A scoping study of IPM compatible options for the management of key vegetable sucking pests

David Carey
QLD Department of Primary
Industries & Fisheries

Project Number: VG06094

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(FINAL REPORT)

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Management options for sucking pests in Australian vegetable crops: A review of relevant research and current industry practice plus future prospects.

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Background Briefing.

The availability of specific soft option products for other pests such as Lepidoptera species control in vegetables has increased the importance of sucking pests in the modern day pest spectrum

Current vegetable sucking pest management practices are still heavily reliant on older broad spectrum pesticides. These non selective products prevent further adoption of an integrated pest management (IPM) system, and their frequent, multiple crop use pattern has the potential to enhance resistance development in the pest population. A limited number of more recently developed, pest specific or “softer” products for example spinosad (Success®) and pymetrozine (Chess®) are registered in some specific vegetable crops. The management of sucking pests is also complicated by the fact that virus transmission and product contamination are as, if not more important than the physical damage they can cause to vegetable crops. To modernise sucking pest control in the vegetable sector, work in a range of overlapping multifaceted areas needs to occur.

A team of entomologist in consultation with crop consultants, growers and specialist reviewers conducted a scoping study of the impact of at least 5 sucking pests commonly found across vegetable crops. Literature reviews, an industry workshop, interstate producer interviews and farm visits were employed to collate information on current best 'fit' management options within an IPM system, relevant to the particular vegetable and potential future management options.

Ideas for future research, development, and extension activities highlighted in the workshop process included ; biopesticides, improved beneficial insect management in current cropping systems, monitoring and early warning, improved knowledge of pest ecology, resistance issues, improved soft option products, increased grower awareness and information, extension and publications. Developing and testing fungal biopesticides against sucking pests, managing insecticide resistance and field testing biocontrol agents against thrips were considered the top three topics for further research of 28 topics listed and prioritised by the workshop participants.

Media Summary

The adoption of Integrated Pest Management (IPM) by the vegetable industry has progressed in recent years, thanks to a number of factors; the availability of new selective soft option products that are effective in controlling the major Lepidopterous pest species; the ability to rotate these selective products in some crops, thus reducing resistance pressure, and a greater awareness of crop scouting techniques used to assess insect pest pressure. This has lead to a reduced dependence, by leading growers, on older broad spectrum chemicals previously used for general pest control.

Producers are under increasing pressure from chain stores, processors, agents, and consumers to supply picture perfect produce. The chain stores move towards on farm bagging and enclosed packaging of product, so that it leaves the farm gate fully packaged and ready for sale, has pushed growers to even lower levels of insect tolerance. Unlike the box packed product, insects are trapped in the packaging and cannot escape. This move towards field packaging has implications for IPM practices and may require the industry to challenge both consumer and the market chains' current perceptions.

We as an industry need to challenge and realign current industry perceptions – our perishable products are produced in the field to a high standard but should not be (as they often are now in some QA systems) compared to a factory prepared product, processed in a sterile artificial environment.

The evolution to a higher level of IPM adoption is currently held back by the lack of specific soft option products to control sucking pests across a range of vegetable crops, effective farm friendly techniques to monitor or predict sucking pest population levels and the negative view amongst buyers and consumers who have come to regard any living insect or slight blemish on produce as totally unacceptable. It is interesting that the "organic buyer" seems prepared to pay a premium for a certified organic product, while in the mainstream market, the presence of an insect – often an indicator of reduced chemical use on farm is regarded as a contaminant and the product either downgraded or rejected.

Technical Summary

Summary of Scoping Study Findings.

FUTURE RESEARCH DIRECTION – APHIDS.

MONITORING
Given the importance of aphids as virus vectors alone, it is interesting that current population detection and monitoring techniques are not more advanced. This is not an oversight by the industry to-date, but is probably more related to the advancement in soft option pesticides for other pests over the past five to ten years.
The time has come to move forward and develop an effective, easily managed tool to allow early detection of the arrival of aphids in commercial vegetable crops. Water traps are not an easily managed tool, and sticky traps are also high maintenance, suffering lots of by-catch and wind blown soil contamination in the field. Just monitoring for aphid numbers in a crop may bear little relationship to virus incidence, as transient aphids play a major role in the transmission of non-persistent viruses. Effective monitoring would need to target these transient aphids as well as those that may settle and establish colonies in a crop. There is a need to develop a better system for monitoring aphids to assist growers in the early detection of aphids.

1. **NEW MONITORING TOOLS.**
Semiochemicals (pheromones) have been identified as having potential deterrent and attractant properties. The need for a practical in - field aphid monitoring tool was highlighted in the review. Semiochemicals need to be fully explored to determine if they have real application potential.

a. Review all world wide information available regarding aphid specific semiochemicals and there potential as monitoring or deterrent tools.
Select, obtain them and trial their performance in Australian conditions or, if information is insufficient, begin investigative work locally. This would involve intensive study of green peach aphid biology to identify and isolate any attractant pheromone compounds produced by this species and other significant aphid pest species e.g. *Aphis gossypii*.
b. Once isolated and tested - develop commodity (e.g. brassica cucurbits, capsicums) specific guidelines for use in population monitoring. These guidelines could be based simply on a percentage population increase above the district norm – rather than complex individual crop data.
c. Run experimental field demonstration sites to introduce the concept to growers
d. Combine this monitoring mechanism with the best soft option products to encourage further IPM adoption.

2. **ALARM PHEMONES – DISRUPTIVE BEHAVOIR.**
In conjunction with the above work identify and obtain samples of any candidate semiochemicals that are regarded as aphid alarm chemicals. Trial these products to determine if they can in fact be used to deter aphid migration into the crop.

3. **EDUCATION and EXTENSION.**
a. Educate the industry, (growers’ consultants and technical representatives) regarding the current soft option aphid specific products available.
Soft option products enhance the role of other bio-control agents such as wasps, mites, spiders, birds, and other general predators and parasites. Why is it that some growers still employ old broad spectrum products for aphid control?
b. Practical demonstration sites on farms may need to be set up to promote the use of aphid specific soft option products. These sites could be used to develop aphid action thresholds in the absence of broad spectrum chemical applications and to determine if the increased cost of aphid specific soft option products is actually offset by the free pest control derived by not killing other beneficial insects. This economic value should be quantified.
c. Improve grower awareness regarding resistance management, and product rotation knowledge. This could be combined with the development of a product rotation guide to slow or prevent resistance from developing further.

d. Communicate to the industry, (growers’ consultants and technical representatives) information on which pathogens are spread by aphids in which crops, and how they are spread. In some cases e.g. sow thistle aphid (*Hyperomyzus lactucae*) and necrotic yellows in lettuce the problem is best managed by managing sow thistles.

4. **SOFT OPTION PRODUCTS**.
a. Lettuce aphid – why is the industry reliant on imidocloprid which we now know can cause the death of beneficial predators. Investigate the efficacy of pymetrozine (CHESS^{R}) as a seedling drench.
b. Co-ordinate this with the work done in the minor use program, and access any overseas data relating to existing soft option products available in Australia. Identify any other international products that are beneficial friendly and would assist our sucking pest control. Trial and champion these products to industry and the APVMA via the minor use office - or at least in conjunction with that minor use program.

5. **ENTOMOPATHOGENS**.
a. Should play more of a role in controlled environment structures where humidity and environment are conducive to their survival. It seems though that many protective cropping structures are not really suitable for such techniques due to their relatively simple design and lack of adequate climatic control mechanisms. If there really is this design constraint it makes the industry more reliant on chemical control measures. This issue should be highlighted and followed up with protected cropping growers.
b. Investigate pairing the entomopathogens with a new method of dispersal such as pheromone lures (as outlined above), artificial feeding stations, light or sound attractants to disperse these pathogens. Overseas collaboration or investigation could play a useful role in determining future direction.

6. **ENVIRONMENT MANIPULATION**.
a. Review the outcomes of the “revegetation by design” project and set up a demonstration trial site to better quantify and promote the planting of plant species that encourage beneficial insect populations. This could be combined with natural

resource type projects looking at revegetation of waterways adjacent to vegetable cropping areas – thus achieving a two fold outcome.
b. Place renewed importance on farm and crop hygiene and remove plants and weeds that are known pest species habitats, or virus sources. Education and demonstration would be necessary. Work across disciplines with this and link with HAL pathology program.

7. **FORECAST MODELS**.

It may be possible to use current knowledge of aphid life cycles and local climatic patterns to forecast probability of aphid incursion into a cropping area, using existing meteorological data. This deserves some consideration, if only on an area wide basis as a way of alerting production areas to a heightened potential for aphid activity. A review of world wide knowledge of aphid biological drivers could be fruitful to improve forecasting ability.

Previous work carried out monitoring aphid movement in Australia on clover species in the late 1970s and early 1980s should be reviewed. This work may provide a basis for future activities, or be instructive regarding previously observed aphid movement drivers (Garrett R.G *et al.* 1983, Guiterrez A.P. *et al.*1974 a & b). Refer to the aphid section reference list.

Five suction traps are currently being set up as part of an Australian PhD project to monitor currant lettuce aphid movement in commercial lettuce crops. These types of traps are used internationally to develop forecasts for a number of pest aphid species; however the labour to screen trap catches is high.

8. **EXTENSION EDUCATION ACTIVITIES**.

a. Cabbage aphids (*Brevicoryne brassicae*) colonise odd single plants in a crop and only spread very slowly. Correct identification and grower recognition should reduce the cost of un-necessary control measures.
b. Improve the industries, (growers' consultants and technical representatives) knowledge and appreciation of the role of predators and parasites.
c. Develop some best bet population trigger points by discussion with growers, consultants and researchers that can be field tested, used and refined into commercially useable population control decision tools.

9. **RESTRICT ACCESS**.

Prevent minor use permits for aphid control being granted for old broad spectrum chemicals if there is a modern specific soft option product that could be "permitted" instead.

Note:

a. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.

b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

Row covers may have benefits for some very small market gardeners; however history reveals they do not appear economic on a commercial scale.

FUTURE RESEARCH DIRECTION – MINOR "BUG" SPECIES.

Rutherglen bug has been identified as the main cause of economic damage and contamination across a wide range of vegetables and herbs, with green vegetable bug and leaf hoppers also identified as issues but generally less problematic. Bugs are an increasing issue as specific soft option products are used to control other pest species. No known "bug" specifics are currently available – though possibly spirotetramat (Movento^{R}) may have some impact.

The vegetable industry needs improved methods of detecting the presence of, and flagging the arrival of influx populations. There is a need for improved data on action thresholds, tolerance levels and impacts across a range of crops as bugs can impact fruit quality and can be a major contaminant issue.

1. **MONITORING.**

1. Develop effective bug monitoring tools to help growers better determine when bug populations appear and need to be controlled. Rutherglen bug should be the basis for this work.

a. Both semiochemical or pheromone attractants and deterrents should be explored.
b. Improved knowledge of the insects biology and weather conditions that lead to population explosion and migration could assist in forecasting influx migration events.
c. Determine if forecast models based on weather data could be used to predict Rutherglen bug migrations – refer to the aphid research needs

2. Determine by further specific industry consultation and trial work, at what population level (e.g. X insects per 20 plants) Rutherglen and green vegetable bugs cause economic damage. This work should target a crop where these bugs are already identified as causing production difficulties. This bug / crop interaction may vary between states and cropping systems. Rutherglen bug is identified as a serious but sporadic problem in lettuce, Chinese cabbage, and many herb and bagged salad mix lines (e.g. high density mechanically harvested (mown) leafy vegetables as well as Asian vegetables – bok choy etc). Green vegetable bug could be studied in a crop such as zucchini.

a. Develop from these studies Australia wide grower action guidelines that can be reviewed and updated over time, to develop district action guidelines.

2. **SOFT OPTION PRODUCTS.**

a. Review worldwide data for availability of soft option specific products to control Rutherglen bug, green vegetable bug and mirid species.
b. Ascertain the likelihood of Australia accessing these products and discuss this with APVMA and the minor use programme co-ordinator.

c. Identify current best control products that have minimal impact on beneficial insects via information generated by HAL's current soft option screening project, and by liaison with the minor use office and minor use project co-ordinator.

d. Conduct screening trials of identified products to confirm efficacy on Rutherglen bug, observe their effect on beneficial insects and, obtain residue data under Australian conditions.This should include exploring and promoting pathogenic fungi or bacteria if they are determined to be economically viable in the future.

3. **IMPROVED PEST KNOWLEDGE**.
a. Study Rutherglen bug to increase our knowledge – there have been reports that Rutherglen bug will predate on *Helicoverpa* sp. eggs. We need to increase our knowledge of this emerging pest.
b. Develop a resistance management system for this and other bug pests.

4. **EMERGING TECHNOLOGY.**
a. Investigate via laboratory trials and improved knowledge of the pests biology if there is any scope for new alternate control or dispersal methods (based on improved pest understanding) such as – radio waves, ultrasonics etc that would be economical and worth trying. Could these or other non-chemical, non- lethal techniques be used to move insects out of the harvest zone of crops destined for field bagging just prior to harvesting? This is essential for multiple harvest crops and rapid growth crops where withholding periods interfere with optimum harvest periods and disrupt or kill beneficial insects.

5. **EDUCATION.**
a. Educate the consumer and the marketing sector to accept the odd live insects in packaged product as an indicator of a well managed, human friendly, environmentally responsible production system.
b. Inform consumers and the market chain about the link between their low levels of tolerance (or nil tolerance) for blemished produce, and insect contaminants, and the pressure this puts on growers to apply more insecticide

Note:

a. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.
b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

FUTURE RESEARCH DIRECTION – THRIPS.

Thrips are small, evasive, highly mobile and difficult to monitor easily with the naked eye. Specialist skills, knowledge, and equipment are needed to correctly identify pest species. Thrips can be responsible for virus transmission and so all species are treated as pests by growers.

1. **SOFT OPTION SPECIFIC PRODUCTS.**

There is a need to develop soft option management approaches across all crops affected by thrips. Western flower thrips control measures are at present largely reliant on spinosad and resistance has developed.

a. Beauveria is an entomopathogenic fungus identified in this review as having the most potential for commercialisation in Australian vegetable crops. Current APVMA registration hurdles are apparently hindering this option. A project to assist and guide the APVMA to actively pursue the registration of the native strain of this bio-pesticide may assist commercialisation, industry acceptance, and adoption.

b. Identify from local and overseas research data any new soft option or entopathogenic products that are specific to sucking pests and may assist in thrips control. Field test these products in our major thrips affected crops.

2. **MONITORING.**

a. Develop an effective, practical, grower friendly monitoring system to allow on farm tracking of thrips numbers.

b. Develop thrips specific control threshold guidelines that can be reviewed and updated over time, to develop and fine tune district action guidelines. This will become more relevant as access to soft option specific products allows growers to stop using broad spectrum products.

c. Investigate a semiochemical (pheromone) based system. Individual on farm monitoring would be ideal so a semiochemical attractant, or similar local population sampling tool should be developed.

d. Consider a weather based population model linked to knowledge of thrips biology and population dynamics to predict pest influxes. This sort of system would need to take an area wide approach.

3. **PREDATORY INSECTS**.

There are two *Orius* species which have been used for WFT control one of which (*Orius armatus*) is native to Australia and has been shown previously in Western Australia to consume large numbers of adult western flower thrips, *Frankliniella occidentalis*. In the USA another *Orius* species is raised and released commercially to control thrips. A previous effort to raise the native *Orius armatus* in Australia failed.

The reason for this failure should be reviewed as Western and South Australian greenhouse growers report very high levels of resistance to methomyl and abamectin in western flower thrips populations. A biological control alternative such as this *Orius* species may be a good addition to an IPM system in protected cropping structures and possibly in the field. A combined release approach with predatory mites (as outlined below) in protected cropping structures should enhance current IPM options and adoption.

