfluthrin, dicrotophos, oxamyl, and thiamethoxam were highly toxic.

In the most recent study, Takeuchi and Endo (2012) determined LD_{50} values for the following insecticides: fenitrothion and fenthion (organophsphates), etofenprox and silafluofen (pythrethroids), dinotefuran and clothianidin (neonicotinoids), and ethiprole (phenyl-pyrazole). The weight of the stink bug and weight of the insecticide applied to each bug were used as explanatory variables in the probit regression analysis. The LD_{50} value of silafluofen for *N*. *viridula* adults was at least 2,338 greater than the other species exposed to each insecticide. Almost all of the LD_{50} values for adults were over 10 times greater than those of the same species nymphs treated with the same insecticide. Thus monitoring of occurring species and their developmental stages is important for controlling effectively the stink bug pest complex by insecticides, especially by silafluofen or etofenprox.

Unpublished work in Australia indicates that the phenylpyrazole insecticide, fipronil (Regent 200SC), has been used effectively against *N*. *viridula* in cotton crops. Fipronil is registered in cotton against *N*. *viridula* at 62.5-125 ml product / ha. In trials, it has been applied successfully at 30ml product / ha in combination with either NaCl at 75g/ha or 2% petroleum spray oil (Stephen Goodwin, Biological Solutions, Australia, Pers. Comm., 2013). There is conflicting evidence over the suitability of fipronil for use in IPM programmes. However, given its broad spectrum of activity (Tingle *et al.*, 2000), it seems unlikely that it could be used in IPM programmes in UK glasshouses.

Information obtained from the Natural Sciences Repository website (sourced 2013) indicates that at least some life cycle stages of *N*. *viridula* are vulnerable to products applied through the irrigation system. Field experiments for the evaluation of the systemic effects of demeton-methyl, dimethoate, monocrotophos, phosphamidon and vamidothion were conducted in soybeans against *N. viridula*. A randomised block design with four replications was used. Each of the five insecticides were applied at a rate of 4000 g ai/ha. Water was applied to the control plots. Ten fourth and fifth instar nymphs, confined inside a nylon mesh bag, were attached to the terminal stem of a soybean plant. Stems on which the insects were confined were covered by plastic bags prior to insecticide treatments. Statistical analysis of mortality showed significant difference compared to the untreated control with monocrotophos having high systemic action. Although these insecticides are not appropriate for use in UK pepper and aubergine crops, the result with monocrotophos indicated that the insect's feeding behaviour could render it vulnerable to other products applied systemically via the plants' roots.

The ketoenol insecticide, spirotetramat (Movento), which works by inhibition of lipid biosynthesis, was released onto the UK market in 2010 for control of aphids on brassicas and lettuce (Bayer, 2008). It is registered for tomato in other parts of the world (*eg* Canada) and is harmless to most beneficials. Unpublished information from Australia indicates that it may have an incidental effect on *N. viridula* when applied against other pests (Scott Ward, Bayer Crop Science, Australia, Pers. Comm., 2012). Spirotetramat has a unique two-way systemic mode of action which could allow it to be applied via the irrigation system. Although not currently available to UK pepper and aubergine growers, this could provide a good IPM compatible solution in the longer-term.

The potential of products recently available to UK growers of protected edible crops is shown in Table 1. In summary, potentially useful products include:

- Pymetrozine (Chess) should be evaluated as a high volume (HV) spray and via the irrigation in a commercial crop situation.
- The neonicotinoids, acetamiprid (Gazelle) and thiacloprid (Calypso, Reggae), may have a role in the IPM programme if they can be applied through the irrigation system to minimise their impact on biological control agents.
- The insect growth regulators, diflubenzuron (Dimilin Flo) and teflubenzuron (Nemolt) should be considered for evaluation against *N. viridula* in laboratory bioassays before being tested on a crop scale.
- The entomopathogenic fungus, *Beauveria bassiana* (Naturalis-L), may be of interest to organic growers who have limited options for control with conventional insecticides.

Table 1. Potential to control *N. viridula* of insecticides recently available to UK growers of protected edible crops

Insecticide 'group'	**Active ingredient / product**	**Notes**	**Potential for use in IPM programme**
Carbamate	Pirimicarb (Aphox)	Although pirimicarb is acutely toxic to aphids, it has no particular toxicity to predatory Hemiptera and other insects of the Heteroptera (Brown, 1989). It is therefore highly unlikely that it will have any effect on *N. viridula*.	Unlikely
Synthetic pyrethroid	Lambda-cyhalothrin (Hallmark) Deltamethrin (Decis)	Probably effective but not IPM compatible	Unlikely

Insecticide 'group'	Active ingredient / product	Notes	Potential for use in IPM programme
Natural pyrethrins	natural pyrethrins (Pyrethrum 5EC / Spruzit)	Baysal and Cinar (2007) report the use of 'botanical extracts from *Chrysanthemum cinerariaefolium*' for the control of *N. viridula* in organic tomato. Natural pyrethrins should provide rapid knock-down and subsequent death of motile stages of *N. viridula* but good coverage to provide contact with the pest would be essential. Natural pyrethrins have a broad spectrum of activity but can often be integrated into IPM programmes by separating from the natural enemies in time or space. However, in this case, the whole plant must be thoroughly treated and this will have a detrimental effect on *Orius* spp. bugs which could lead to secondary problems with thrips and TSWV. The product is therefore unacceptable for this purpose.	Unlikely
Neonicotinoid	Acetamiprid (Gazelle)	Shown to have 'moderate' activity against *N. viridula* in tests in other countries (Greene *et al*., 2001). It is not particularly IPM friendly when used as a HV spray but the adverse effects could possibly be minimised if applied via the irrigation.	Application via the irrigation system requires evaluation in a commercial crop situation
	Thiacloprid (Calypso, Reggae)	Sold for the control of aphids and whiteflies but is known to have a much broader range of activity. It has an off-label for the control of *Lygus rugulipennis* (European tarnished plant bug) on an outdoor and protected berry crop in the UK. In addition, the IOBC 'side-effects' lists show the chemical to be harmful to *Macrolophus* spp. and *Orius* spp, thus indicating that it could have efficacy against other Heteropteran bugs. However, when Calypso was previously used in pepper, for the control of leafhoppers, it resulted in the breakdown of biological control of thrips and subsequent infection with TSWV (Jacobson, 2009). This history of adverse effects and disruption to IPM probably precludes its use against *N. viridula* in these crops unless it could be applied via the irrigation system.	
Azomethine	Pymetrozine (Chess WG)	No specific information found about effect on *N. viridula* but it is known to be effective against a range of Hemipteran species. It is the primary product for the control of *Lygus rugulipennis* in UK cucumber crops where HV and ULV sprays provide protection from feeding damage for up 7 days post-treatment (Jacobson, 2002). Pymetrozine has also been shown to be effective against aphids on pepper when applied via the irrigation system (Jacobson, 2010).	Pymetrozine should be evaluated as a HV spray and via the irrigation in a commercial crop situation