The predatory mite *Transeius montdorensis*, or commonly known in the industry as Monties, was discovered and developed by the NSW Department of Primary Industries at the Gosford Horticultural Institute. Monties are predators of western flower thrips and provide excellent levels of controls in several crops including cucumbers and tomatoes. Monties also manage populations of other thrips that are present in crops and are often used in conjunction with other predatory mites such as *Neoseiulus cucumeris* and *Stratiolaelaps scimitus* (*Hypoaspis*) in greenhouse production.

Whilst Monties are commercially available, work is underway to further develop their rearing potential so that the market may be expanded for their use. Research is also being undertaken examining their role as predators of many other pests in greenhouse horticulture (pers.com. Dr Leigh Pilkington NSW DPI)

4. **EDUCATION.**

Educate growers, consultants, plant suppliers, and resellers about the importance of farm hygiene.

a. Continue to educate growers and industry groups regarding the important role of good farm hygiene practices, the removal of virus affected weeds, crop plants and residues which can both harbour resident thrips populations and be a continual source of virus spread.
b. Publicise more widely the major weeds that act as virus hosts and in some way demonstrate visually to growers the exponential infection nature of the virus/sucking pest interaction.
c. Manage resistance influences by providing a multiple control strategy, involving soft option products, monitoring, product rotation, and exclusion recommendations for covered cropping structures.
d. Link with virology research programs in conjunction with HAL to ensure work already done by virologists is recognised and integrated into IPM education and programs.

5. **ENVIRONMENT MANIPULATION.**

a. Enclosed or protective cropping structures are often associated with year round cropping of virus susceptible crops – this is a growing sector of the industry and often involves growers who speak and read English as a second language, if at all. Coupled with this is an element of direct marketing to the consumer via local “Saturday” markets or via direct supply to the local corner store. This sector of ground and hydroponic growers should be targeted with educational activities and demonstration events to assist the adoption of good hygiene and sucking pest control practices. This should include a push towards education about, and release of predators and entomopathogens in these enclosed structures. To ensure good adoption and the best results from such options, education about the potential to improve the environmental controls and general hygiene within the structures may have to occur to maximise pest and disease control results

b. Areas around protected cropping structures often suffer from poor hygiene practices and weed infestation. The promotion and adoption of the planting of beneficial plants (refer to Re-Veg by design projects) in these areas could provide a source of beneficial insect breeding sites – while also fostering the removal of weeds and other potential virus host plants.

Note:

a. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.
b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

FUTURE RESEARCH DIRECTIONS – SLW.

1. DISPERSAL CONTROL.

Silverleaf whitefly (SLW) dispersal from neighbouring crops or from infested crop residues is the major source of SLW invasion in vegetable production areas.

a. Identify workable, “cost-effective’ dispersal control strategies.
b. Crop hygiene /cleanup measures need to be improved – simply ploughing in residues is not sufficient. Carry out trial work to quantify the effect of spraying off SLW infested crop residue with several carefully selected knockdown insecticide and herbicide products, such as “Spray Seed®”. Quantify the effect this has on dispersal, compared to simply ploughing in crop residue. Products should be chosen carefully with the cost of the treatments compared and results communicated clearly and concisely to growers.
c. Dispersal effects created by the various treatments should be measured, documented, and communicated to growers.

2. EXTENSION / EDUCATION ACTIVITIES.

Research and grower education on certain SLW insecticides remains a priority to ensure these tools deliver maximum benefit. Key candidates for this type of research and extension under Australian conditions are the IGR pyriproxyfen, and the soon-to-be-registered lipid biosynthesis inhibitor spirotetramat (Movento®). Pegasus® should also be considered – refer to point three below.

3. SOFT OPTION PRODUCTS.

The unique mode of action product diafenthiuron (Syngenta: Pegasus®) is only registered for SLW and aphid control in cotton. The barriers to possible registration for use against SLW in vegetables should be discussed with the manufacturers, APVMA and industry bodies. It is an important SLW management option for vegetables.

4. **FORECAST MODELS.**

Develop population models based on increased use of climate/season-based risk assessments to guide deployment of prophylactic soil-applied insecticides, and guide timely application of the newer slow acting IGRs to maximise SLW control. Greater awareness of climatic factors influencing SLW risk could assist some growers to identify when prophylactic imidacloprid application could be avoided
(or most needed) at planting. This would benefit resistance management, production costs and should be pursued on an area wide basis.

5. **EDUCATION and COLABORATION**.

a. Invest in relationships, structures and agreements to deliver best practice regional SLW management.

b. In some regions, a high degree of mutual understanding, co-operation and agreement will be required between competing vegetable growers and/or different commodities (e.g. melons and cotton) to effectively manage SLW populations and delay the development of insecticide resistance. Therefore significant effort and resources should be devoted to developing relationships, structures and agreements that will facilitate the best possible outcomes for all sectors. Greater co-operation between the grains/cotton and horticultural industries would be desirable in regions where cross-commodity issues are identified as significant barriers to progress in regional SLW management.

6. **VIRUS VECTOR RECOGNITION**

Recognition of SLW as a vector of begomoviruses.

Industry need to be conscious of the fact that SLW is a vector of begomoviruses which pose a significant threat to both the vegetable and field crops industries. Tomato yellow leaf curl virus is now present in Queensland and many viruses in this group are widespread throughout South East Asia.

7. **ADAPTATION OF EXISTING KNOWLEDGE**.

Adapt population growth models and the ‘population management threshold’ concept as used in cotton to vegetable production systems

The potential for applying and refining/validating the cotton industry’s decision support models for SLW management ought to be investigated within vegetable cropping regions. A different tack may need to be taken due to multiple cropping of different crops on a continual basis in the production season. There may still be value in forecasting, or advising growers when optimum SLW breeding conditions are expected. You could possible predict a” window of maximum activity”.

It must be remembered that cotton is concerned about lint contamination while many vegetable crops have physiological responses at very low densities, so thresholds etc may be very different.

Note:

a. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.
b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

REVIEWERS' NOTE.

Mite control is a separate area not dealt with in this specific review of sucking pests. However grower feedback also identified that mite control is still largely dependant on broad spectrum chemical intervention in vegetable crops.

Suggested Complementary Review Work.

A project similar in structure to this scoping study of sucking insect pests in vegetables should be carried out on mites in vegetables. Such a review should assess current control options in vegetables and identify what soft option specific mite control products are available to the industry. IPM adoption and advancement within the vegetable industry should not be constrained by reliance on older broad spectrum pest control products.

Feedback obtained in this current review suggested that *Orius tantillus* is known to predate on mite eggs and adults in Rhodes Grass seed heads.

Summary Section: Table 1

IMPORTANT VIRUSES IN VEGETABLE CROPS IN AUSTRALIA

Virus/virus group	Means of spread	Important crop hosts
Bean common mosaic virus (Potyvirus)	Seed, aphids (non-persistent)	Beans
Bean yellow mosaic virus (Potyvirus)	Aphids (non-persistent)	Legumes, some ornamentals
Beet western yellows virus (Polerovirus)	Aphids (persistent)	Brassicas, lettuce, legumes, brassica weed species
Capsicum chlorosis virus (Tospovirus)	Thrips (three species)	Capsicum, tomato, peanut
Carrot virus Y (Potyvirus)	Aphids (non-persistent)	Carrot
Celery mosaic virus (Potyvirus)	Aphids (non-persistent)	Celery
Cucumber mosaic virus (Cucumovirus)	Seed, vegetative propagation, aphids (non-persistent)	Wide host range including legumes, cucurbits, capsicum, tomato, lettuce, ornamentals, weeds
Iris yellow spot virus (Tospovirus)	Thrips (*Thrips tabaci*)	Onion
Johnson grass mosaic virus (Potyvirus)	Aphids (non-persistent)	Sweet corn, maize, sorghum
Lettuce mosaic virus (Potyvirus)	Lettuce seed, aphids (non-persistent)	Lettuce
Mirafiori lettuce virus (Ophiovirus*)*	Zoospores of the soil-borne fungus *Olpidium brassicae*	Lettuce
Papaya ringspot virus – type W (Potyvirus)	Aphids (non-persistent)	Cucurbits
Pea seed-borne mosaic virus (Potyvirus)	Pea seed, aphids (non-persistent)	Pea and several other legumes
Potato leaf roll virus (Polerovirus)	Aphids (persistent), vegetative propagation	Potato, tomato

Virus/virus group	Means of spread	Important crop hosts
	(tubers)	
Potato virus Y (Potyvirus)	Aphids (non-persistent)	Potato, tomato, capsicum
Squash mosaic virus (Comovirus)	Seed, several leaf chewing beetles	Cucurbits
Subterranean clover stunt virus (Nanovirus)	Aphids (persistent)	Legumes, including beans, pea, broad beans
Sweet potato feathery mottle virus (Potyvirus)	Vegetative propagation (cuttings, roots); aphids (non-persistent)	Sweet potato
Tomato mosaic virus (Tobamovirus)	Seed, contact by handling, contaminated implements	Tomato
Tomato spotted wilt virus (Tospovirus)	Thrips (persistent, propagative)	Wide host range among vegetable, ornamental and weed species
Tomato yellow leaf curl virus (Begomovirus)	Silverleaf whitefly (*Bemisia tabaci*) (persistent)	Tomato, bean, capsicum, several weed species
Turnip mosaic virus (Potyvirus)	Aphids (non-persistent)	Brassicas, lettuce, rhubarb
Watermelon mosaic virus (Potyvirus)	Aphids (non-persistent)	Cucurbits
Zucchini yellow mosaic virus (Potyvirus)	Aphids (non-persistent)	Cucurbits

Types of insect vector transmission

Non-persistent: the virus can be acquired from an infected plant or transmitted to another plant in less than one minute; the virus is usually retained on the insect's mouthparts for only a few hours.

Semi-persistent: the insect can be acquired after 15-30 minutes of feeding and the ability to transmit is retained for a few days.

Persistent or circulative transmission: the insect needs to feed for up to several hours on an infected plant to acquire virus which then needs to circulate through the insects body to the salivary glands for transmission to occur. The insect may retain the ability to transmit for life.

In some instances, the virus may also replicate or reproduce in the insect during the circulative transmission process (Propagative).

Compiled by: Denis Persley, July 2008.

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Background of Project

Sucking insects such as aphids, whiteflies, thrips and Rutherglen bugs, are just some of the suite of pests to be expected within vegetable crops. One of the special priorities identified during an IPM stock take (McDougall 2006) was the specific importance, difficulties, and potential of implementing IPM for sucking insect pests in vegetable crops.

Introduction

A comprehensive effective working IPM system targeted at a specific crop has not yet been achieved for many crop groups. While substantial progress has been made towards integrated management of caterpillars in crops such as sweet corn and brassicas, IPM compatible management options for sucking pests has not evolved as rapidly. Unfortunately many current management options for sucking pests compromise the integrated pest management system being used to control caterpillar pests.

Sucking insects such as aphids, whiteflies, thrips and Rutherglen bugs, are but part of the suite of pests to be expected within specific vegetable crops. One of the special priorities identified during an IPM stock take (McDougall 2006) was the specific importance, difficulties, and potential of implementing IPM for sucking insect pests in vegetable crops.

In field vegetable crops current sucking pest management practices depend on broad spectrum pesticides such as dimethoate (Rogor®), or an over reliance on limited more recent chemistry such as imidacloprid (Confidor®) for soil treatment or new foliar pesticides such as spinosad (Success®). While effective in the short term, these current practices all have an impact on, the biological control part of an integrated pest management (IPM) system, and increase the potential for resistance to develop in the pest population.

The importance of sucking insect pests is greatly magnified by their role as vectors of a range of plant pathogens within vegetable crops. The distribution and importance of some of these pathogens are already well known, however recent incursions, e.g. Tomato Leaf Curl Gemini Virus have the potential to explode out of their current limited occurrence and decimate areas infested with sweet potato and silverleaf whitefly.

The potential to develop a traditional IPM system for sucking pests is inhibited some what, because traditionally an IPM system involves some tolerance of a low level of pest presence in the crop system. However the impact of virus occurrence in vegetable crops can be so devastating that there is little or no tolerance to even low levels of the vector pests.

The high mobility bug species, such as Rutherglen bug and green vegetable bug are often infrequent pests of vegetable crops, however when these pest influxes occur they can cause devastating damage. The mobility and migratory influx potential of these pest populations means that an area wide, “population pressure approach”, may be necessary in order to forecast pest potential. .

Successful lPM strategies include a synthesis of a large amount of information from incremental studies of the individual components of an IPM system for each crop. For sucking pests, independent studies fit into the categories:

- the impact of at least 5 sucking pests commonly found across vegetable crops,
- potential management options that fit under the three main areas of, biological, chemical and cultural control; within which are a set of subgroups;
- options relevant to different climatic zones within Australia and
- IPM options relevant to the particular vegetable.

It is therefore important to gather as much published and anecdotal information on the viability of an IPM approach. Specific individual studies on the IPM of particular pests have been done in the past but few have been synthesized into a "best bet option". This project seeks out key researchers, and consultants in the field of individual sucking pests and their management, to distil the most practical options and to forge the whole into a series of best bet options for vegetable crops.

This information then serves as a foundation to develop projects that can field test these options against current non-IPM practice.

Method

A team of 4 entomologists conducted a literature search on sucking pests and put it into a reporting framework. The framework consisted of what research had been conducted on sucking insect pests in vegetable crops and other crops in Australia, and internationally. The draft document was then circulated to industry members and entomologists working in the vegetable industry. A feedback sheet was provided that collected their input on missing information within the draft.

The cumulative knowledge and experience of entomologists and industry consultants with over 100 years of combined experience of sucking pests and their management between them was captured at a two day workshop held in Brisbane. Three Queensland consultants and seven leading entomologists working on vegetable crops or sucking pests from WA, SA, NSW and Qld provided feedback on a draft scoping study for management options of key sucking pests of vegetable crops, including information they could add, and highlighting the remaining gaps. Discussion of grower experiences also described what IPM of sucking pests currently involved in the field. Lastly, participants discussed what research, development or extension activities could be carried out to improve IPM of sucking pests in the field.

The participants commented that the draft document was comprehensive, and useful for bringing them up to date on sucking pest management and research. They were able to strengthen the scoping study by bringing current field knowledge to the workshop that wouldn't have otherwise been captured.

Lastly consultation with farmers on current management practices, and further ideas for future research was undertaken through telephone interview and visits. In addition follow-up with entomologists and industry consultants (especially from other States) who couldn't attend the workshop was carried out via phone, e-mail and visits. The information obtained was also cross referenced with information already gathered in the IPM stock take project.

The scoping study discussion has been structured to address each key sucking pest: aphids, thrips, silverleaf whitefly and 'other bugs'. Within each pest section is included a section on current knowledge of the pests biology, damage to crops, monitoring practices, threshold information, biological, chemical and cultural control practices plus integrated strategies.

Progress to Date.

(In relation to where sucking insect pests fit into Horticultural production systems)

A comprehensive review of the issues surrounding sucking pest control in vegetables and current pest knowledge and management techniques is outlined in this document under the headings; Aphids, Minor"bug" species, Thrips and Silverleaf Whitefly.

The adoption of Integrated Pest Management by the vegetable industry has progressed in recent years, thanks to a number of factors; the availability of new selective soft option products that are effective in controlling the major Lepidopterous pest species; the ability to rotate these selective products in some crops, thus reducing resistance pressure, and a greater awareness of crop scouting techniques used to assess insect pest pressure. This has lead to a reduced dependence, by leading growers, on older broad spectrum chemicals previously used for general pest control. The evolution to a higher level of IPM adoption is currently held back by the lack of specific soft option products to control sucking pests across a range of vegetable crops, and effective farm friendly techniques to monitor or predict sucking pest population levels.