Insecticide 'group'	Active ingredient / product	Notes	Potential for use in IPM programme
Cyclic ketoenole	Spiromesifen (Oberon)	Sold in the UK for the control of spider mites and whiteflies. Although whiteflies are distantly related to shieldbugs, no records have been found of any effect on Pentatomid bugs. Furthermore, the IOBC 'side-effects' lists show the chemical to be safe to the predatory bugs, *Macrolophus* spp. and *Orius* spp.	Unlikely that spiromesifen will provide control of *N. viridula.* No justification for including in trials.
Benzoylurea-type insect growth regulators (IGR)	Diflubenzuron (Dimilin Flo) Teflubenzuron (Nemolt)	Dimilin has an off-label for pepper in the UK (2433/99) and, until recently, there was an off-label (2130/10) for Nemolt on pepper and tomato. Both products are most commonly considered for the control of Lepidpterous pests. The mode of action involves inhibiting chitin production which is used by insects to build the exoskeleton. Both products are therefore potentially toxic to any species which undergo moulting within their life cycle. Although no information has been found about the effect of these IGRs on *N. viridula*, Mohaghegh *et al.* (2000) reported an adverse impact on the related Pentatomid bug, *Podisus maculiventris*. Teflubenzuron was found to be highly toxic to immature *P. maculiventris*. Although the IGR did not kill female adults, there was a marked decline in reproductivity capacity measured as a 63% reduction in egg hatch.	Both products should be considered for evaluation against *N. viridula* in laboratory bioassays before being tested on a crop scale.
Entomo-pathogenic fungi	*Beauveria bassiana* (Naturalis-L)	Refer to 'Biopesticides' section of this report. *B. bassiana* has provided promising results against some other Pentotomid bugs when applied HV or ULV. The frequency of sprays required would suggest that only the ULV treatment would be acceptable.	This product may be of interest to organic growers who have limited control options
	Verticillium lecanii (Mycotal).	No information to suggest this product will have any impact on *N. viridula* populations	Unlikely

Alternative insecticides:

Plant essential oils (PEOs) are complex, natural, volatile compounds characterised by a strong odour and are generally formed by aromatic plants as secondary metabolites. Many PEOs have insecticidal properties and are considered by many researchers to be excellent alternatives to traditional insecticides due to their short residual period and low toxicity to humans and wildlife. In a series of laboratory-based bioassays, Argentinian researchers have tested PEOs from *Aloysia polystachya*, *Aloysia citriodora*, *Origanum vulgare* and *Thymus vulgaris* against various life stages of *N. viridula.* In addition, they have evaluated the repellent effects of PEOs from leaves and fruits of *Schinus molle* var. *areira*, as well as N, N-diethyl-*m*-toluamide (DEET), against adults of *N. viridula* in a choice-test arena.

Aloysia polystachya (carvone) and *A. citriodora* (citronellal and sabinene) reduced egg hatch by up to 97% and 100% respectively at doses of 12.5 µg / egg. At 88 µg / mL. Complete insect mortality was achieved after 6 hours of exposure using *A. polystachya* and 97% mortality was achieved after 48 hours using *A. citriodora* (Gonzalez *et al.,* 2010). The PEOs from *O. vulgare* and *T. vulgaris* inhibited *N. viridula* egg hatch to 4% and 30% at doses of 0.625 µg egg. Both essential oils also had strong fumigant and contact activity against nymphs and adults of *N. viridula* (Gonzalez *et al.,* 2011a). The authors concluded that the oils form these four plant species could be good options for the management of *N. viridula* populations but all require further evaluation in whole plant situations.

In the repellency tests (Gonzalez *et al.,* 2011b), PEOs from leaves (157.2 µg / cm^2 and 314.4 µg / cm^2) showed repellent effect at 1 hour and PEOs from fruits at these same doses maintained the activity for 24 hours. DEET was repellent at all doses evaluated. The authors concluded that PEOs from fruits of *S. molle* and DEET had good repellent properties against *N. viridula* and could be used in the development of agricultural repellents.

Soft soaps (Savona, Safers Soap), dodecylphenol ethoxylate (Agri 50) and maltodextrin (Eradicoat) are all available for use in specific protected edible crops in the UK. The most common targets for these products are aphids and whiteflies. There is very little information about their efficacy against Pentatomid bugs. Several soft soap-based products are marketed for use against 'stink bugs' for the domestic market in the USA but the most effective also contain natural pyrethrins and / or neem oil (Skinner, University of Vermont, USA, Pers. Comm., 2013). Soft soaps and / or maltodextrin had to be used weekly to suppress population growth of *Macrolophus* spp. bugs in organic tomato (Jacobson and Morley, 2007) and these intensive spray programmes became detrimental to both plant growth and other biological control agents. Despite an urgent need to control *Lygus* bugs in cucumber, soft soaps, dodecylphenol ethoxylate nor maltodextrin have been adopted. Based on the limited information available, it seems unlikely that these products would be sufficiently effective against *N. viridula* populations in pepper or aubergine crops.