Producers are under increasing pressure from chain stores, processors, agents, and consumers to supply picture perfect produce. The chain stores move towards on farm bagging and enclosed packaging of product , so that it leaves the farm gate fully packaged and ready for sale, has pushed growers to even lower levels of insect tolerance. Unlike the box packed product, insects are trapped in the packaging and cannot escape. Product will be rejected if it is contaminated by the occasional insect in the package – even if those insects are beneficial.

This move towards field packaging has implications for IPM practices and may require the industry to challenge both consumer and the market chains' current perceptions.

The majority of these occasional incidental insects caught up in the field packing process are non pest species. Why is it that they are not regarded as a sign of a healthy, robust, non chemical dependent production system?We as an industry need to challenge and realign current industry perceptions – our perishable products are produced in the field to a high standard but should not be compared to a factory prepared product, processed in a sterile artificial environment.

The review outcomes and future potential areas of research or educational activities are summarised at the beginning of each individual sucking pest section.

This individual outcome is a result of the combination of the expert review combined with grower and industry feedback. In some cases the future outcome may differ from those expressed by the individual reviewer, this reflects the industry consultatative style of this review.

The outcomes are grouped under similar headings for each sucking pest group. They are not prioritised as to individual importance. This should allow HAL and future research and extension decision makers flexibility in future work directions. There are however significant areas of overlap – such as semiochemicals (pheromones) and monitoring systems to list but two, where one project could possibly provide information across the range of sucking pests. Equally there are individual issues, such as Rutherglen bug biology for example, that could form distinct individual projects.

Chapter 1

APHID ISSUES HIGHLIGHTED BY THE REVIEW AND CONSULTATION PROCESS.

THE PROBLEM IN GENERAL.

Aphids are a major source of virus transfer within all vegetable cropping areas. Aphids are a pest in a wide range of crops and as a contaminant are becoming more of an issue as a result of the retailers push towards in -field bagging of many Australian grown vegetable and herb lines.

The availability of specific soft option products for other pests such as the Lepidoptera species has increased the importance of aphids in the modern day pest spectrum. Aphid specific soft option products are available in a range of crops but their pest specific nature and effectiveness needs to be highlighted and promoted to growers and resellers, to encourage and foster greater adoption of their use. These pest specific products becoming more widely available for a broad range of vegetable crops will reduce the current reliance on older broad spectrum chemistry and enhance soft option pest management techniques that encourage IPM.

Aphids as vectors of virus particularly potyvirus such as necrotic yellows in Lettuce, watermelon mosaic virus , Papaya ring spot virus, and Celery mosaic virus currently cause major economic loss. In fact the virus vector role of aphid is significantly more important in terms of economic impact than physical damage. The virus vector role of aphid within the vegetable industry would currently cause more economic loss than either product contamination or physical damage.

FUTURE RESEARCH DIRECTION – APHIDS.

MONITORING

Given the importance of aphids as virus vectors alone, it is interesting that current population detection and monitoring techniques are not more advanced. This is not an oversight by the industry to-date, but is probably more related to the advancement in soft option pesticides for other pests over the past five to ten years.

The time has come to move forward and develop an effective, easily managed tool to allow early detection of the arrival of aphids in commercial vegetable crops. Water traps are not an easily managed tool, and sticky traps are also high maintenance, suffering lots of by-catch and wind blown soil contamination in the field. Just monitoring for aphid numbers in a crop may bear little relationship to virus incidence, as transient aphids play a major role in the transmission of non-persistent viruses. Effective monitoring would need to target these transient aphids as well as those that may settle and establish colonies in a crop. There is a need to develop a better system for monitoring aphids to assist growers in the early detection of aphids.

1. NEW MONITORING TOOLS.

Semiochemicals (pheromones) have been identified as having potential deterrent and attractant properties. The need for a practical in - field aphid monitoring tool was highlighted in the review. Semiochemicals need to be fully explored to determine if they have real application potential.

a. Review all world wide information available regarding aphid specific semiochemicals and their potential as monitoring or deterrent tools.
Select, obtain them and trial their performance in Australian conditions or, if information is insufficient, begin investigative work locally. This would involve intensive study of green peach aphid biology to identify and isolate any attractant pheromone compounds produced by this species and other significant aphid pest species e.g. *Aphis gossypii*.
b. Once isolated and tested - develop commodity (e.g. brassica cucurbits, capsicums) specific guidelines for use in population monitoring. These guidelines could be based simply on a percentage population increase above the district norm – rather than complex individual crop data.
c. Run experimental field demonstration sites to introduce the concept to growers
d. Combine this monitoring mechanism with the best soft option products to encourage further IPM adoption.

2. **ALARM PHEMONES – DISRUPTIVE BEHAVOIR.**
In conjunction with the above work identify and obtain samples of any candidate semiochemicals that are regarded as aphid alarm chemicals. Trial these products to determine if they can in fact be used to deter aphid migration into the crop.

3. **EDUCATION and EXTENSION.**
a. Educate the industry, (growers' consultants and technical representatives) regarding the current soft option aphid specific products available.
Soft option products enhance the role of other bio-control agents such as wasps, mites, spiders, birds, and other general predators and parasites. Why is it that some growers still employ old broad spectrum products for aphid control?
b. Practical demonstration sites on farms may need to be set up to promote the use of aphid specific soft option products. These sites could be used to develop aphid action thresholds in the absence of broad spectrum chemical applications and to determine if the increased cost of aphid specific soft option products is actually offset by the free pest control derived by not killing other beneficial insects. This economic value should be quantified.
c. Improve grower awareness regarding resistance management, and product rotation knowledge. This could be combined with the development of a product rotation guide to slow or prevent resistance from developing further.

d. Communicate to the industry, (growers' consultants and technical representatives) information on which pathogens are spread by aphids in which crops, and how they are spread. In some cases e.g. sow thistle aphid (*Hyperomyzus lactucae*) and necrotic yellows in lettuce the problem is best managed by managing sow thistles.

4. **SOFT OPTION PRODUCTS**.

a. Lettuce aphid – why is the industry reliant on imidocloprid which we now know can cause the death of beneficial predators. Investigate the efficacy of pymetrozine (CHESS^R) as a seedling drench.

b. Co-ordinate this with the work done in the minor use program, and access any overseas data relating to existing soft option products available in Australia. Identify any other international products that are beneficial friendly and would assist our sucking pest control. Trial and champion these products to industry and the APVMA via the minor use office - or at least in conjunction with that minor use program.

5. **ENTOMOPATHOGENS**.

a. Should play more of a role in controlled environment structures where humidity and environment are conducive to their survival. It seems though that many protective cropping structures are not really suitable for such techniques due to their relatively simple design and lack of adequate climatic control mechanisms. If there really is this design constraint it makes the industry more reliant on chemical control measures. This issue should be highlighted and followed up with protected cropping growers.

b. Investigate pairing the entomopathogens with a new method of dispersal such as pheromone lures (as outlined above), artificial feeding stations, light or sound attractants to disperse these pathogens. Overseas collaboration or investigation could play a useful role in determining future direction.

6. **ENVIRONMENT MANIPULATION**.

a. Review the outcomes of the "revegetation by design" project and set up a demonstration trial site to better quantify and promote the planting of plant species that encourage beneficial insect populations. This could be combined with natural resource type projects looking at revegetation of waterways adjacent to vegetable cropping areas – thus achieving a two fold outcome.

b. Place renewed importance on farm and crop hygiene and remove plants and weeds that are known pest species habitats, or virus sources. Education and demonstration would be necessary. Work across disciplines with this and link with HAL pathology program.

7. **FORECAST MODELS**.

It may be possible to use current knowledge of aphid life cycles and local climatic patterns to forecast probability of aphid incursion into a cropping area, using existing meteorological data. This deserves some consideration, if only on an area wide basis as a way of alerting production areas to a heightened potential for aphid activity. A review of world wide knowledge of aphid biological drivers could be fruitful to improve forecasting ability.

Previous work carried out monitoring aphid movement in Australia on clover species in the late seventies and early nineteen eighties should be reviewed. This work may provide a basis for future activities, or be instructive regarding previously observed aphid movement drivers (Garrett R.G *et al.* 1983, Guiterrez A.P. *et al.*1974 a & b). Refer to the aphid section reference list.

Five suction traps are currently being set up as part of an Australian PhD project to monitor currant lettuce aphid movement in commercial lettuce crops. These types of traps are used internationally to develop forecasts for a number of pest aphid species; however the labour to screen trap catches is high.

8. **EXTENSION EDUCATION ACTIVITIES**.

a. Cabbage aphids (*Brevicoryne brassicae*) colonise odd single plants in a crop and only spread very slowly. Correct identification and grower recognition should reduce the cost of un-necessary control measures.

b. Improve the industries (growers' consultants and technical representatives) knowledge and appreciation of the role of predators and parasites.

c. Develop some best bet population trigger points by discussion with growers, consultants and researchers that can be field tested, used and refined into commercially useable population control decision tools.

9. **RESTRICT ACCESS TO OLDER CHEMISTRY**.

Prevent minor use permits for aphid control being granted for old broad spectrum chemicals if there is a modern specific soft option product that could be "permitted" instead.

Note:

a. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.
b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

Row covers may have benefits for some very small market gardeners; however history reveals they do not appear economic on a commercial scale.

Aphid Pests in Vegetables

by: Jianhua Mo.

Description

Aphid are small soft-skinned insects that are often found in clusters on plants. They feed on plant sap through their specialised sucking mouth parts. Taxonomically they belong to the large insect group called Hemiptera which also includes scales, mealybugs, leafhoppers, psyllids, and whiteflies. They can be distinguished from the other Hemipteran insects by the presence of paired tube-like structure on the back of the abdomen called siphunculi. Aphids possess complex life cycles. Adult females can be winged (alate) or wingless (apterous). Females mostly produce live young without mating (parthenogenesis) but at some stage of the life cycle they mate with males and lay eggs.

Economic significance and threshold

Aphid damages plants directly by reducing plant vigour and stunt plant growth and indirectly by encouraging sooty mould, contaminating plant produce, and transmitting plant diseases. The latter is of particular concern as outbreaks of plant diseases can wipe out entire crops. Most aphid species are capable of transmitting plant viruses. Green peach aphid alone is known to be capable of transmitting over a dozen plant diseases including lettuce mosaic virus (Xia *et al.* 1997), zucchini yellow mosaic virus (ZYMV) (Katis *et al.* 2006), cauliflower mosaic virus (CaMV) (Namba & Sylvester 1981), turnip mosaic virus (TMV) (Fujisawa & Lizuka 1985), potato virus Y (PVY)(Gibson *et al.* 1988), carrot virus Y (CarVY) (Jones *et al.* 2006), and potato leafroll polerovirus (PLRV) (Brisson 1983).

Economic thresholds have been reported for some cereal aphids (Ba-Angood *et al.* 1980, Li *et al.* 1995, Sekha *et al* 2003). However there have been no such investigations for aphids in vegetable crops worldwide. Management decisions to control aphid infestations in vegetable crops appear to be based mainly on nominal or empirically thresholds or action thresholds. Generally less tolerance is placed on aphid damage on quality than on yield (Walgenbach 1997, Nieto *et al.* 2006). Zero tolerance of aphid infestation was suggested for head contamination in broccoli (Nieto *et al.* 2006) and cabbage (Chen *et al.* 2000). On the other hand, Trumble *et al.* (1982) observed that broccoli was able to tolerate > 100 aphid/plant without suffering significant impact on yield. As high as 3000 aphids/plant was considered tolerable for pre-cupping stage of cabbage (Chet *et al.* 2000). A lot of the action thresholds used in vegetables were proportion-based. Examples include 37% aphid infested leaflets for processing tomato (Whittenborn & Olkowski 2000), 25-50% infested leaves for fresh-market tomato (Walgenbach 1997), 30% of plants with aphid presence on the oldest trifoliate for strawberry (Trumble *et al.* 1983). Hildenhagen & Hommes (1997) used both proportion-based and density-based threshold to determining the need for controlling cabbage aphid in cabbage.

Pest status in Australia

Many aphid species are recognized as pests of vegetables in Australia including green peach aphid (*Myzus persicae*), cabbage aphid (*Brevicoryne brassicae*), potato aphid

(*Macrosiphum euphorbiae*), melon aphid (*Aphis gossypii*), carrot aphid (*Cavariella aegopodii*), cowpea aphid (*Aphis craccivora*), bean root aphid (*Smynthurodes betae*) (Hely *et al.* 1982), sowthistle aphid (*Hyperomyzus lactucae*) (McDougall *et al.* 2002), and recently currant lettuce aphid (*Nasonovia ribisnigri*) (McDougall & Creek, 2006).

Green peach aphid is highly polyphagous attacking almost all major vegetable crops. In a recent survey of pest status of insects and diseases of 10 vegetable crops in Australia including bean, beetroot, capsicum, carrots, celery, Chinese cabbage, cucumber, pumpkin, sweet potato and zucchini, green peach aphid was identified as major/regular pests in all except beetroot and carrots (McDougall 2007). Cabbage aphid is major pest of Brassicas including cabbage, broccoli, cauliflower, and Brussels sprouts worldwide and was identified as major/regular pest of Chinese cabbage in the survey. Other aphid species identified as major/regular pests in the survey include cowpea aphid in capsicum, celery, pumpkin, and zucchini, melon aphid in cucumber, pumpkin, sweet corn and zucchini, carrot aphid in carrot and celery, and potato aphid in capsicum. Geographically, green peach aphid was identified as major/regular pest in all vegetable growing centres in Australia whereas the pest status of other aphid species were relatively more restricted (McDougall 2007). Green peach aphid was identified as the major aphid vector of common diseases in Brassica, carrot, Allium crops, lettuce, tomato and potato in Australia (McDougall 2007).

Monitoring

Winged aphids are mainly monitored with yellow water pan traps and suction traps. Yellow water pan traps have been used in the monitoring of green peach aphid, cabbage aphid and mustard aphid (*Lipaphis erysimi*) in broccoli (Trumble *et al.* 1982), and various aphid species in potato (Whalon *et al.* 1978, Muller 1987, Seyedoleslaami *et al.* 1995, Tahtacioglu & Ozbek 1997, Lakhanpal & Desh 2002). Yellow is the most used colour for water pan traps. Water pan traps are cumbersome to operate in the field. A cheap alternative is the commercially available yellow sticky cards.

Networks of tower suction traps (Johnson & Taylor 1955) have been used in Europe to monitor airborne aphid populations since 1982 (Robert 1987, Harrington *et al.* 2004). Recently these traps were used in detecting and tracking the movement of the newly arrived currant lettuce aphid in New Zealand (Stufkens *et al.* 2000, Stufkens & Teulon 2003). Suction traps have proven to be an essential tool in aphid vector monitoring in Europe (Robert 1987, Pickup & Brewer 1994, Strazynski & Ruszkowska 2004). However, the high cost incurred in building and maintaining tower sucking traps have limited their use to researches or nation-wide or international monitoring networks.

Trap catches from any traps may or may not correlate well with aphid density in plants. Sometimes traps of more than one type have to be used to obtain satisfactory correlation (Avinent *et al.* 1993). In other cases, trap catches never give a good indication of aphid density suggesting non-uniform airborne aphid populations (Trumble *et al.* 1982). The best use of aphid traps appears to be in detecting the onset of aphid colonisations in crops and to some extend in the monitoring of the seasonal patterns of aphid populations. This pattern varies depending on, the aphid species, crop type, growth stage, geographic location, and local weather conditions making local knowledge and data invaluable.