Physical monitoring and use of trap plants

In low level outdoor crops such as cotton and soybean, monitoring is usually based on 'sweeping' the crop canopy and recording the numbers of insects captured. For example, when investigating insecticides for *N. viridula* control, McPherson *et al.* (1995) used a standard 38 cm diameter sweep net to take 25 sweeps per experimental plot (plot size 9.1m x 15.2m). This was based on a method originally devised by Kogan and Pitre (1980) that has also been adapted by other researchers and practitioners. Such methods are not appropriate for high wire crops in UK glasshouses and will not be further discussed in this document.

Coombs (2000) used mercury vapour light traps (400 w) for monitoring adult *N. viridula* in Australian pecans. The paper contains very little detail about the methodology but this technique could have potential for use in UK glasshouses. It should be further investigated.

Panizzi (1997) provided a review of the importance of weed hosts in maintaining populations of Pentatomids of economic importance, including *N. viridula.* The objective was to understand which non-cultivated plants were used by *N. viridula* and to identify what contribution they made toward the pest's population growth. The implication was that good weed management could contribute to the overall management of the pest. However, most researchers have taken a different approach and sought plants which are very attractive to *N. viridula* and thereby draw the pest away from the crop.

Plants which are more attractive to *N. viridula* than the crop have been extensively used as traps in and around valuable broad acre crops in various parts of the world. In one of the earlier papers on this subject, McPherson and Newsom (1984) reported 70-85% of all *N. viridula* in a soybean crop were attracted to trap crops strips covering only 1-10% of the total crop area. Similar success had been reported by Newsom and Herzog (1977). However, McPherson and Newsom (1984) stated that trap crops would only be effective if the *N. viridula* were controlled within those traps to prevent subsequent spread into the main crop. They advocated chemical control of early instars of the pest in the trap crops.

Experiments using trap plants in corn-cotton landscapes in the USA during 2002 and 2003 demonstrated that *N. viridula* adults strongly preferred sorghum to cotton (Tillman, 2006b). Most adults that dispersed into sorghum plots remained there instead of moving into the cotton crops. The author concluded that sorghum could serve as a trap crop for *N. viridula* adults in cotton fields.

Soybean trap crops adjacent to cotton crops have been studied in Australia. The results suggested that small areas of soybean trap crop contained *N. viridula* for the whole season indicating that soybean was a far more attractive host than cotton (unpublished data cited in

Knight and Gurr, 2007). However, Knight and Gurr (2007) stated the main drawback to be the cost of sacrificing between 1-10% of land area to crop production.

Rea *et al*. (2003) used a border planting of white mustard (*Sinapis albus*) as a trap crop with organic sweet corn in New Zealand. Numbers of *N. viridula* were much higher in the mustard than the sweet corn.

Three trap crops (oil radish, oil rape and white mustard) were evaluated as a protection method against *Eurydema* spp. (cabbage stink bugs) on two hybrids of white cabbage (Bohinc and Trdan, 2012). Oil rape was the most attractive trap crop for *Eurydema* spp.

In contrast to other studies, Velasco and Walter (1992) suggested that there was no difference between plant species in attractiveness to *N. viridula*. However, adults were known to be strongly attracted to podding soybeans in preference to plants in earlier stages of development. They are therefore attracted to plantings of earlier maturing soybean cultivars (Todd and Schumann, 1988). In laboratory bioassays, Panizzi *et al.* (2004) further investigated the attractiveness to *N. viridula* of semiochemicals extracted from soybean pods and leaves. Methanol extract of pods stimulated the greatest oviposition. Further fractionation of this material by thin layer chromatography gave no single fraction with demonstrated activity, but the recombined fractions were again active, indicating that multiple components are probably involved in eliciting oviposition. In the long-term these semiochemicals may provide a method of monitoring and / or controlling *N. viridula.*

It is difficult to predict from the published work whether the plant species which have been shown to be more attractive than (say) cotton would also be more attractive than peppers or aubergines. Nonetheless, the previous studies have indicated which plant species could have potential for use as traps in these crops. Sorghum and soybean would appear to be good candidates, particularly when podding. Closer to home, unpublished reports from allotments in the London area, suggest that podding beans are very attractive to adult *N. viridula* and could form the basis of a trapping system. The size and growth habit of dwarf French beans could make them ideal candidates. Ideally, they should be tested with and without effective insecticides to control any offspring hatching from egg masses. Synthetic pyrethroids could be used in this situation without impacting upon natural enemies operating within the main crop canopy.

Semiochemicals:

Many research workers have investigated sex pheromones and aggregation pheromones produced by Pentatomid bugs. Combinations of laboratory and field studies have shown that *Halyomorpha halys* (brown marmorated stink bug) **(**Leskey *et al.,* 2012; Aldrich *et al.,* 2009), *Euschistus servus* (brown stink bug) (Cottrell and Horton, 2011), *Euschistus tristigmus* (dusky stink bug) (Cottrell and Horton, 2011), *Acrosternum hilare* (green stink bug) (Aldrich *et al.,* (2009), *Euschistus heros* (Neotropical brown stink bug) (Borges *et al.*, 2011) and the *Plautia stali* (brown-winged green bug) (Khrimian *et al*., 2008) all respond to pheromones. In addition, Moraes *et al.,* (2008) evaluated blends of defensive compounds produced by the Pentatomid bugs *Chinavia impicticornis*, *Chinavia ubica*, *Dichelops melacanthus*, *Euschistus heros*, *Piezodorus guildinii*, *Thyanta perditor* and *Tibraca limbativentris*. The present study has taken note of these publications but focused on published work of direct relevance to *N. viridula*.

Several studies during the last 30 years have clearly demonstrated that sexually mature males of *N. viridula* release a sex pheromone that is attractive in the field to conspecific females, males and late-stage larvae, and to the parasitoid *Trichopoda pennipes* (Aldrich *et al*., 1987; Miklas *et al.,* 2003; Tillman *et al.,* 2010; Shimizu and Tsutsumi, 2011; DoBae *et al.,* 2012).