Monitoring of apterous (wingless) aphids relies on plant sampling. Berlandier (1997) investigated the seasonal distribution of aphids in potato in south western Australia and noted that leaf sampling often detected green peach aphid before sticky or water traps . Berlandier (1997) also suggested that potato crops grown on the southern coast will be least vulnerable to infection by aphid-borne viruses due to the prevailing south westerly winds (sea breeze). Accurate counting of all aphids in whole plants is difficult due to the relatively small sizes of aphids and often large aphid clusters. The solution is partial plant sampling. In partial plant sampling, plant parts which give best indication of aphid density in the plant are checked. Whitaker *et al.* (2006) used the number of aphids on the most infested leaf to estimate the density of apple aphid (*Aphis pomi*) in apple. Wright *et al.* (1990) estimated the density of hop aphid (*Phorodon humuli*) in hop with leaf samples at 2-m height. Sometimes different plant parts may have to be sampled for plants of different growth stages to maintain acceptable accuracy in estimating aphid density (Manjunatha *et al.* 2005). For research purposes, the extraction methods of Wright & Cone (1988) using Berlese-Tullgren funnel may also be used.

Binomial and sequential sampling plans are used in the estimation of aphid density and in decision making of aphid management (deciding wether or not the infestation levels has exceeded the action threshold). Fixed-sample-size binomial sampling plans have been developed for green peach aphid in lettuce (Fujiie 1972), sugarbeet (Tamaki & Weiss 1979), and potato (Kabaluk *et al.* 2006), potato aphid in tomato (Wittenborn & Olkowski 2000, Hummel *et al.* 2004), and melon thrips in potato (Cho *et al.* 2000). Sequential binomial sampling plans have been developed for green peach aphid and cabbage aphid in Brussels sprouts (Wilson *et al.* 1983). Sequential enumerative sampling plans have been developed for green peach aphid in potato (Hollingsworth & Gatsonis 1990), pea aphid in peas (Badenhausser 1989), and potato aphid in tomato (Walker *et al.* 1984).

Resistant varieties

Aphid resistant crop varieties have been reported for all major crops and are an important component of aphid IPM. Lettuce varieties carrying the currant lettuce aphid resistance gene Nr caused 100% mortality in currant lettuce aphid (Liu *et al.* 2006). Two butterhead lettuce varieties in Netherlands also resulted in zero survival of currant lettuce aphid (Ester 1998). Lettuce aphid resistant lettuce varieties are commercially grown to a limited extent in Australia. Smaller head size and short growing windows that suit these varieties in Australia's climatic conditions have to date limited commercial acceptance, as chemical treatment (imidacloprid) of current commercial varieties is at this stage still effective. Recently lettuce currant aphid has been found in previously resistant lettuce varieties in Europe (pers.com. S M^{c} Dougal). Similarly, tomato lines carrying the Meu-1 gene caused 100% mortality in potato aphid (Kaloshian *et al.* 1997). However, perfect resistance is rare rather than the norm. Singh & Ellis (1993) reviewed cabbage aphid resistance in Cruciferae and found 93 brassica genotypes with moderate to high levels of resistance. Lal (1991) screened over 50 cabbage varieties for resistance against cabbage aphid in India and detected only moderate resistance in some varieties. Aphid establishment can also be reduced by the use of transgenic crop lines (Ashouri 2004). Development and application of resistant varieties in aphid IPM are complicated by several factors. Some varieties are resistant to one aphid species but not to the other aphid species of the same crop (Karl & Eisbein 1987, Reinink & Dieleman 1989). Selection for resistance against aphids may make the plants more susceptible to infestation by non-aphid pests. Eigenbrode *et al.* (2000) observed that the cabbage aphid resistant varieties of oilseed Brassica with reduced waxbloom attracted higher populations of flea beetle (*Phyllotreta cruciferae*). Resistance varieties or crop lines may also have undesirable effects on beneficial insects (Eigenbrode *et al.* 2000, Ashouri 2004). Finally there is the issue of consumer acceptance. Resistance alone can not solve the aphid problem. Other management methods (eg. insecticides, natural enemies, etc) have to be used to maintain aphid population level below action thresholds (Tatchell 2000).

Cultural practices

Cultural practices can reduce aphid infestations and delay or prevent the need for pesticide use. Ploughing in or spraying off crop remnants immediately after harvest, removing alternate hosts, including mustards and related weeds around field borders, and the use of pest free seedlings are some of the most important cultural practices for aphid management (UC IPM Online – Cole crops/cabbage aphid). In addition to reducing source aphid populations, these practices also help with insecticide resistance management (Wilson *et al.* 2001).

Intercropping with non-brassica crops is a commonly used cultural practice to control cabbage aphid in organic Brassica crops. The non-brassica companion crops are planted either as separate rows or as a cover crop (living mulches) within the brassica crop, the latter method being more widely used. Cover crops reported to have reduced cabbage aphid infestation in Brassica crops include various clover species (Wiech & Wnuk 1991, Wiech 1993, 1996, Lehmhus *et al.* 1999), dill (*Anethum graveolens*) (Kenny & Chapman 1988), malting barley (*Hordeum vulgare*) (Bukovinszky *et al.* 2004), ryegrass (*Lolium perenne cv. Surprise*) (Vidal 1997) and French beans (*Phaseolus vulgaris*) (Tukahirwa & Coaker 1982). Percentage reduction of cabbage aphid population in intercropped Brassica crops as compared with Brassica monoculture was as high as over 60% (Tukahirwa & Coaker 1982). Intercropping with ryegrass as a cover crop also reduced infestation of potato aphid and green peach aphid in potato (McKinlay 1985). One likely mechanism for the reduced aphid populations is that cover crops decreased early-season light reflectance patterns at certain spectral wavebands and this makes them less attractive to incoming aphids (Costello & Altieri 1994), resulting in a lower rate of colonization by winged aphids (Lehmhus *et al.* 1999). Increased abundance of natural enemies in the intercropped area may have also played a role (Altieri *et al.* 1985). In fact, just the provision of flowering plants, which provide food for natural enemies, has been shown to reduce cabbage aphid abundance (Kienegger *et al.* 2003). The benefit of a cover crop may be overshadowed by yield reduction caused by competition between the commercial crop and the cover crop (Andow *et al.* 1986).

Various mulches have been tested for aphid control. Basky (1984) found that transparent and blue plastic foils reduced virus inoculum in cucumber by 70 and 77% respectively by reducing abundance of the aphid vectors (cabbage aphid, green peach aphid, melon aphid and pea aphid). Aluminium foil covering of whole cabbage plots effectively repelled green peach aphid and cabbage aphid (Sasaki *et al.* 1988).

Mulching with rice straw and the use of a resistant variety effectively protected the plants from attack by cabbage aphid in cabbage (Lara *et al.* 1982). Two sprayed-on mulches, micronized mica dust and hydromulches (wood fibres plus adhesive), provided good control of cabbage aphid in cabbage (Bunescu 2000) and broccoli (Liburd *et al.* 1998), respectively.

Johnstone *et al.* (1982) showed that aphid borne virus infection in sugar beet increased as plant density decreased and as plant arrangement altered from rectangular to more square patterns, indicating the possibility of reducing virus infection by manipulation of plant density and arrangement.

Semiochemicals

A range of semiochemicals have been reported as having repellent effects against various aphid species. Fourteen essential oils including ginger oil and white pepper oil showed repellent effects against green peach aphid and melon aphid, while rosemary oil showed repellent effects against melon aphid (Hori 1999). Dispensers loaded with rosemary oil reduced aphid numbers by over 30% in tobacco fields (Hori 1999). Essential oil of *Laurus nobilis* showed a maximum repellence of 65% against cabbage aphid (Padin *et al.* 2002). In a separate study, Ricci *et al.* (2002) noted a maximum repellence of 72-90% by laurel and lemon grass (*Cymbopogon citratus*) essential oils against cabbage aphid. Methanol extracts of *Eupatorium adenophorum*, *Melia azedarach*, and *Lantana camara* reduced the settlement of cabbage aphid by over 50% (Sood *et al.* 2000). Tansy (*Tanacetum vulgare*) volatiles repelled cabbage aphid but 3-butyl isothiocyanate was attractive to the aphid (Nottingham *et al.* 1991). There are yet no practically applications of semiochemicals in aphid management for reasons unknown. However potentially they can be used to reduce initial establishment of aphids (Tatchell 2000). The push-and-pull system which moves the pests away from infestation sites through the paired use of attractants and repellents (Tol *et al.* 2007) appears to be an ideal model of applying the semiochemicals in aphid IPM. One potential attractant to use in the push-and-pull system for cabbage aphid could be glucosinolates as a study by Yusuf & Collins (1998) suggested that cabbage aphid was attracted to leaves with highest synthesis of the chemical.

Biological control

A huge number beneficial organisms attack aphids including predators, parasitoids, and pathogens. Common aphid predators are ladybirds (Coccinellidae), hoverflies (Syrphidae), lacewings (Chrysopidae & Hemerobiidae), Cecidomyiids (Cecidomyiidae), damsel bugs (*Nabis* spp.), and spiders. These are general predators and will feed on any aphid species and other small insects. Although rare, large congregations of predators can wipe out local aphid populations, as was observed for the ladybird *Hippodamia variegata* in a lettuce trial in NSW in 2002 (Andrew Creek, pers. comm..). Among parasitic wasps, *Diaeretiella rapae* stood out as the most studied parasitic wasp species of aphids. It attacks a range of aphid species including cabbage aphid, and green peach aphid (Pike *et al.* 1999), although cabbage aphid is a much more suitable host (Wilson & Lambdin 1987). In laboratory, it also attacks many other aphid species. Hyperparasitism is a key factor affecting *D. rapae* performance. In a study in cauliflower in Switzerland, the hyperparasitoid *Alloxysta sp.* effectively wiped out local *D. rapae* populations (Freuler *et al.* 2001). When free from hyperparasitism, field parasitism by *D. rapae* can at times reach high enough level to free crop produce from cabbage aphids (Freuler *et al.* 2001). Other important parasitoids of aphids in vegetables in Australia are *Aphidius spp.* and *Lysiphlebus spp.*, which attack melon aphid and green peach aphid (Wilson *et al.* 2001). Four fungal pathogens have shown some potential for aphid control, *Verticillium lecanii* (Askary *et al.* 1998, Fournier & Brodeur 1999, Palande & Pokharkar 2005, Zhang *et al.* 2006), *Pandora (= Erynia) neoaphidis* (Sivcev 1991, Shah *et al.* 2000, Shah *et al.* 2004), *Beauveria bassiana* (Zhang *et al.* 2001b), and *Metarhizium anisopliae* (Tatchell 2000). Performance of the pathogens were influenced by temperature (Zhang *et al.* 2001a, Shah *et al.* 2002). High humidity is essential for pathogen survival (Khalil *et al.* 1985).

Natural populations of beneficial organisms of aphids are usually not high enough to keep aphid damage to below economic thresholds, especially when the focus is on disease transmission by aphids. A number of practices are used to enhance the performance of natural enemies including avoiding the use of harsh chemicals, provision of alternative aphid hosts, artificial releases of natural enemies, and, in the case of pathogens, directly spraying spore solutions to the plants. Sprays host plants with an aqueous suspension of spores of a strain of the entomogenous fungus *Verticillium lecanii* significantly reduced populations of the pea aphid and the rose grass aphid (*Macrosiphum rosae*) under laboratory conditions (Harper & Huang 1987). Intercropping can increase the abundance of aphid predators (Lehmhus *et al.* 1997). Provision of alternative aphid hosts through early planting of crops or planting of non-crop aphid hosts help build up parasitoid populations for controlling the target aphid species (Perring *et al.* 1988, Freuler *et al.* 2001, 2003). Artificial releases of biological control agents can be used when populations of natural enemies are low. The following biological control agents of aphids are commercially available in Australia: green lacewings (*Mallada signata*), brown lacewings (*Micromus tasmaniae*), ladybird *Hippodamia variegata*, Damsel bugs (*Nabis kinsbergii*), and parasitoids *Aphidius colemani* (for green peach aphid), *A. rosae* (for rose aphid) (Australian Biological Control Association). No pathogens have been registered for aphid control in Australia.

Insecticides

Plant-derived chemicals that have shown some efficacy against aphids include neem products (azadirachtin) (Iannacone-Oliver & Murrugarra-Bringas 2002, Binage *et al.* 2004, Pavela *et al.* 2004, Duchovskiene 2005), rotenone (Singh *et al.* 1988, Zeng *et al.* 2002), pyrethrin (Merz 1987, Singh *et al.* 1988, Giannetti & Baldi 1995), nicotin sulphate (Singh *et al.* 1988), essential oils of *Nepeta cataria* and *Lavandula augustifola* (Pavela 2006), and extracts from toxic solanaceae plants *Solanum fastigiatum var. fastigiatum and var. acicularium* (Lovatto *et al.* 2004). While they may not be as efficacious as synthetic insecticides, botanic insecticides may be needed for aphid control in organic crops. It should be noted however that plant-derived chemicals may also impact negatively on beneficials (Johnson & Krugner 2004, Peveling & Ely 2006).

Synthetic insecticides remain an important component in aphid management in conventional crops. Among them, pirimicarb, pymetrozine and various neonicotinyl insecticides (imidacloprid, thiamethoxam, thiacloprid, acetamiprid, etc) are some of the more widely used for aphid control. Compared with other synthetic insecticides, pirimicarb and pymetrozine are generally more selective (Rihim *et al.* 1986, Senn *et al.* 1994, Gusmao *et al.* 2000, Bacci *et al.* 2001) and thus more IPM compatible.

Neonicotinoids are less selective than pirimicarb or pymetrozine (Mizell & Sconyers 1992, Maienfisch *et al.* 2001). However, because of their excellent systemic properties and their different mode of action from old synthetic insecticides, they are widely used in controlling sap-sucking insects including aphids. Imidacloprid and thiamethoxam are used more often in vegetables than other neonicotinoids. Imidacloprid can be used as foliar application (Sekhar & Singh 2001, Narkiewicz-Jodko *et al.* 2003) or soil/seed application (Dewar & Read 1990, Ester & Brantjes 1999, Ester *et al.* 2003) whereas thiamethozam is mainly used in the latter form (Maienfisch *et al.* 2001, Schroeder & Dumbleton 2001). Soil/seed application of neonicotinoids generally have less impact on beneficial organisms than foliar applications as direct contact toxicity is avoided (Mizell & Sconyers 1992). Soil/seed application is also environmentally safer than folia application (Dewar & Read 1990). However, applying neonicotinoids this way does not completely eliminate negative impact problem. A study in lettuce showed that imidacloprid at 11 ml ai per 1000 seedlings and thiamethoxam at 0.5 g ai per 1000 seedlings were highly toxic to brown lacewings that consumed aphids from the seedlings for up to 4 weeks after application (Cole & Horne 2006). In addition to toxicity-associated impacts, all insecticides, regardless how selective they are, impact on beneficial organisms by depriving them of their food (pests) (Alexandrescu & Hondru 1981).

Insecticide resistance is a serious problem in the management of aphids. Studies in cotton in Queensland showed that melon aphid and green peach aphid were widely resistant to dimethoate/omethoate, profenofos and pirimicarb and that no organophophates (OPs) controlled this green peach aphid (Wilson *et al.* 2001). Of particular significance was the strong cross-resistance between OPs and carbamates (pirimicarb), e.g. aphid populations resistant to OPs were also likely to be resistant to pirimicarb. This study also detected low level of resistance of melon aphid to endosulfan and pyrethroids but no resistance to imidacloprid. Low levels of resistance to endosulfan, cypermethrin, deltamethrin, methamidophos, profenofos and chlorpyrifos in field populations of cabbage aphid have also been reported overseas (Munir & Muhammad 2005). Currant lettuce aphid populations in UK showed low-level resistance to pirimicarb and higher resistance to pyrethroids, namely cypermethrin, deltamethrin, and lambda–cyhalothrin (Barber *et al.* 2002).

Various insecticide resistance mechanisms have been reported, including preventing insecticides from reaching their targets and changing the targets so they are less sensitive (Anon. 2000). Insecticide resistance levels vary widely between regions and years (Wilson *et al.* 2001), indicating the importance of active resistance monitoring. The key to managing insecticide resistance is to minimise insecticide applications and spray only when pests reach economic thresholds (Anon. 2000, Wilson *et al.* 2001). Another commonly used insecticide management strategy is rotation of insecticide groups but bear in mind that certain insecticide groups may have cross-resistance (Wilson *et al.* 2001, Foster *et al.* 2002) and have to be considered as a single group (Wilson *et al.* 2001).

Petroleum spray oils (PSOs) (e.g. Canopy, Biopest) have been used to control mirids and aphids either as stand alone applications, or in combination with reduced rates of synthetic insecticide the aim being to minimise the impact on natural enemies (R. Mensah, NSW DPI pers. comm., Najar *et al.* 2006)).

IPM

There are no silver bullets for managing aphids; instead, a number of integrated control tactics are needed. Tatchell (2000) proposed a two-step strategy to integrate various strategies for controlling aphids in lettuce:
(1) preventing aphid establishment either by using semiochemicals to modify aphid host-finding behaviour to reduce crop colonisation, or by using resistant varieties.

(2) should aphids colonise crops, they can be killed by soft aphid selective insecticides, or in the case of *P. bursarius* by the use of the fungus *Metarhizium anisopliae* incorporated in modules (transplant pots) at planting.
Collier (1999) also stressed the importance of non-insecticidal methods, which included cultivars of lettuce resistant to either foliage or root aphids, entomopathogenic fungi to control *P. bursarius*, semiochemicals to manipulate insect behaviour and undersowing crops with clover, in the management of aphids in lettuce. In addition, he highlighted the need to use weather data (temperature, wind, cloud etc.) to forecast aphid attacks in conjunction with careful crop sampling and pest tolerance levels, to make spray decisions.
Although focused on aphids in lettuce, the recommendations from the two studies can be readily applied to other aphid-vegetable systems. In summary, aphid control in vegetables should start with prevention or reduction of colonisers through the use of semiochemicals, resistant varieties, or careful selection of planting time, followed by cultural practices that conserve or enhance natural enemies, regular monitoring or forecasting models to determine/estimate population levels relative to action thresholds, and finally use IPM compatible insecticides or commercially available biocontrol agents to control the target aphids species when the thresholds are exceeded. Selection and timing of insecticide applications should conform to insecticide resistance management strategies.

Based on this review, future investigations into the management of aphid pests and associated diseases of vegetables in Australia should centre around:

- Establishment of efficient national monitoring and forecasting systems using combined aerial sampling with tower mounted suction traps, ground sampling, and population models to predict the movement of aphids and biosecurity threats such as lettuce aphid and the newly arrived Mediterranean mint aphid (*Eucarazzi elegans*).

- Evaluation of intercropping and use of semiochemicals in reducing or delaying aphid infestation in vegetables. Intercropping appears to be particularly effective for managing aphids in Brassica crops. Nitrogen-fixing legume plants such as various species of clover are promising candidates. Semiochemicals worth investigating are some of the readily available essential oils.

- Investigation of the potential of pathogens in aphid management. Promising pathogens include *Verticillium lecanii* , *Pandora neoaphidis*, *Beauveria bassiana*, and *Metarhizium anisopliae*

- Development of IPM strategies based on effective monitoring and incorporating the use of resistance varieties and cultural, biological and chemicals strategies to manage aphid vectors in major vegetable crops

    - For example: The application of kaolin clay film to plants, in conjunction with a waterproofing treatment has been demonstrated to reduce the abundance of a range of arthropod pests (pear psylla, aphids, leafhoppers, two-spotted mites), and assist in the control of a range of foliar bacterial and fungal diseases (Glenn *et al.* 1999). The films have previously been shown to reduce the incidence of virus by reducing aphid infestation, not only because of the interference of the film with the aphid, but also by changing the reflectance of the plant material to which it is applied. A commercial particle film material, called Surround ® is used in the Pacific Northwest pear industry for the early season control of pear psylla and in the Washington state apple industry to reduce sunburn damage. The pears and apples are sold in the fresh food market after washing in a standard grading line. An effective fruit washing line uses a dump tank, often with surfactants added a minimum of a 10 m bed of brushes, and overhead high pressure sprayers. Waxing the fruit obscures trace amounts of kaolin residue that did not wash off. Residue removal from the stem and calyx end of fruit is difficult but brush and sprayer criteria as described above are effective (DM Glenn evbc.org/.../biorantional_biological_pest_control/Use%20of%20Particle%20**Film**%20Technology%20Surround.pdf).

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Chapter 2

Minor "Bug" Species

FUTURE RESEARCH DIRECTION – MINOR "BUG" SPECIES.

Rutherglen bug has been identified as the main cause of economic damage and contamination across a wide range of vegetables and herbs, with green vegetable bug and leaf hoppers also identified as issues but generally less problematic. Bugs are an increasing issue as specific soft option products are used to control other pest species. No known "bug" specifics are currently available – though possibly spirotetramat (Movento^{R}) may have some impact.
The vegetable industry needs improved methods of detecting the presence of, and flagging the arrival of influx populations. There is a need for improved data on action thresholds, tolerance levels and impacts across a range of crops as bugs can impact fruit quality and can be a major contaminant issue.

1. **MONITORING.**

1. Develop effective bug monitoring tools to help growers better determine when bug populations appear and need to be controlled. Rutherglen bug should be the basis for this work.
a. Both semiochemical or pheromone attractants and deterrents should be explored.
b. Improved knowledge of the insects' biology and weather conditions that lead to population explosion and migration could assist in forecasting influx migration events.
c. Determine if forecast models based on weather data could be used to predict Rutherglen bug migrations – refer to the aphid research needs

2. Determine by further specific industry consultation and trial work, at what population level (e.g. X insects per 20 plants) Rutherglen and green vegetable bugs cause economic damage. This work should target a crop where these bugs are already identified as causing production difficulties. This bug / crop interaction may vary between states and cropping systems. Rutherglen bug is identified as a serious but sporadic problem in lettuce, Chinese cabbage, and many herb and bagged salad mix lines (e.g. high density mechanically harvested (mown) leafy vegetables as well as Asian vegetables – bok choy etc). Green vegetable bug could be studied in a crop such as zucchini.
a. Develop from these studies Australia wide grower action guidelines that can be reviewed and updated over time, to develop district action guidelines.

2**. SOFT OPTION PRODUCTS.**
a. Review worldwide data for availability of soft option specific products to control Rutherglen bug, green vegetable bug and mirid species.
b. Ascertain the likelihood of Australia accessing these products and discuss this with APVMA and the minor use programme co-ordinator.
c. Identify current best control products that have minimal impact on beneficial insects via information generated by the current HAL funded soft option screening project, and by liaison with the minor use office and minor use project co-ordinator.

d. Conduct screening trials of identified products to confirm efficacy on Rutherglen bug, observe their effect on beneficial insects and, obtain residue data under Australian conditions.This should include exploring and promoting pathogenic fungi or bacteria if they are determined to be economically viable in the future.

3. **IMPROVED PEST KNOWLEDGE**.

a. Study Rutherglen bug to increase our knowledge – there have been reports that Rutherglen bug will predate on *Helicoverpa* sp. eggs. We need to increase our knowledge of this emerging pest.

b. Develop a resistance management system for this and other bug pests.

4. **EMERGING TECHNOLOGY.**

a. Investigate via laboratory trials and improved knowledge of the pests' biology if there is any scope for new alternate control or dispersal methods (based on improved pest understanding) such as – radio waves, ultrasonics etc that would be economical and worth trying. Could these or other non-chemical, non- lethal techniques be used to move insects out of the harvest zone of crops destined for field bagging just prior to harvesting? This is essential for multiple harvest crops and rapid growth crops where withholding periods interfere with optimum harvest periods and disrupt or kill beneficial insects.

5. **EDUCATION.**

a. Educate the consumer and the marketing sector to accept the odd live insects in packaged product as an indicator of a well managed, human friendly, environmentally responsible production system.

b. Inform consumers and the market chain about the link between their low levels of tolerance (or nil tolerance) for blemished produce, and insect contaminants, and the pressure this puts on growers to apply more insecticide

Note:

a. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.

b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

Minor "Bug" Species

(Rutherglen bug, green vegetable bug, leafhoppers / jassids and green mirid)

by Melina Miles.

Description

The Hemipteran species covered in this review are green vegetable bug (GVB) (Pentatomidae) (*Nezara viridula*), green mirid (Miridae) (*Creontiades dilutus*) and Rutherglen bug (Lygaeidae) (*Nysius vinitor*). The leafhoppers (Cicadellidae) include a number of species, with two species most commonly recorded in vegetables, vegetable leafhopper (*Austroasca viridigrisea*) and cotton leafhopper (*Amrasca terraereginae*).

These species are, in general, reported as minor or infrequent pests in vegetable crops. Readily accessible literature on the production of vegetable crops (State Government web sites NSW, Vic, SA, WA, Qld,), do not address, or just briefly mention, these species. The most comprehensive recent review of insect pest status in vegetable crops (McDougall 2007) confirms this assessment with the exceptions being;

- the major and regular pest status of leafhoppers in green beans in Queensland ; the major status attributed to Rutherglen bug in Chinese cabbage in South Australia, Sydney basin ,the Lockyer Valley in Queensland as well as reports of its major but infrequent occurrence in the Stanthorpe region.
- The major pest status of GVB in capsicum in Bowen, Queensland, and of zucchini in the Lockyer and Fassifern valleys as well as the Stanthorpe area of Queensland.
- The major pest status of GVB in cucumber in Bowen, Queensland.
- In Carnarvon, Western Australia, Rutherglen bug is identified as a major pest of pumpkin
- Green mirid identified as a regular pest of zucchini in the Lockyer and Fassifern Valleys of Queensland

The review of McDougall (2007) covered 11 vegetable crops (green beans, beetroot, capsicum, carrot, celery, Chinese cabbage, cucumber, pumpkin, sweet potato and zucchini). These bug species were not recorded as pests of beetroot or sweetpotato.

This review is not exhaustive of the vegetable crops grown in Australia, and further review literature found mention of these species as pests in:

- Tasmania
  - onions – Rutherglen bug (Wardlaw, 2004)
  - brassicas – Rutherglen bug (Wardlaw, 2004)
- Victoria
  - potato - leafhopper (*Zygina zealandica*), Rutherglen bug (Henderson, 1999)
  - Eggplant – leafhoppers (Dimsey, 1994)
  - Pumpkin - leafhoppers (Dimsey, 1994)
- New South Wales
  - crucifer – Rutherglen bug (Hamilton & Toffolon, 2003)

  - lettuce – leafhoppers (Napier, 2004)
  - Asparagus – Rutherglen bug (Neeson 2004)
- Queensland
  - Capsicum – Green vegetable bug, leafhoppers, (Brown, 2005)
  - Tomatoes – Rutherglen bug (Brough *et al.* 1994)
  - Sweet corn – Green vegetable bug (DPI&F, 2006b)
  - Cucurbits (Pumpkin, zucchini, melons) – Green vegetable bug (Brough *et al.* 1994), Rutherglen bug (DPI&F, 2006),
  - Green beans – Green mirid, leafhoppers, green vegetable bug (Brough *et al.* 1994, Duff 2006)
  - Potatoes – Green vegetable bug, vegetable leafhopper (Brough *et al.* 1994)
  - Peas - Green vegetable bug (Brough *et al.* 1994)
  - Chinese cabbage and lettuce – Rutherglen bug (D. Carey pers.comm. 2007)
- Tasmania, South Australia and New Zealand
  - Seed carrots – Rutherglen bug (Spurr *et al.* 2001)
- Western Australia
  - Sweetpotato – Rutherglen bug (Burt 2000)

Table 1.0. Vegetable crops with reported bug pests (McDougall 2007, Wardlaw 2004, Henderson 1999, Dimsey 1994, Hamilton & Toffolon 2003, Napier 2004, Brown 2005, DPI&F 2006, Duff 2006), Spurr *et al.* 2001, Neeson 2004, Brough *et al.* 1994

Crop	Bug			
	Rutherglen bug	Leafhopper	Green mirid	Green vegetable bug
Eggplant		■		
Tomato	■			■
Capsicum	■	■		■
Potato	■	■		■
Sweet potato	■			
Chilli				
Lettuce	▨	■		
cucumber				■
zucchini			■	■
Pumpkin	■	■		■
Green beans	■	■	■	■
Brassica	■			
onion	■			
Sweet corn				■
Asparagus	░			
Carrot seed	■			
Chinese cabbage	▨			
Peas				■
■	Indicates species identified as causing crop loss			

▨	Indicates species identified as product contaminant		
░	Indicates species identified as pest, but impact not specified		

Review of the pest status of the key bug pests in relation to their impact, and the relevant ecology/biology that supports it.

Rutherglen bug (*Nysius vinitor*)

Rutherglen bug (RGB) is identified as having the capacity to cause direct crop damage to a range of crops (Table 1.0). Its pest status is generally a function of the coincidence of large migrating populations and crops that are susceptible to feeding damage, most commonly to cotyledons or growing points (Henderson 1999, Brown 2005, Hamilton & Toffolon 2003). The abundance of Rutherglen bug in crops is typically determined by the abundance of local weeds, and influxes of large migratory populations in late spring – summer (McDonald & Farrow 1998, McDonald & Smith 1988). As a result of alternative host use being a major factor in pest occurrence, the management of Rutherglen bug in vegetable crops is largely based on controlling local weeds to prevent its movement from weed hosts to crops as the weeds dry off in summer (Henderson 1999, Hamilton & Toffolon 2003, Wardlaw 2004). There is also a suggestion that the migration of *Nysius* sp. may be long distance, with populations infesting crops in NSW and south during spring and early summer originating in the sub-tropics (McDonald & Farrow 1988).

Although reference to Rutherglen bug as a crop contaminant could only be found for lettuce (Bechaz 2006), it seems likely that the minor but regular pest status attributed to this pest across a wide range of vegetable crops (McDougall 2007) is as a result of the influx of this species in large numbers over a period of weeks into crops with low, or zero, tolerance for insects in the saleable produce. The sudden infestation by large numbers of immigrant bugs can cause crop damage simply by weight of numbers. Grower awareness of the damage potential of Rutherglen bug, combined with grower uncertainty about the amount of damage that could be caused, by these insect influxes contribute to an elevated pest status.

Drought conditions in recent seasons have seen an increase in the importance of this pest in leafy vegetables in Queensland. High numbers of adults migrate to green irrigated crops, from surrounding drought affected landscapes (D. Carey pers. comm. Nov 2007).
The potential for mass movement of the species, whether it be long-distance or locally from weed hosts as they dry off in early summer, is important in the management of this species.

Green vegetable bug (*Nezara viridula*)

Green vegetable bug adults and nymphs feed on developing fruit, seeds and pods resulting in dark sunken spots on the fruit surface and damage to the developing fruit and seed. In the case of fleshy fruits like zucchini and eggplant, feeding by GVB results in young fruit browning and aborting, or being misshapen and unmarketable.

In sweet corn, GVB pierce kernels on the developing and maturing cobs allowing entry of fungal diseases. Crops are also susceptible when fruit is mature and the bugs pierce the fruit to feed on the seed (Brough *et al.* 1994, DPI&F 2006b, Brier & McLennan 2006).Green vegetable bug has a wide host range, including a large number of cultivated and wild legumes and wild crucifer hosts. Wild hosts, particularly wild crucifer species, are important in building and maintaining populations of green vegetable bug in cropping areas through spring when the adults come out of their winter diapause (Velasco & Walter 1992). In coastal Queensland areas e.g. Bundaberg, GVB build up on a succession of hosts during summer, reaching damaging numbers by autumn. Adult bugs live for up to 3 weeks in hot weather, longer over winter when they diapause. In south east Queensland, green vegetable bug is thought to have two generations per year (Velasco *et al.* 1995), whilst in northern NSW three generations are reported (Coombs & Sands 2000). Adult bugs move from weed hosts, or over wintering sites, into crops in late summer. In warmer regions (e.g. coastal central Queensland) green vegetable bug is potentially a pest of winter vegetables having bred up on local pulse crops in summer (Brough *et al.* 1994).