Gilby and Waterhouse (1965) defined 18 compounds in the scent of *N. viridula*. The sex pheromone was shown to be a novel epoxybisabolene (*Z*)-(1′*S*,3′*R*,4′*S*)(–)-2-(3′,4′-epoxy-4′-methylcyclohexyl)-6-methylhepta-2,5-diene whose structure was confirmed by spectroscopic studies and synthesis of eight possible stereoisomers (Baker *et al.,* 1987). The pheromone blend typically includes (*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). More recent studies have confirmed the existence of an inter-individual variation of the *trans* to *cis* epoxide ratio within populations of *N. viridula* but indicated that each individual reproducibly emits both isomers in the same proportion (Miklas *et al.,* 2000 & 2003). The PE014 project team has identified sources of the chemicals that make up the sex pheromone and these will be formulated for evaluation in UK glasshouses during 2013.

Fucarino *et al.,* (2004) investigated cues that mediate the aggregation behaviour of immature Pentatomid bugs by using nymphs of six different pentatomid bug species (*Nezara viridula, Acrosternum hilare, Chlorochroa ligata, Chlorochroa sayi, Thyanta pallidovirens*, and *Euschistus conspersus*). When first instars of any two species were put together in a Petri dish, they readily formed heterospecific aggregations similar to their natural conspecific aggregations. The chemical profiles of first and second instar nymphs of each species were determined by solvent extraction with pentane, followed by GC-MS analysis. Immature bugs of the different species had some compounds in common and some that were more species specific. Within a species, there were distinct differences in the profiles of compounds extracted from first and second instars. Bugs did not aggregate around untreated polysulfone beads (1mm dia.) that were glued together in groups approximating bug egg masses, suggesting that tactile cues alone were insufficient to induce aggregation. Furthermore, when tested over a range of doses, groups of polysulfone beads treated with crude whole-body extracts of bugs did not induce or maintain aggregations. However, first instar *N. viridula* nymphs did respond to beads treated with two of the three major components of bug extracts. 4-Oxo-(*E*)-2-decenal induced significant aggregations at two doses, whereas tridecane, the major component in extracts from all six species, did not, and (*E*)-2-decenal was repellent. The repellence of (*E*)-2-decenal may explain why Fucarino *et al.* and previous researchers were unable to induce aggregations of first instar *N. viridula* using whole-body extracts. It is not immediately obvious how this knowledge may be exploited in practical IPM programmes.

A commercially available electronic nose (Cyranose 320) comprising an array of 32 carbon-black composite sensors has been used to detect Pentatomid bugs and their damage in cotton crops (Henderson *et al.,* 2010). The performance of the equipment was evaluated under laboratory and field conditions. Four of 32 sensors responded to volatile chemicals produced by bugs. Under laboratory conditions, internal cotton boll injury was predicted 95% of the time and the presence of bugs predicted 100% of the time. There was a strong correlation (R2 = 0.95) between the number of stink bugs in a sample and the response of Cyranose sensors. This technique could form the basis of a useful monitoring technique in UK glasshouses.

Example of a whole IPM programme:

Knight and Gurr (2007) proposed the following regime for IPM in field crops in Australia:

- Trap crops that are monitored throughout the season.
- Education for growers and consultants on therapeutic measures such as scouting, sampling methods, thresholds, beneficial insect identification etc
- Ecological engineering using carefully selected floral resources or refuges for beneficial insects.
- Releases of biological control agents as *Trissolcus basalis, Pristhesancus plagipennis* and *Trichopoda giacomellii* especially into trap crop and refuge areas.

- Experimentation with cultural methods such as row spacing, no till and reduced herbicide regimes that may decrease the crops attractiveness to *N. viridula*.
- Monitoring of main crops' plant health, pest numbers, beneficial numbers.
- Spraying main crop with synthetic insecticides only when necessary.

Anthomonus eugenii (Pepper weevil)

Cultural control:

Several 'cultural' control measures have been employed against *A. eugenii* in the Americas but these generally relate to outdoor situations and have little relevance to the more intensively grown and continuously harvested pepper and aubergine crops in UK glasshouses. For example, cultural controls include avoiding locations with pepper weevil infestations when selecting sites for a new pepper crop. Crop-free periods, accompanied by destruction of alternate hosts (*e.g.* neighbouring wild solanaceous host plants), are also recommended as means of disrupting the pest's life cycle (Capinera, 2008).

Berdegue *et al*. (1994) state that differences in varietal susceptibility are mainly due to the timing of ripening and concentration of fruit production of the crop. Synchronous and concentrated fruit production reduces the period of susceptibility to attack by the pepper weevil and enhances the effectiveness of management programmes which involve removing infested dropped fruit. It is reported that varieties which readily shed fruit infested by *A. eugenii* suffer lower overall damage levels than cultivars that retain fruits.

Crop hygiene measures are said to be of paramount importance. By destroying crop residue a carry-over of weevils from one crop to the next can be avoided. Similarly, removing and destroying fallen fruit will result in destruction of larvae and pupae (Riley and Sparks, 1998).

Invertebrate natural enemies:

Parasitoids

Seven species of parasitoids which attack *A. eugenii* were reported in the literature during the 1990s; *Pyometes venticosis, Catolaccus hunteri*, *Catolaccus incertus, Pediculoides ventricosus, Bracon mellitor, Habrocytus piercei,* and *Zatropis incertus* (Riley and Sparks, 1995 & 1998). Subsequent surveys in Mexico and Pacific regions of Central America have revealed further species; *Triaspis eugenii*, *Urosigalphus* spp., *Eurytom*a spp., *Eupelmus* spp, *Ceratoneura* spp., *Eupelmus cushmani* and *Balyscapus* spp. (Wharton and Lopez-

Martinez, 2000; Cortez *et al*., 2005; Rodriguez-Leyva *et al*., 2007; Rodriguez-Leyva *et al*., 2012). *Catolaccus hunteri, T. eugenii* and *Urosigalphus* sp. represented 96% of all specimens recovered by Rodriguez-Leyva *et al*., (2007) and *C. hunteri* has been the most often collected overall (Rodriguez-Leyva *et al*., 2012). The biology of the braconids, *T. eugenii* and *Urosigalphus* spp., would seem to make them best suited for biological control of pepper weevil due to their presumed host specificity and habit of attacking the host egg. Neither are thought to be indigenous to the UK although this may be worthy of further investigation.