Leafhoppers/Jassids

A large numbers of species have been identified as leafhoppers, or jassids, in vegetable crops. The list includes *Austroasca viridigrisea* (vegetable leafhopper) and *Amrasca terraereginae* (cotton leafhopper), *Zygina zealandica*, *Austroasca alfalfae* (lucerne leafhopper), *Cicadulina bimaculata* (maize leafhopper) and *Austroagallia torrida* (spotted leafhopper) (Henderson 1999, Duff 2006). Leafhoppers cause stippling or silvering on the leaves in beans, particularly of young plants (Duff 2006), and the impact of such stippling is to reduce the effective photosynthetic area available to the plant. The impact of this feeding tends to be low, except when the growth of seedlings is slowed by dry conditions. Seedling crops are in general, considered more susceptible to leafhopper infestation. In subtropical areas, sweet corn is susceptible to yield loss as a result of a physiological condition, called wallaby ear, caused by a toxin injected by the maize leafhopper (*C. bimaculata*) while feeding (DPI&F, 2006b). The brown leafhopper (*Orosius argentatus* (Evans)) transmits tomato big bud in tomatoes, a mycoplasma in the ‘yellows’ complex (Bowyer 1974).

It is likely that leafhoppers build up in numbers on weed hosts (e.g. Solanaceae and *Chenopodium* spp.) and move into crops in late spring-early summer, as these hosts dry off (L. Wilson *pers.comm.*) .

Green mirid (*Creontiades dilutus* (Stal))

Descriptions of the damage caused by green mirid, *C. dilutus*, in vegetable crops are limited. In McDougall’s review (2007) the pest status of this species is minor and it is recorded only as a pest in crops in the Melbourne region and in zucchini in SE Qld.

NSW DPI (Anonymous 1997) describes the green mirid as feeding on developing parts of lucerne, cotton and other crops, so reducing crop production; and indicates that green mirid is known to destroy young flower shoots on beans. Qld DPI&F (Duff 2006) indicate that green mirid cause damage to flower buds. In other crops (cotton, lucerne, soybean, mungbean, peanuts and adzuki bean) mirids damage buds, flowers and developing pods, often resulting in the abortion of these parts (Foley & Pyke 1985, Hori & Miles 1993, Brier & McLennan 2006, Knight *et al.* 2007)

In the 1997 review of green mirid taxonomy, *Creontiades* spp are recorded from a wide range of horticultural crops including stone fruits, cotton, lucerne, grapes, potato, passionfruit, beans, carrots, cucurbits, asparagus, cucumber, tomato, bean, potato and parsnips (Malipatil & Cassis 1997).

Green mirid is predominantly a warm season pest, known to diapause as adults during winter (Miles 1996). The species is thought to reproduce in inland Australia and migrate from these regions in spring on storm fronts, bringing adults into eastern cropping areas (Miles 1996). There is also evidence that in some seasons, probably those with wet winters and springs that encourage local weed growth, that the species will reproduce in large numbers in eastern cropping areas. In northern NSW, 8 weed species were identified as primary hosts of green mirids during winter and spring. The 3 species supporting the largest populations of green mirids were wild turnip (*Rapistrum rugosum*, Brassicaceae), hairy carpet weed (*Glinus lotoides*, Aizoaceae), and common joyweed (*Alternanthera nodiflora*, Amaranthaceae). Other species that supported large populations at different times of the year were lucerne (*Medicago sativa*, Fabaceae) and verbena (*Verbena supine*, Verbenaceae) (M. Khan 1999). The potential for mass movement of the species, whether it be long-distance or locally from weed hosts as they dry off in early summer, is important in relation to the management of this species.

Monitoring

For the most part, monitoring of the bug species in vegetable crops in Australia relies on visual inspection of the plant to estimate pest numbers, or an indirect estimation of numbers of adults and nymphs in the field, using techniques that dislodge the bugs from the plant e.g. beat sheeting or sweep netting. Eggs are generally not scouted for in the field.

Several of the key species (Rutherglen bug, green vegetable bug, leafhoppers) are known to breed on non-crop hosts in and around susceptible crops. Consequently, there are numerous recommendations to monitor the size of the pest population in nearby weed hosts, to manage weed hosts to minimise pest build up locally, and to monitor the condition of the alternative hosts as a means of predicting the likely movement of the pests into nearby crops (Wardlaw 2004).

The most refined monitoring strategy for these bug pests is for RGB in sunflower, where the spatial distribution of RGB is described and fixed-precision and sequential sampling plans derived (Allsopp 1988). Review of the literature for Miridae, Pentatomidae and Cicadellidae shows that pest densities are estimated directly by visual search of adults and nymphs (Nath and Dutta 1994, Brough *et al.* 1994)) or indirectly with sweep nets (Page 1996), beat sheet (Brier & McLennan 2006) beating tray (UC IPM Online 2006), and damage indices (Nagai *et al.* 1987, Lye and Story 1989, Dupont 1993, Greene and Herzog 1999).

There are several overseas examples of where devices have been developed monitor the movement of bug species, and the potential for invasion of susceptible crops. For example, Mizzel (http://ufinsect.ifas.ufl.edu/stink_bugs/stink_bugs.htm) (accessed 30/7/08) describes a Florida Stink Bug Trap used to monitor the movement of a range of stink bugs into orchards. The number of species attracted to the trap includes 19 species of pentatomids (stink bugs), seven species of coreids (leaf-footed bugs), six reduviid (assassin and ambush bugs) species – including green vegetable bug. The trap has a visually attractive base (yellow) and a collecting device at the pinnacle. Where available, the addition of synthetic pheromone has increased trap catches of particular species. The benefit of the trap is that it indicates the movement of bugs into crops, taking the guess work out of predicting when the bugs may infest crops based on the condition of surrounding weeds, crop stage, cessation of hibernation and weather. Further research is required to validate the usefulness of the trap in crops other than peaches and pecans, but it is considered to have potential in vegetables. Similarly, the evaluation of traps for stink bugs in orchards in Washington State (McGhee 1997) found that the potential of traps was in identifying when movement occurred. Trap catches were not correlated with fruit damage, so there is little potential to use trapping as an alternative to physically monitoring stink bug abundance.

There are few records of traps being deployed in Australian vegetable crops, or field crops, for monitoring bug species. The one exception is the study by Mensah (1996) on sticky traps to monitor vegetable leafhopper (*Austroasca viridegriesea*) in cotton. The study found that yellow sticky traps were more effective than sticky traps of other colours and that higher number of adults was caught by traps placed at 25-75 cm above ground than by traps placed higher. Yellow sticky traps were found to be more attractive to *Lygus lineolaris* (Hemiptera: Miridae) than white sticky traps that had been adapted to strawberries from orchards. These sticky traps, in conjunction with white pan beat method for nymphs, are considered to provide adequate early warning of pest populations in strawberries, and allow the application of economic thresholds (Wold & Hutchison 2003).

In Australia, there are practical challenges reported in relation to the use of sticky traps for pest monitoring, particularly in dusty and wet areas e.g. on lane ways and under sprinklers. However, workshop participants indicated that they persisted with the use of yellow sticky traps and used the information from the traps as a trigger for closer monitoring of crops for aphids, thrips and other bug species. Suction sampling is not widely used, but is used in lettuce as a quick sampling technique to evaluate what spectrum of species is present (S. McDougall pers.comm. 2007).

Recently, research by P. Gregg (University of New England, Cotton Catchment Communities CRC) on the pheromone of green mirid has seen testing of traps baited with synthetic pheromone. Whilst this work is still experimental, it may provide a way of detecting movement of this highly mobile species into cropping regions, or between hosts in a local area. Alternatively, the pheromone may be used in combination with a toxicant in an attract-and-kill formulation to reduce the size of the pest population, either within a crop, or on an area-wide basis (P. Gregg pers.com. 2007).

The use of pheromones for monitoring or manipulating bug populations does not have many precedents. One example is the use of pheromone to manage *Campylomma verbasci*, a pest of apples in Canada. In this case, pheromone has been tested for use in population suppression (McBrien *et al.* 1997), rather than simply monitoring the pest.

Economic significance and economic thresholds

For the bug species being reviewed, there are references to their ability to cause direct feeding damage at certain stages of crop development, but their pest status is for the most part not further quantified by estimates of damage, or economic thresholds, which would guide management decisions.

The absence of clearly defined relationships between pest density and crop loss is a significant handicap in terms of enabling growers to calculate an economic threshold for their particular situation. With the knowledge of the potential of a particular species to cause crop loss, but without any way of determining an economic control threshold, growers are left with little option other than to control these pests on sight. This approach is further complicated by the highly unpredictable nature of many of these pests, and the tendency for many of them to migrate into crops over an extended period (sometimes weeks). To allow targeted insecticide use for these pests, growers need to know (a) when their crops are susceptible to the different species, and when they are not, (b) what the relationship is between pest density and crop loss, and (c) how to calculate an economic threshold using (b) and their own estimates of crop value and costs of control.

The examples for which there is sufficient information on which to calculate an economic threshold are:

- The impact of Rutherglen bug on germination in hybrid carrot seed production, where the potential reduction in viability is quantified (Spurr *et al.* 2001).
- GVB damage to tomatoes ,green beans and sweet corn

There are additional records where management advice appears to be based on notional thresholds, based on the experience and 'best bet' of those involved in the industries. For example those quoted in Brough *et al.* (1997) for Rutherglen bug in tomatoes, green vegetable bug in cucurbits, green beans, and potatoes (Table 2.0).

For the remainder, where there are published recommendations, pest management advice is vague, for example: "use insecticides if there is a heavy infestation" [*Nysius* in carrots], and in Brassica to "apply registered insecticides if infestation is high" (Table 2.0).

Crop loss vs contamination

Contamination of produce is implied, but not expressed in the literature, but was raised as a major issue at the workshop. In particular, Rutherglen bug was identified as a regular issue as it moves in to crops in large numbers in late spring and early summer. The issue of contamination of produce by insects (pest or otherwise) is exacerbated by the trend towards more in-field bagging of crops such as lettuce. In field bagging removes the opportunity for 'trapped' insects to escape from boxes between the field and the point of sale. Pre and post harvest decontamination is clearly an issue that warrants attention.

No Australian research on quantifying pest impact or disinfestation techniques related to these species in vegetable crops was found.

Table 2.0, Recommended action thresholds for bug pests in vegetable crops in Australia.

Crop	Bug			
	Rutherglen bug	Leafhopper	Green mirid	Green vegetable bug
Asparagus				
Brassica	Apply registered insecticide if infestation is high (Wardlaw 2004)			
Capsicum				
Celery		Spray if more than 5 out of 30 plants infested (Brough *et al*. 1994)		
Chilli				
cucumber				
Cucurbits				More than 30 bugs in 30 plants examined (Brough *et al*. 1997)
Carrot seed				
Carrots	Use insecticides if there is a heavy infestation (Wardlaw 2004)			
Chinese cabbage	> 3 per plant (w/s comment)			
Eggplant				
Green beans				1 or more per m row (Brough *et al.* 1994)
Lettuce				
onion				

Peas				More than 1 bug per m row (Brough *et al.* 1994)
Potato		More than 10 adults per plant (plants < 300 mm) (Brough *et al.* 1994)		More than 3/30 terminals are wilted up to flowering and 27/30 plants after flowering (Brough *et al.* 1994)
Pumpkin				
Sweet corn		More than 10 insects per plant and wallaby ear symptoms present (Brough *et al.* 1994)		
Sweet potato				
Tomato	More than 90 bugs in 30 plants (Brough *et al.* 1997)			
zucchini				

Approaches to sucking bug management, and progress towards IPM

This section deals with developments in bug management either in Australia, or overseas, that may have some application in Australian vegetable production. For a general overview of chemical control also refer to the silverleaf whitefly section, biopesticides section of the thrips review and the biological control section below.

Chemical control (with almost no access to soft sucking pest specific products) is the mainstay of bug control in vegetable crops. The reliance on insecticides to control these pests is primarily driven by the massive impact these pests can have on fruit yield and quality in crops such as zucchini, cucumber, tomato, eggplant etc and the low tolerance of the markets for misshapen and defective produce. Reliance on mainly broad spectrum products used to control sucking pests and consequentially any beneficials present, may presumably have to-date hindered the development of action thresholds. This combined with a lack of knowledge about what the damage potential of the different species is, in each crop is also likely to contribute to the low tolerance of bugs in vegetable crops.

Strategies for chemical control in vegetables include repeat application directly to the crop, treatment of surrounding weeds, when there are large infestations/plagues, and border spraying when there are weed hosts on the margins of the crop (Hamilton & Toffolon 1987, Wardlaw 2004, McDougall 2007).

The chemical control of GVB has been complicated for some crops by the withdrawal of endosulfan by the APVMA. Endosulfan is considered by some in the industry as relatively soft on natural enemies, compared with synthetic pyrethroids and was often the product of choice for GVB control. In field crops (cotton and pulses), the search for alternatives to endosulfan for GVB and green mirid, that are compatible with the conservation of natural enemies has focused on the use of salt in combination with reduced rates of synthetic insecticides (fipronil, dimethoate) to control green vegetable bug.

The addition of 10g salt (NaCl) per litre of water combined with half the label rate of registered product has given efficacy at the same level as the full insecticide rate application without the cost or detrimental impact on natural enemy populations. The mechanism works by arresting the movement of bugs where salt is applied, leading to increased duration of feeding and a higher uptake of insecticide (Corso & Gazzoni 1998, Khan *et al.* 2002, Khan *et al.* 2004). Note this broad acre technique is based on spray volumes of one hundred litres of water per hectare and may have no place in vegetable production, where salt application, successive quick cropping, salt sensitive crops, and higher water application are all limiting factors.

The use of some other synergist in combination with lower rates of existing insecticides may have some application in vegetable crops where no true “soft option” product is available.

Recent work on the management of green mirids in cotton has included the development of semiochemicals as attractants for mirid species (R. Mensah, NSW DPI pers. comm.). The plants from which the extracts are made are commercial-in-confidence. The plant extracts have been shown to elicit an avoidance response in green mirids, and are currently under trial and refinement for use in the cotton industry. There may be potential to use semiochemicals either alone, or in mixtures with reduced rates of synthetic insecticide to reduce mirid populations without causing major disruption to natural enemy populations (R. Mensah, NSW DPI pers. comm.). These semiochemicals are being manufactured by a Sydney-based company Native Fires Pty Ltd

It may be worth further investigating the use of petroleum spray oils (PSOs) (e.g. Canopy, Biopest) to control mirids and aphids in certain crops or growth stages in the crop cycle. These or similar spray oils or surfactants may be useful either as stand alone applications, or in combination with reduced rates of synthetic insecticide to minimise the impact on natural enemies (R. Mensah, NSW DPI pers. comm., Najar *et al.* 2006)). Ideally though, the identification of new specific soft option products or alternative control techniques would be a major advancement along the road to beneficial insect conservation and best crop management.

Pheromones

A pheromone for green mirid has been identified and synthesised by P. Gregg and Alice Del Soccorro (UNE, CCC CRC). The application of this technology as an attract-and-kill formulation has been proposed. The feasibility and effectiveness of the pheromone both as an attractant for population monitoring, and as an attract-and-kill lure is currently being tested in the field (P. Gregg pers.comm. 2007).