Catolaccus hunteri is both the most abundant and most studied of these parasitoids. It is an external parasitoid of *A. eugenii*, attacking third instar larvae within flower buds and small fruit (Riley and Schuster, 1992). Detailed information regarding the biology and behaviour of *C. hunteri* is available in a series of papers (*eg.* (Riley and Schuster, 1992; Rodriguez-Leyva *et al*., 2000; Seal *et al*., 2002; Schuster, 2007; Gomez-Dominguez *et al.,* 2012).

Laboratory studies showed that *C. hunteri* has greater fecundity and intrinsic rate of increase than *A. eugenii* which stimulated and supported the plan of evaluating *C. hunteri* as a biological control agent of pepper weevil. Weekly releases of *C. hunteri* at a rate of 1600 adults per 0.2 ha plot in organically-grown bell pepper (*C. annuum*) beginning at first bloom, resulted in fewer weevil infested fruit compared to 0.2 ha plots where no parasitoids were released. Weekly releases of *C. hunteri* adults on nightshade, *Solanum americanum*, during the autumn / winter off-season followed by weekly releases of the same parasitoid in adjacent bell pepper during the spring in-season resulted in fewer infested pepper fruit compared to off-season nightshade and in-season pepper where no parasitoids were released. The results demonstrated the potential of augmentative releases of *C. hunteri* for suppressing infestations of pepper fruit by pepper weevil larvae (Schuster, 2007 and 2012).

Catolaccus hunteri is not listed as a UK species. It is known to be a generalist ectoparasitoid of at least 17 species of Curculionidae and two species of Bruchidae (Cross and Cheshunt, 1971; Rodriguez-Leyva *et al*., 2007) and as such it is unlikely that it could be released under licence in the UK as part of an IPM programme.

Predators

There are very few reports of predators attacking *A. eugenii* and no reports have been found which refer to the possibility of biological control programmes. Riley and King (1994) mentioned *Solenopsis geminata* (fire ant), *Tetramorium guineese* (ant) and *Strunella magna* (meadow lark) but none of these have any relevance to UK glasshouses.

Biopesticides:

Very little published material refers to the use of entomopathogenic fungi or other biopesticides against *A. eugenii*. This is perhaps because such products usually depend on contact action and a large proportion of the pest's life cycle stages are protected within the plant. Coutinho and Oliveira (1991) and Gomez and Jimonez (1995) refer to the potential of *Beauveria* spp. against adult *A. eugenii* and this work appears to have prompted further studies by Carballo *et al*. (2001). The latter undertook a laboratory study with the objective of evaluating different isolates of *Beauveria bassiana* in order to select the most virulent for control of *A. eugenii*. Several concentrations of fungus in water and oil suspension were evaluated to determine the half-lethal concentration (LC50) using immersion and aspiration application methods. All the isolates were pathogenic to the weevil. The greatest percentage mortality, the lowest lethal time and the greatest yield of conidia on rice was determined for the isolates 447, RL9-1, 113, 9205, 9218, 9006, 35 and 290. The suspensions of *B. bassiana*, both in water and in water mixed with oil at 3%, increased the weevil mortality and reduced the LC 50 in accordance with the increased concentration. The LC50 in water was 1.2×10^6 conidia / ml and in oil 2.2×10^4 conidia / ml, indicating that the efficacy of the fungus increased on adding oil to the suspension.

Several low-key publications and web sites make vague references to the use of entomopathogenic fungi for the control of *A. eugenii* in field situations but none have been found which provide any reliable supportive data. This seems to be a poorly investigated subject.

In the UK, Naturalis-L is the only product containing *B. bassiana* that is currently available to UK growers. It may be worth further investigating this product although the authors believe that it would have to be part of a larger IPM strategy.

Chemical insecticides:

Until DDT became available, there was no satisfactory chemical control for *A. eugenii* and even then control was said to be 'difficult' in peppers. Elmore and Campbell (1954) wrote that failure to cover the plants thoroughly with DDT or if applications were made at insufficiently frequent intervals, then survivors of each succeeding generation would be permitted to lay eggs in enough pods to cause considerable damage. Although the insecticides used have changed over the years that principle has remained true.

In 1953, Elmore and Campbell (1954) tested multiple applications of dust applications of seven insecticides, including DDT, aldrin, heptachlor, malathion and parathion. None of the treatment programmes were significantly different to untreated controls in terms of punctured pods until after the fifth application.

Numerous insecticides which showed potential against adult *A. eugenii* in the laboratory were tested in the field during the 1970s and 1980s. The most notable were carbamates (*eg*. methomyl, carbaryl, oxamyl), organophosphates (*eg.* parathion, chlorpyrifos, methamidiphos, acephate), early generation synthetic pyrethroids (*eg.* permethrin, fenvalerate) and cryolite (fluoride-containing mineral). The results can best be described as variable, sometimes with significantly reduced numbers of weevils but continued damage to fruit (*eg.* Genung and Ozaki, 1972; Ozaki and Genung, 1982; Schuster and Everett, 1982; Acosta *et al.,* 1987). Around this time, there were concerns over the development of insecticide resistance among *A. eugenii* populations. Some such claims were probably due to the inadequacies of spray programmes as had been highlighted by Elmore and Campbell in 1954. However, at least one laboratory study demonstrated some genuine reduction in activity of acephate, chlordimeform, methomyl, toxaphene and endosulfan (Rolston, 1977). Later studies confirmed resistance to carbaryl, endosulfan and methomyl (Servin-Villegas *et al.,* (2002).

Until the 1990s, the emphasis was placed on very intensive spray programmes. For example, Cartwright *et al* (1990) reported that up to 15 spray applications were applied per crop against *A. eugenii* alone. Several researchers then began to focus on detailed crop monitoring and the development of action thresholds (see below) as a means of reducing the number of sprays and improving the timing / efficiency of spray applications. However, insecticides such as permethrin, esfenvalerate, cryolite and oxamyl (alone and in combination with azinphos-methyl or methomyl) still formed the basis of control programmes (*eg.* Riley and Sparks, 1995).

New generations of synthetic pyrethroids and new insecticides with novel modes of action have become available during the last decade. It has been difficult to find scientific papers which report the efficacy of these insecticides against *A. eugenii* but they have begun to appear in lists of products recommended by extension services throughout the USA. Table 2 shows an extract from a recent publication by the New Jersey Agricultural Station (Rutgers, 2013) which provides a good indication of current thinking in terms of the control of this pest in the USA. The listed neonicotinoids may have potential within an IPM programme in UK glasshouse if they are active when applied through the irrigation system and if it is proven that they are harmless to pollinators.

Table 2. Products listed for use against *A. eugenii* by New Jersey Agricultural Station (Rutgers, 2013)

Insecticide group	Active ingredient	Example of product	Potential to use within an IPM programme
Carbamate	Oxamyl	Vydate	None
Synthetic pyrethroid	bifenthrin	Bifenture 2EC	None
	permethrin	Permethrin 3.2EC	None
	zeta-cypermethrin	Mustang Maxx	None
	zeta-cypermethrin + bifenthrin	Hero EC	None
Neonicotinoid	acetamiprid	Assail 30SG	Only if possible to apply via irrigation and proven to be harmless to pollinators
	imidacloprid	Admire	
	thiamethoxam	Actara	
	clothianidin	Belay	
	dinotefuran	Scorpion	
Neonicotinoid + Anthranilic diamide	thiamethoxam + chlorantraniprole	Voliam	Chlorantraniprole requires investigation
Flouride-containing mineral	cryolite	Kryocide 96W	Unlikely

There are very few references to successful use of 'alternative' insecticides against *A. eugenii*. Garcia-Nevarez *et al* (2012) evaluated the efficacy against *A. eugenii* of what they describe as two biorational insecticides; azadirachtin and spinetoram. The products were compared to other more conventional insecticides including thiamethoxam and chlorpyrifos. In isolated treatments azadirachtin and spinetoram performed relatively poorly. However, the results were more encouraging when spinetoram was incorporated into the following four spray programme:

Spinetoram → chlorpyrifos → chlorpyrifos → thiametoxam

Potentially useful products which are or have been recently available to UK growers of protected edible crops include:

- Spinosad (Conserve) is known to be effective against some Coleoptera but we have no information about its efficacy against *A. eugenii*. It has been shown to have systemic activity and can be used through the irrigation system under the Extension of Authorisation 0325/2013. It therefore has the potential to control *A. eugenii* within plant material. This product should be tested against *A. eugenii* at the first opportunity.
- The neonicotinoids, acetamiprid (Gazelle) and thiacloprid (Calypso, Reggae), should be effective against *A. eugenii* but are not particularly IPM friendly. The adverse effects

could be minimised if applied via the irrigation but this would require evaluation in a commercial crop situation.

- The entomopathogenic fungus, *Beauveria bassiana* (Naturalis-L), may be of interest to organic growers who have limited options for control with conventional insecticides.

Physical trapping, crop monitoring and action thresholds:

Considerable literature relates to methods of trapping *A. eugenii* and monitoring the pest's population development as well as decision making via the use of action thresholds in field crop situations in the Americas. Although the techniques have little relevance to glasshouse crops in the UK, some potentially useful information may be extrapolated.

Riley and Sparks (1995) summarised the various methods of detecting *A. eugenii* in the field as:

- Inspection of terminal buds or bud clusters for adult weevils
- Making direct weevil counts using whole plant inspections
- Checking for feeding damage or egg laying in terminal bud clusters
- Use of coloured sticky traps for adults
- Use of pheromone baited traps

Leigh *et al.* (1970) provided a foundation for future crop inspection studies by developing a sampling device for estimating absolute insect populations in cotton. By comparison to this method, other researchers could accurately determine the efficiency and reliability of less time consuming techniques (*eg*. Riley, 1990; Riley *et al*. 1992a and 1992b). The combined findings showed that the pest had clumped distribution in the field and good coverage with numerous sample points was essential to provide reliable results. They also showed that monitoring should focus on exposed terminal buds in the morning when most weevils are found. Based on these findings, a reliable action threshold of one adult *A. eugenii* per 400 terminal buds was developed. Use of this action threshold was claimed to save twelve insecticide applications over the season compared to a routine spray programme (Riley *et al*., 1992b). An alternative method developed by Cartwright *et al*. (1990) claimed that use of an action threshold of '1% buds infested' saved 10 insecticide applications per season at 'light' *A. eugenii* pressure. This was broadly similar to earlier findings which indicated that economic damage occurred at weevil populations of 0.01 adults per plant (Segarra-Carmona and Pantoja, 1988b). Although not directly relevant to UK glasshouse crops, this series of studies clearly established that action must be taken very promptly to avoid economic damage.

Anthomonus eugenii is attracted to yellow sticky traps (Segarra-Carmona & Pantoja, 1988a). One 375 cm^2 yellow sticky trap placed 10-60 cm above the ground will capture as many adults as are detected by inspecting 50 terminal pepper buds in field-grown peppers (Riley and Schuster, 1994). Parasitoid wasps are also attracted to yellow sticky traps. Populations of the parasitoid, *C. hunteri*, may be monitored with yellow, red or white sticky traps, all of which caught 3.3 times as many parasioids as green or blue traps (Schuster, 2012).

Pheromone baited yellow sticky traps (Trécé Inc. http://www.trece.com/agmon.html) can be used to monitor pepper weevil adults and to time insecticide applications which target adults (Bottenberg and Lingren, 1998; Natwick and Trumble, 2007).

Semiochemicals:

Anthomonus eugenii are attracted to host plants by visual cues, host plant volatiles, feeding damage volatiles (Addesso *et al.*, 2009) and / or the male-produced aggregation pheromone (Patrock *et al*., 1992).