The application of kaolin clay film to plants, in conjunction with a waterproofing treatment has been demonstrated to reduce the abundance of a range of arthropod pests (including leafhoppers), and assist in the control of a range of foliar bacterial and fungal diseases (Glenn *et al.* 1999). The films have previously been shown to reduce the incidence of virus by reducing aphid infestation, not only because of the interference of the film with the aphid, but also by changing the reflectance of the plant material to which it is applied. A clay based particle film material, called Surround ® is commercially available (DM Glenn evbc.org/.../biorantional_biological_pest_control/Use%20of%20Particle%20Film%20Technology%20Surround.pdf). Such techniques that change the pest / host relationship or make the crop less attractive to the pest could be a useful tool to add to a future multidisciplined response in some crops.

Biological control using natural enemies is one factor that contributes to an integrated pest management (IPM) program. Accurate locally derived information about the potential contribution of natural enemies to control in crop pests is important to developing in growers the confidence to factor in to their decision-making the pest mortality that may accrue due to natural enemy activity.

The green vegetable bug has been the focus of two classical biological control release programs in Australia. The first, *Trissolcus basalis* (Wollaston) (Hymenoptera: Scelionidae) is an egg parasitoid, which has subsequently found to be non-specific, also parasitising the eggs of predatory pentatomids such as *Oechalia* sp. and *Cermatulus* sp. (Loch & Walter 1999). The second key biological control introduced against green vegetable bug is the parasitic fly *Trichopoda giacomellii* (Blanchard) (Diptera: Tachinidae). *Trichopoda* was originally released in western NSW and south-eastern Queensland (1996-1999), and more recently in cotton and soybean growing regions of Queensland and northern NSW and is recorded as being established in the South Burnett, Darling Downs, Moree (NSW) and Bundaberg (Coombs & Sands 2000, Knight & Gurr 2007). Parasitism of *N. viridula* by *T. giacomellii* ranges from 20-60% in cotton in Queensland production areas (Khan & Murray 2002). Parasitism by *T. basalis* is regularly recorded, but has not been quantified. Green vegetable bug remains a regular pest in soybeans, cotton and other field crops in Queensland (H. Brier, DPI&F pers.comm.)

The relationship between natural enemy abundance and reduction in pest impact is not always direct or predictable. For growers to reliably factor in the contribution of natural enemies there needs to be adequate information on, and understanding of, the relationships between pest, natural enemy, crop, alternative hosts and environment. For example, in Washington State fruit orchards, high levels of stink bug egg parasitism by Scelionidae (*Trissolcus* and *Telenomus* species) and an Encrytidae species was recorded in weed hosts around orchards (McGhee 1997). However, high levels of parasitism did not result in reduced rates of fruit damage. Whilst the provision of weedy 'traps' may increase the rate of stink bug parasitism, reducing the population before it can move into nearby crops, it is unlikely that this tactic will result in reduced crop loss.

Another species that has demonstrated some potential via inundative release in crops is the assassin bug *Pristhesancus plagipennis*. This species will feed on green vegetable bug nymphs in the laboratory, and is proposed as potential augmentative biological control for this species (Grundy & Maelzer 2000).

The complement of biological control organisms includes diseases, in particular viruses and fungi. All the bug species are susceptible to infection with entomopathogens (*Metarhizium* and *Beauvaria*) (C. Hauxwell, DPI&F pers comm. 2007). Recent work on GVB with metarhizium has shown promise, but the speed of kill is relatively slow which is problematic in crops with a low tolerance for cosmetic damage, such as many horticultural crops. However, targeting nymphs has potential to result in faster mortality and lower levels of damage (Knight & Gurr 2007).

The distribution of entomopathogens through the crop for the control of a range of bug species, may be facilitated by the activity of other insects e.g. natural enemies, honey bees (Roy & Pell 2000, Al Mazra'awi *et al.* 2006).

No records of predation or parasitism of leafhoppers were found in the literature relating to Australian horticultural crops, or field crops. There are records of parasitism of leafhopper eggs in overseas cropping systems by *Anagrus* spp. in the family Mymaridae (Hymenoptera) (Prischmann *et al.* 2007). The potential impact of the parasitoids is reported to be enhanced by the presence of floral resources (flowering cover crops) in vineyards (Nicholls *et al.* 2000, English-Loeb *et al.* 2003).

Wolf spiders and carabids are recorded as impacting on leafhopper populations in maize in the USA (Lang *et al*. 1999).

Two entomopahogenic fungi (*Metarhizium anisopliae* strain Ma43, and *Paecilomyces fumosoroseus* strain Pfr12) (Deuteromycotina: Hyphomycetes) effective against the leafhopper *Empoasca decipiens* were shown to have no impact on adult emergence or longevity of the egg parasitoid *Anagrus atomus* (Hymenoptera: Myrmaridae). However, the level of egg parasitism was decreased where the entomopathogens were used. The reason for the decline is not clear, but is suggested to be either avoidance of treated plants, or a host density impact (Tounou *et al.* 2003).

There are few observations, published or unpublished, of biological control of green mirid in the field. Spiders (lynx, jumping, yellow night stalker) have been observed to feed on mirid adults and nymphs, as have damsel bugs (Hemiptera: Nabidae) (Whitehouse 2005). Parasitism of adults has not been recorded in Australia, nor are there any published records of egg parasitism. However, there is currently research underway to determine the impact of hymenoptera egg parasitoids on eggs in the families Myrmaridae and Scelionidae (N. Schellhorn pers. comm.). There are records of a native assassin bug species, discussed as a potential biological control agent, (*Pristhesancus plagipennis* predating on green mirid nymphs (Grundy and Maelzer 2003). A mite species, *Nabisieus melinae* (Acarina: Mesostigmata) has been identified from *Creontiades* species, and is thought to be parasitic (Halliday 1994). However, there is no empirical data on the impact of the mites on survival or fitness of the hosts.

Rutherglen bug adults are parasitised by *Alophora lepidofera* (Malloch), a native tachinid fly (Loudon & Attia 1981). However, the records of this parasite are limited, and indicate low levels of parasitism in sunflower, and a higher proportion of females parasitised than males (Forrester 1979). This same species is recorded as parasitising the cottonseed bug *Oxycarenus luctuosus* Monrouzier & Signoret, related to coon bug *O. arctatus* (Loudon & Attia 1981).

The egg parasite, *Telenomus* sp. was implicated in the parasitism of Rutherglen bug eggs in sunflower, but this relationship was not conclusively determined (Forrester 1979).

In sunflowers in north-western NSW, a nematode (Mermithoidea), and the fungus *Beauvaria bassiana* have both been recorded from Rutherglen bug at low levels (Forrester 1979).

There was no Australian literature on parasitism or predation of Rutherglen bugs in horticultural crops.

Cultural Control

Cultural control plays an important role in the management of insect pests, by affecting the ability of the pest species to find, reproduce on, or establish in crops. Planting borders or strips in the field of non-crop species can provide valuable habitat for natural enemies which can slow the establishment and spread of pest species into the crop (Fouche *et al*. 2000, Bellows & Diver 2002). Cultural control methods are particularly important for organic production systems where available ‘insecticides’ may suppress rather than control the population.

Where pests are known to breed on weed hosts in and around crops, there are recommendations to manage weeds to prevent pest populations developing on them and then moving into the crop (Wardlaw 2004, McDougall 2007). Hamilton & Toffolon (1987) suggest that when immature Rutherglen bug are swarming off weeds into crops, they can be stopped by a furrow with the steep side nearest the crop. This would presumably be less effective in some soil types and situations than others, but highlights other possible methods of influencing pest movement and population dynamics.

Crop rotation, planting to avoid known periods of high pest pressure, and avoiding successive planting of crops in which pests or transmissible diseases may build up are all important cultural control methods for vegetable production (Fouche *et al*. 2000, Bellows & Diver 2002).

Mulches

The use of mulches, particularly reflective mulches, are reported to repel aphids and leafhoppers from landing on vegetable crops e.g. aster leafhopper in lettuce in the US (Caldwell *et al.* 2005). Mulches also provide the opportunity for crops to be planted earlier (opaque or clear plastic) by warming the soil, enabling crops to potentially avoid peak pest pressure (Delahaut 2002).

Row Covers

Floating row covers can be effective in protecting seedling crops by providing a physical barrier between crop and pest, although these are only appropriate for high value crops (Bellows & Diver 2002). Row covers were discussed by participants in the project workshop in relation to reducing the incidence of virus transmission by thrips to seedling crops. There was no discussion of, or experience with these options for other sucking pests. Tarnished plant bug (*Lygus lineolaris*) damage to flowers and buds can be minimised by the use of row covers in eggplant, pepper and tomato. However, the use of row covers is not recommended in mid-summer (Caldwell *et al.* 2005).

Species that over winter or breed outside fields and move into crops during spring and summer may be trapped in an alternate crop (trap crop) and then contained, or controlled in this trap before they move into the main crop (Fouche *et al*. 2000).

Trap Crops.

Trap cropping has been proposed to manage pests in conventional crop and organic vegetable production. For example, in New Zealand, trials using border plantings of white mustard and field pea, and black mustard around sweet corn resulting in a significant decrease in the percentage of cobs damaged by green vegetable bug (Rea *et al*. 2002). In another study on managing a Pentatomid species (*Murgantia histrionica* (Hahn), harlequin bug) in broccoli, bugs were attracted to the trap (broccoli, mustard, rape), but moved into the main crop when their numbers were high (Ludwig & Kok 1998). Sorghum was trialled as a trap crop to intercept green vegetable bug as they moved from spring crops (peanuts and corn) to cotton in the southern US (Tillman 2006). Coordinated use of early and late-maturing cultivars of soybean potentially lengthens the period of trap crop attractiveness to green vegetable bug (Bundy & McPherson 2000).

Trap cropping has also been proposed as a useful management tool for green mirid in cotton system. Cotton is intercropped with lucerne (a minimum 2.5% of the cotton area) planted in strips of 8, 12 or 16 rows every 300 rows of cotton. Alternatively slashing half the lucerne strips at four weekly intervals results in new growth on which the green mirid population can be maintained and prevented from moving into adjacent cotton (Mensah & Khan 1997, Deutscher *et al*. 2005).

The technique of inter row cover cropping in vineyards with buckwheat and sunflower in order to maintain greater floral diversity resulted in lower densities of leafhoppers. It was also noted that increased numbers of both egg parasitoids and predators were recorded in vines nearest the cover crops when the over crops were mown (Nicholls *et al*. 2000).

Other issues related to bug management

There are few examples of host plant resistance being investigated for tolerance to sucking pests. Screening potato germplasm with different foliar glandular trichomes for resistance to *Empoasca fabae* (Homoptera: Cicadellidae) indicated that phenolic oxidation chemistry and the physical barrier provided by the trichomes contributed to the observed resistance (Medeiros & Tingey 2006).

Contamination.
Contamination of the marketable product by insects is an issue for many vegetable crops (Vegetable Entomology Workshop Brisbane 2006). Rutherglen bug can be a significant contaminant in some seasons, but with a move to more in-field packaging of vegetables, any insects are considered contaminants. This makes pre and post-harvest disinfestation important areas of research. Chemical crop disinfestation prior to infield bagging using broad spectrum non-specific products undermines any previous efforts by growers to embrace and adopt IPM principles and techniques. Why is it that market forces, advertising and consumer perceptions all seem to push growers toward an attitude of nil tolerance for insect presence in maturing crop approaching harvest?

Overall Recommendations

Based on this review, the following investigations are recommended.

- Clarification of the pest status of these bug pests is required across a range of vegetable crops. There is a need to clarify whether the pest status is related to the real damage potential of the species, or uncertainty about the potential impact – which often results in prophylactic treatment. The application of synthetic insecticides to crops to control these pest species is disruptive to natural enemies, with consequences for IPM and often results in the flaring of other pest species due to the disruption of pest / predator population balance.

- The development of monitoring and management strategies for sources of bug pests.

- Develop tools that can predict the influx of these species into crops and provide an ‘early warning’ of potentially damaging or contaminating populations that are present in cropping areas. Rutherglen bug, green vegetable bug, green mirids and leafhoppers are all highly mobile pests which move into vegetable crops from external sources, principally weed hosts in which they take refuge and/or breed until they die. The potential for mass immigration into crops means that the potential of species like Rutherglen bug to damage the crop is a result of the size of the influx - rather than a progressive build up of the population within the crop.

    - Trap cropping may be an option in regions where sources of pests (like wild hosts) cannot be managed. Trap cropping may alleviate the need to control the pest in the vegetable crop.
    - The use of pheromones to monitor green mirids may be useful in crops where direct sampling of the crop is difficult e.g. seedling.

Monitoring tools that are linked to thresholds for a specific crop or crop group are essential in assisting decisions about the need for control.

- Refined monitoring may be warranted to allow for targeted control only when there is potential for crop damage or significant contamination. Exploration of the potential of sticky traps and pheromone traps, where appropriate, may provide better monitoring information. Development of efficient monitoring and sampling techniques for Rutherglen bugs would be a good test case.

- Refined recommendations including information on damage potential, thresholds and the implications of insecticide control for IPM need to be made available to vegetable industries. Researchers may need to place greater emphasis on aesthetic injury levels that impact on market acceptance of the crop rather than simple economic injury levels.

- Educational activities

- Informing consumers about the link between their low levels of tolerance (or nil tolerance) for blemished produce, and insect contaminants, and the pressure this puts on growers to use more insecticide.

- Re aligning consumer and market preference away from "picture perfect" blemish and insect-free produce would provide more opportunities for growers to take up available soft options or IPM.

- Crop contamination is becoming more of an issue with the chain stores demanding more in field bagging of vegetable lines. New post harvest or even pre harvest disinfestation methods may be worth consideration (washing, ultrasonics). Some alternative to disruptive chemical treatment of the crop to remove non-damaging species needs to be developed.

- Changing consumer perception – surely a bagged lettuce with a beneficial insect trying to escape from it is a positive sign of an environmentally friendly farming operation.

- Non-chemical options should be explored more widely in an effort to reduce the influx of these pest species into crops. Alternative techniques need to be assessed e.g. semiochemicals, petroleum spray oils, particle films, and other emerging non-conventional management tools are worthy of exploration in terms of both efficacy and market acceptability.

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Chapter 3

THRIPS

FUTURE RESEARCH DIRECTION – THRIPS.

Thrips are small, evasive, highly mobile and difficult to monitor easily with the naked eye. Specialist skills, knowledge, and equipment are needed to correctly identify pest species. Thrips can be responsible for virus transmission and so all species are treated as pests by growers.

1. **SOFT OPTION SPECIFIC PRODUCTS.**

There is a need to develop soft option management approaches across all crops affected by thrips. Western flower thrips control measures are at present largely reliant on spinosad and resistance has developed.

a. Beauveria is an entomopathogenic fungus identified in this review as having the most potential for commercialisation in Australian vegetable crops. Current APVMA registration hurdles are apparently hindering this option. A project to assist and guide the APVMA to actively pursue the registration of the native strain of this bio- pesticide may assist commercialisation, industry acceptance, and adoption.

b. Identify from local and overseas research data any new soft option or entopathogenic products that are specific to sucking pests and may assist in thrips control. Field test these products in our major thrips affected crops.

2. **MONITORING.**

a. Develop an effective, practical, grower friendly monitoring system to allow on farm tracking of thrips numbers.

b. Develop thrips specific control threshold guidelines that can be reviewed and updated over time, to develop and fine tune district action guidelines. This will become more relevant as access to soft option specific products allows growers to stop using broad spectrum products.

c. Investigate a semiochemical (pheromone) based system. Individual on farm monitoring would be ideal so a semiochemical attractant, or similar local population sampling tool should be developed.

d. Consider a weather based population model linked to knowledge of thrips biology and population dynamics to predict pest influxes. This sort of system would need to take an area wide approach.

3. **PREDATORY INSECTS**.