Patrock *et al*. (1992) showed that boll weevil traps baited with male *A. eugenii* captured more conspecific weevils than did female-baited or unbaited traps. In addition, males and females were captured in all traps in similar proportions over the study. The boll weevil traps alone also caught some pepper weevils. In 1994, Eller *et al*. (1994) published the identity of six male-specific *A. eugenii* aggregation pheromones; ((Z)-2-(3,3-dimethylcyclohexylidene)ethanol, (E)-2-(3,3-dimethylcyclohexylidene) ethanol, (Z)-(3,3-dimethylcyclohexylidene)acetaldehyde, (E)-(3,3-dimethylcyclohexylidene) acetaldehyde, (E)-3,7-dimethyl-2,6-octadienoic acid (geranic acid) and (E)-3,7-dimethyl-2,6-octadien-1-ol (geraniol). Collections were made by gas chromatography and the emission rates from feeding males were approximately; 7.2, 4.8. 0.45, 0.30, 2.0 and 0.30 µg / male / day respectively. The synthetic pheromone was tested in field trials using sticky traps. Traps with the pheromone captured more *A. eugenii* (both sexes) than unbaited traps or pheromone-baited boll weevil (*Anthonomus grandis*) traps. However, it is thought that this trap did not reach its full attractive potential as the geraniol was not released properly.

There is some cross attraction of the pheromone with other weevil species (Kim *et al*., 2009); for example the boll weevil lure and trap is attractive to *A. eugenii* although less so than the *A. eugenii* synthetic pheromone. The boll weevil pheromone is also attractive to the cranberry weevil (*A. musculus*) and the pecan weevil (*Curculio caryae*). Cranberry weevil adults were highly attracted to traps baited with *A. eugenii* aggregation pheromone

(Szendrei *et al*., 2011). It is not known if there is any cross attraction with UK pest species (*eg. A. pomorum* and *A. rubi*) although there is considerable overlap of aggregation pheromone and host volatile components (Table 3).

In addition to male produced aggregation pheromones, *A. eugenii* are also influenced by host plant volatiles and much recent research has focused on their attraction to insect pests. Host plant volatiles not only often attract more of the damaging sex (*i.e.* females) but also enhance the catch of pheromone traps (e*g*. raspberry beetle traps, *Byturus tomentosus*). Male and female *A. eugenii* are attracted to volatiles released by whole plants of pepper, American black nightshade, aubergine and tomato (Addesso *et al*., 2009), although females showed different preferences for oviposition hosts depending on their age and sex. *Anthomonus eugenii* orientate and move upwind to host plants even in the absence of visual cues, conspecific feeding damage, or the presence of their aggregation pheromone (Addesso *et al*., 2009). Mated weevils prefer feeding on plants where feeding damage has already occurred (Addesso *et al*., 2011). Female weevils prefer fruit where eggs have not yet been laid but also where there is no female weevil frass or 'oviposition plug'. It is likely that the oviposition plug contains a deterrent (Addesso *et al*., 2007).

Anthomonus eugenii monitoring traps (4-Station Kit, 6 week lures, 4 traps & 4 dual lures) are available from Trece (http://www.trece.com/agmon.html) but pheromone controls are not yet available. There is obvious scope to optimise the aggregation pheromone and to include Solanacious plant volatiles and feeding damage volatiles in traps to make them more sensitive. These systems could be developed for mass trapping in UK glasshouse crops but approval would be required. In addition, the volatiles in the female's 'oviposition plug' would make an excellent candidate for repellent control strategies when the buds and young fruitlets are forming.

Table 3. Known pheromones and attractants of *Anthonomus* species.

[Table adapted from 'http://www.pherobase.com']

	Anthonomus eugenii	*Anthonomus grandis*	*Anthonomus musculus*	*Anthonomus pomorum*	*Anthonomus rubi*
	ATTRACTANT				
3-carene				X	
7S-germacrene D					X
alpha-pinene		X			
beta-bisabolol		X			
beta-caryophyllene		X		X	
E,E-alpha-farnesene				X	
lavandulol					X
limonene		X			
perylene				X	
Z3-6OH				X	
	PHEROMONE				
1R2S-grandisol		X			
beta-caryophyllene		X		X	
grandlure II	X	X	X		X
grandlure III	X	X	X		
grandlure IV	X	X	X		
E2-6OH		X			
E2-3me3me-cyclo-hexylidene ethanol	X				
geranic acid	X				
geraniol	X	X			
grandisol		X			X
	Eller 1994	Dickens 1990 Dickens 1989 a,b,c Hedin 1979 Hardee 1974 Tumlinson 1971 Minyard 1969 Tumlinson 1969	Szendrei 2011	Kalinova 1996	Cross 2006 Innocenzi 2001

Conclusions

The desk study has identified several monitoring and control measures that could be exploited by UK growers in the short, medium and longer-term. It should be possible to develop monitoring methods that can be used to accurately time IPM compatible treatments based on biological, physical and chemical techniques. However, it must be stressed that all the measures highlighted for *N. viridula* must be studied in greater depth before they can be recommended with any degree of confidence for use in UK crops. *Anthomonus eugenii* is not indigenous to the UK and its status is currently being reviewed by Plant Health. Possible sightings of the pest must be immediately reported to Plant Health who will implement a programme of control measures. The development of IPM compatible strategies for *A. eugenii* must be done in quarantine facilities in liaison with Plant Health.

Nezara viridula (Southern green shieldbug)

Monitoring systems:

- Sexually mature males of *N. viridula* have been shown to release a pheromone which is attractive in the field to females, males and late-stage larvae of the same species. In parallel to the HDC desk study, the chemical components of the pheromone have been formulated into lures which can now be tested in traps in and around glasshouses in the north London area.
- Mercury vapour light traps could have potential as an alternative to pheromone traps and should be evaluated in UK glasshouses. If effective, the study could be extended to investigate alternative sources of light.

Trap plants:

- Plants which are more attractive to *N. viridula* than the crop have been used as traps in and around valuable broad acre crops in the USA, Australia and New Zealand. Unpublished reports from allotments in the London area suggest that dwarf French beans could be a useful trap plant in UK glasshouses.
- Ideally, trap plants should be tested with and without effective insecticides to control the spread of any offspring hatching from egg masses. Even synthetic pyrethroids could be used in this situation without impacting upon natural enemies operating within the main crop canopy.

Parasites and predators:

- *Trichopoda giacomellii* is reported to be a specific parasitoid of *N. viridula* and has been introduced to control the pest at sites in western New South Wales and south-eastern Queensland. It is not indigenous to the UK but could be considered as a licensed biological control agent if it is proved it to be specific to *N. viridula*. However, the cost of mass rearing the host bug in sufficient numbers to make the production system economically viable could be a limiting factor.

- The ability of *Orius* spp. and *Macrolophus pygmaeus* to feed on *N. viridula* eggs / nymphs should be evaluated as both ese predators are already released in many UK pepper and aubergine crops and may make a contribution to the control of the pest.

Entomopathogenic fungi:

- Published information indicates that the entomopathogenic fungi, *Metarhizium anisopliae*, *Beauveria bassiana* and *Paecilomyces* spp., could all have the potential to contribute to an IPM programme against *N. viridula* and should be evaluated in greater depth. Such products may be of particular interest to organic growers who have limited options for the use of conventional insecticides.
- In the short term, crop-scale trials would be restricted to the only available product in the UK market; *i.e.* Naturalis-L (*B. bassiana*).
- In the longer term, it would be sensible to screen a range of isolates from all genera.

Chemical insecticides:

- The newer generations of synthetic pyrethroids are the products most commonly used against *N. viridula* throughout the world. Although the majority have been reasonably effective, they are incompatible with IPM programmes in UK glasshouse crops.
- Of the chemical insecticides recently available to UK growers of protected edible crops, potentially useful products include:
    - Pymetrozine (Chess) should be properly evaluated both as a high volume spray and via the irrigation in a commercial crop situation.
    - The neonicotinoids, acetamiprid (Gazelle) and thiacloprid (Calypso, Reggae), may have a role in the IPM programme if they can be applied through the irrigation system to minimise their impact on biological control agents and pollination.
    - The insect growth regulators, diflubenzuron (Dimilin Flo) and teflubenzuron (Nemolt) should be considered for evaluation against *N. viridula* in laboratory bioassays prior to being tested on a crop scale.
- Spirotetramat (Movento) was released onto the UK market in 2010 for control of aphids on brassicas and lettuce. It is registered for tomato in other parts of the world (*eg.* Canada) and is said to be harmless to most beneficials. Unpublished information from Australia indicates that it may have had an incidental effect on *N. viridula* when applied against other pests. Although not currently available to UK pepper and aubergine growers, this could provide a good IPM compatible solution in the longer-term.

'Alternative' insecticides:

- Argentinian researchers have shown that plant essential oils (PEOs) from *Aloysia polystachya*, *Aloysia citriodora*, *Origanum vulgare*, *Thymus vulgaris* and *Schinus molle* var. *areira,* as well as N, N-diethyl-*m*-toluamide (DEET), have activity against various life stages of *N. viridula*. These PEOs are worthy of further evaluation.

Anthomonus eugenii (Pepper weevil)

Monitoring:

- Considerable literature relates to methods of monitoring the pest's population development as well as the use of action thresholds in field crop situations but the techniques and thresholds have little relevance to glasshouse crops in the UK.
- Adult *A. eugenii* are attracted to yellow sticky traps. One 375 cm^2 yellow sticky trap has been shown to capture as many adults as detected by inspecting 50 terminal pepper buds in field-grown peppers.
- As well as visual cues, adult *A. eugenii* are attracted to host plants by various semiochemicals. These include male-produced aggregation pheromones, host plant volatiles and feeding damage volatiles. The aggregation pheromone has been incorporated into monitoring traps but has not been exploited as a control measure. There is obvious scope to optimise the aggregation pheromone and to include Solanacious plant volatiles and feeding damage volatiles in traps to make them more sensitive. These systems could be developed for mass trapping in UK glasshouse crops but approval would be required. In addition, volatiles believed to be present in the female's 'oviposition plug' would make an excellent candidate for repellent control strategies when the buds and young fruitlets are forming.

Cultural control:

- General hygiene has been shown to be of paramount importance; destroying crop residue avoids a carry-over of weevils to the next crop and removing fallen fruits interrupts the pest's life cycle by destroying larvae and pupae.

Parasitoids and predators:

- *Catolaccus hunteri* is the most abundant and most studied of the parasitoids reported to attack *A. eugenii*. However, it is known to be a generalist ectoparasitoid of at least 17 species of Curculionidae and two species of Bruchidae and as such it is unlikely that it could be released in the UK under licence as part of an IPM programme.

- There are very few reports of predators attacking *A. eugenii* and no reports have been found which refer to the possibility of biological control programmes.

Entomopathogenic fungi:

- Very little published material refers to the use of entomopathogenic fungi or other biopesticides against *A. eugenii*. This is perhaps because such products usually depend on contact action and a large proportion of the pest's life cycle stages are protected within the plant.
- *Beauveria bassiana* has been shown to infect adult *A. eugenii* in laboratory bioassays but no reliable data has been found to support its use in field situations. In the UK, Naturalis-L is the only product containing *B. bassiana* that is currently available to UK growers. It may be worth further investigating this product as part of a larger IPM strategy.

Chemical insecticides:

- Typical control programmes recommended by extension services throughout the USA include oxamyl (Vydate), a broad range of synthetic pyrethroids and neonicotinoids, as well as cryolite (a fluoride-containing mineral).
- Potentially useful chemical insecticides which are or have been recently available to UK growers of protected edible crops include:
    - Spinosad (Conserve) is known to be effective against some Coleoptera but we have no information about its efficacy against *A. eugenii*. It has been shown to have systemic activity and can be used through the irrigation system under the Extension of Authorisation 0325/2013. It therefore has the potential to control *A. eugenii* within plant material. This product should be tested against *A. eugenii* at the first opportunity.
    - The neonicotinoids, acetamiprid (Gazelle) and thiacloprid (Calypso, Reggae), should be effective against *A. eugenii* but are not particularly IPM friendly. The adverse effects could be minimised if applied via the irrigation but this would require evaluation in a commercial crop situation.

Knowledge and Technology Transfer

This project was of relatively short duration and there have been few opportunities to transfer the information to the growers and practitioners. Nonetheless, an interim report covering *N. viridula* was submitted to the Chairman of the British Pepper Growers' Technology Group on the 9 April 2013 and a Technical Briefing Note covering the same subject was posted on the HDC website on 10 May 2013.

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