There are two *Orius* species which have been used for WFT control one of which (*Orius armatus*) is native to Australia and has been shown previously in Western Australia to consume large numbers of adult western flower thrips, *Frankliniella occidentalis*. In the USA another *Orius* species is raised and released commercially to control thrips. A previous effort to raise the native *Orius armatus* in Australia failed.

The reason for this failure should be reviewed as Western and South Australian greenhouse growers report very high levels of resistance to methomyl and abamectin in western flower thrips populations. A biological control alternative such as this *Orius* species may be a good addition to an IPM system in protected cropping structures and possibly in the field. A combined release approach with predatory mites (as outlined below) in protected cropping structures should enhance current IPM options and adoption.

The predatory mite *Transeius montdorensis*, or commonly known in the industry as Monties, were discovered and developed by the NSW Department of Primary Industries at the Gosford Horticultural Institute. Monties are predators of western flower thrips and provide excellent levels of controls in several crops including cucumbers and tomatoes. Monties also manage populations of other thrips that are present in crops and are often used in conjunction with other predatory mites such as *Neoseiulus cucumeris* and *Stratiolaelaps scimitus* (Hypoaspis) in greenhouse production.
Whilst Monties are commercially available, work is underway to further develop their rearing potential so that the market may be expanded for their use. Research is also being undertaken examining their role as predators of many other pests in greenhouse horticulture (pers.com. Dr Leigh Pilkington NSW DPI)

4. **EDUCATION.**

Educate growers, consultants, plant suppliers, and resellers about the importance of farm hygiene.

a. Continue to educate growers and industry groups regarding the important role of good farm hygiene practices, the removal of virus affected weeds, crop plants and residues which can both harbour resident thrips populations and be a continual source of virus spread.
b. Publicise more widely the major weeds that act as virus hosts and in some way demonstrate visually to growers the exponential infection nature of the virus/sucking pest interaction.
c. Manage resistance influences by providing a multiple control strategy, involving soft option products, monitoring, product rotation, and exclusion recommendations for covered cropping structures.
d. Link with virology research programs in conjunction with HAL to ensure work already done by virologists is recognised and integrated into IPM education and programs.

5. **ENVIRONMENT MANIPULATION.**

a. Enclosed or protective cropping structures are often associated with year round cropping of virus susceptible crops – this is a growing sector of the industry and often involves growers who speak and read English as a second language, if at all. Coupled with this is an element of direct marketing to the consumer via local "Saturday" markets or via direct supply to the local corner store. This sector of ground and hydroponic growers should be targeted with educational activities and demonstration events to assist the adoption of good hygiene and sucking pest control practices. This should include a push towards education about, and release of predators and entomopathogens in these enclosed structures. To ensure good adoption and the best results from such options, education about the potential to improve the environmental controls and general hygiene within the structures may have to occur to maximise pest and disease control results

b. Areas around protected cropping structures often suffer from poor hygiene practices and weed infestation. The promotion and adoption of the planting of beneficial plants (refer to Re-Veg by design projects) in these areas could provide a source of beneficial insect breeding sites – while also fostering the removal of weeds and other potential virus host plants.

Note:

c. Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.
d. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

The link below will allow you access to more detailed information on :

THRIPS and TOSPOVIRUS - A MANAGEMENT GUIDE. (Persley. D. *et al.* 2007)

Link to Thrips and Tospovirus

THRIPS

Biology and management of pest thrips (Thysanoptera: Thripidae) with reference to Australia.

by: Caroline Hauxwell

This paper reviews the biology and distribution of the key thrips species in Australia, and then addresses different issues around thrips management and monitoring. We discuss the practical difficulties in identifying thrips and the lack of valid data on thresholds and damage, and discuss three situations requiring different approaches to management: thrips as disease vectors, economic damage through damage or yield loss, and phytosanitary restrictions on thrips for export or at market. We address the different management practices for thrips, and discuss options for management and further research in these different circumstances. There are also some situations in which control may not be necessary.

Description.

Pest thrips (Thysanoptera: Thripidae) are typically very small (a few millimetres long), reproduce rapidly and prolifically, have a wide host plant range, are highly mobile and are generally adaptable and opportunistic (Palmer *et al.* 1995). Thrips pierce plant cells and feed on cell contents of flowers and leaves, pollen, seeds, mites and small insects, including their own immature stages (Childers 1997; Kirk, 1997a). They do not rasp, as earlier thought. They are typically found in restricted parts of plants, for example between tightly closed petals or in rolled or curled leaves (Kirk 1997b), which makes them difficult to find and to control.

The typical life cycle is 10 to 30 days, and is quickest at warmer temperatures up to 30ºC. Eggs are inserted into the plant leading to small 'blisters', often visible along leaf veins. There are two larval instars that feed actively and two largely inactive, non-feeding instars (the pre-pupa and pupal instars) that may be found on the plant or in the soil, and an adult with delicate fringed wings. Eggs and pupae are not susceptible to most insecticide sprays, however the physical separation of three different life stages – plant feeding larvae, soil pupae, and highly mobile adults, offers opportunities of direct control at different life stages.

The most serious pest thrips are rapidly selected for resistance to chemical insecticides and are vectors of important plant pathogenic viruses, particularly tomato spotted wilt virus (TSWV) and other tospoviruses (Bunyaviridae) such as capsicum chlorisis virus (CaCv). The most serious problems from thrips may arise not from direct pest damage but from the transmission of these plant pathogens.

Thrips in Australia

Over 650 thrips species are recognised in Australia, of which six are of importance as pests in Australian vegetable crops (Mound 2004, Lewis 1997b, MacDougal IPM inventory 2006). The four most significant pest species in Australia, western flower thrips (*Frankliniella occidentalis*, shortened throughout this text to WFT), tomato thrips (*F. schultzei*), onion thrips (*Thrips tabaci*) and melon thrips (*T. palmi*) are all introduced.

These four important plant pests are polyphagous and are a problem in a range of crops and are vectors of tospoviruses. Tomato thrips and onion thrips are found throughout Australia, while melon thrips is restricted to the tropical Northern Territory, parts of Queensland and in Western Australia.

WFT and tomato thrips are efficient vectors of TSWV, while onion thrips is a vector of variable efficiency (Cabrera La-Rosa & Kennedy 2007). Tomato thrips (*F. schultzei)* is probably the most important thrips pest and vector in Australia (Clift & Tesoriero 2002). Regional differences are important, however, as Capsicum chlorosis virus (CaCV), and one of its vector melon thrips is a more significant problem in Queensland. Plague thrips (*T. imaginis*) are native to Australia and are not vectors of TSWV or other tospoviruses.

WFT was first detected in 1993 in Western Australia (Malipatil *et al*. 1993). Although less mobile than other species, the area infested with WFT is expanding and it has the potential to become a very serious pest. WFT rapidly develops resistance to many classes of chemical insecticides (Lewis 1997d) and resistance has been reported in most classes of insecticides in Australia. Repeated applications may lead to increased selection for resistance (Horne & Wilson 2006). Resistance by *T. tabaci* to pyrethroids was reported in populations in South Australia and Tasmania in 2006 and occasional control failure has been reported (Herron 2006).

Identification of the species is important as thrips species have different capacity to damage plants, vector disease and develop resistance to insecticides. For example, WFT aggregate in cucumber flowers and damage immature fruit while melon thrips feed on foliage and cause little economic damage even though they may be more abundant (Johnson 1995). Duff (2006) reports 10 species of thrips found on green beans in Queensland of which only 4 (WFT, tomato, plague and bean blossom thrips) are significant pests.

The closely related WFT and tomato thrips are especially difficult to differentiate but if a population is predominantly WFT, it may be resistant to several chemical insecticides and control may fail or resistance may be worsened unless appropriate chemicals are selected. Some species, e.g. melon thrips, an important vector of CaCV, are particularly small and very difficult to detect at all.

Although identification is important, many growers find identification practically impossible and are therefore reliant on limited professional services. Even then, morphology cannot be used to identify species of larvae or eggs, and although molecular methods are being developed, these are primarily for use in quarantine and are not practical for field diagnostics.

For many crops, however, there is little data to determine which species are causing damage, or if presence leads to economic damage at all. This leads to significant practical difficulties in deciding if control is necessary. In practice, growers may resort to control of thrips whenever present if there is any risk of virus transmission.

Thrips dynamics

Build up of thrips is an interaction between suitable host vegetation, for example early season rain provides lush weed hosts for thrips to breed on, and warmer spring temperatures, when thrips begin breeding (Kirk 1997b). WFT in the southern Australian states build up from low numbers in spring, becoming a more significant problem in late summer (Steiner & Goodwin 2005a). Onion thrips reproduce at higher temperatures and thus does not begin to build up in numbers until late spring or early summer (October in southern Australia) (Evans (1932). Rain events reduce numbers of thrips by up to 95% by knocking thrips off the plant or drowning them on the plant surface (Kirk 1997b, Hamilton & Toffolon 2003). Conversely, plague thrips build up with vegetation following winter rain in desert areas, and a dry spring can lead to large numbers migrating into cropping areas (Steiner & Goodwin 2005a).

In the warmer climates of northern and tropical states of Australia, thrips may breed continuously as long as there is sufficient moisture to maintain host plants, completing up to 12 or 15 generations in a year. This can lead to migration of thrips off weed vegetation and on to irrigated winter crops (Clift & Tesoriero 2002). Overlapping or sequential planting of vegetable crops throughout the year with winter irrigation has the potential to lead to maintenance of large populations of mobile thrips such as tomato thrips and vectored diseases.

Several thrips are parthenogenetic, which has a significant impact on seasonal dynamics and response to chemical treatments, since predominantly female populations can reproduce more rapidly. Early season (predominantly male) WFT populations are slower to recover from applications of insecticide but late season (mostly female) populations can recover rapidly, especially in the absence of natural enemies resulting from chemical use. All populations of onion thrips are in Australia predominantly female (Evans 1932; Mound, pers.comm. cited in Steiner & Goodwin 2005a).

Thrips numbers may build up by reproduction in a crop through the season, or appear suddenly as a result of mass migration. Over-wintering sites on weeds or surrounding crops is important in thrips movement into crops (review in Parella & Lewis 1997). Thrips breeding on weeds or in crops will migrate to surrounding crops when weeds or pastures dry out in hot weather or when crops or pastures mature and are harvested (Taverner & Woods 2006; Steiner & Goodwin 2005a, Clift & Tesoriero 2002).

Although thrips are not strong flyers, infestations are usually founded by airborne immigrants, either from a local population or sometimes carried over large distances by weather fronts (Lewis 1997b, Kirk 1997b). In susceptible crops, thrips often alight on the plants around the margins of the field, resulting in a characteristic pattern of heavy infestation at the edges and reduced numbers in the middle of a crop. This pattern is often reproduced in the distribution of tospovirus infection (Westmore *et al.* 2007; review in Lewis 1997b). This pattern of distribution has consequences for monitoring, with sampling required across the whole field area to get an accurate picture of distribution in the whole crop.

Monitoring and thresholds

Monitoring of thrips can be challenging as they are small and cryptic and difficult to find. Multiple species can occur on a plant, but not all may cause economic damage. Species are difficult for growers to identify, and larvae are impossible to identify by morphology even by experts.

Sampling can be based on plant tappings, whole plant counts, counts on flowers and leaves (depending on plant stage) or on counts in traps. Counts of thrips on plant parts are typically used to establish a threshold, though this may be an approximate guideline at best and may be only locally relevant. Sticky traps are often used for monitoring of adults to detect arrival and species composition and are reviewed in Shipp *et al.* (1995).

The only standard is placement, which should be vertical with the base of the trap situated at or just above the canopy. Size and colour of trap are not standardised.

There is little data on the relationship between counts in traps and damage in Australian vegetables. Steiner & Goodwin (2005b) found a correlation between the proportion of female WFT in trap catches and damaging populations on strawberry flowers: that a proportion of 65% females in the population also corresponded with the incidence of damage to fruit. However, the trap count was predicted by the counts on flowers in the previous week, i.e. trap counts do not predict plant counts, so plant counts were still necessary to detect an action threshold.

Traps can be useful to detect initial occurrence (i.e. first arrival) of thrips before they are detected by on-plant monitoring, for example in onions (Mo 2006b) or the first arrival of vector species. The 'WFT insecticide resistance management plan' (Herron *et al.* 2007) recommends 3 to 10 traps per hectare for field crops, with traps checked twice weekly.

'Monitor plants' such as petunias and faba beans can be used to monitor for virus as well as thrips (Broughton *et al.* 2004). However, there is considerable lack of standardisation among methods, and even within trapping methods. Presence/absence (binomial sampling) may be easier to use than counts, but only a few examples of their use in thresholds in vegetable (for onions and tomatoes) have been found during in this review.

Overall, there is little available information on thrips monitoring and relationship to thresholds in Australia and some work should be conducted in this area. Virus monitoring is also of concern, and surveys of TSWV and IYSV using hand-held antibody test kits might be useful to determine when thresholds for management of vectors need to be applied.

Thrips as an economic pest in Australia

Economic losses due to thrips falls into 3 rough groups: yield loss or blemishing and distortion caused by thrips feeding, infestation at packing or harvest that leads to rejection by markets, and virus transmission. There are also some situations in which thrips or some species of thrips are tolerated, and a few crops (e.g. brown onions) there may be little damage even though thrips are present in large numbers. However, thresholds are, in general, poorly established.

The loss in revenue due to thrips may be high as a result of vectored diseases, blemishing and rejection at market. Vegetable crops are at particular risk because blemished product significantly reduces crop value, even if total yield (as mass) is not much reduced. Similarly, market access, both international and interstate, can be prevented by the presence of thrips, and supermarkets have low tolerance for contaminating insects. In crops where TSWV and other tospoviruses are a serious concern, growers have very low tolerance for virus vector species. Since damaging or virus vector species are difficult to distinguish from other thrips, this may translate into zero tolerance for all thrips by growers, with obvious economic consequences in cost of control.

Thrips tolerance:

Thrips or some species of thrips are tolerated in some crops where damage may not occur until very high thrips densities are reached. Alternatively thrips presence may coincide with a more tolerant plant growth stage. Brown onions can tolerate very high infestations after establishment with little or no yield loss; however, lower thresholds are generally used commercially in Australia. Lower thresholds are recommended in green or bunching onions where excessive leaf damage is viewed as unacceptable by the consumer. Beans can tolerate levels of thrips in vegetative stages from first trifoliate (true leaf) stage up to flowering, though with a lower tolerance if thrips are actively feeding at the growing point. Consultants report tolerance of thrips up to 2 thrips per growing point or 10 adults per plant but any infestation must be controlled prior to bud emergence. Similarly, consultants report that melons, squash and eggplant, which are not susceptible to vectored diseases, can tolerate thrips during early vegetative stages but with a very low tolerance after flowering as fruit begin to set.

WFT thrips may be present in large numbers on hot chillies without damage in central Queensland, since WFT is not a vector of CaCV. Growers and consultants who can differentiate WFT from tomato thrips or melon thrips, which are significant vectors of CaCV, may avoid the cost of spraying. However, some varieties may be susceptible to other thrips, with consultants reporting severe scarring caused by thrips in banana chillies from Stanthorpe, Qld.

Physical damage: yield loss and blemishing

Estimates of yield reductions are highly variable and may often not be attributable to any one species (Lewis 1997a). For many crops data are lacking to differentiate economic damage from occurrence, and to determine which species are causing critical damage and to which plant part. Thrips are a particular problem under hot and dry conditions. Heavily attacked plants lose moisture more readily, causing them to wilt (Lewis 1997; Kirk 1997a; Fournier *et al.* 1995).

WFT is particularly damaging. The 'WFT insecticide resistance management plan' (Herron *et al.* 2007) lists the damage caused by WFT to a number of crops and includes silvering or bronzing on leaves, scarring and distortion of fruit, or even flower abortion in heavy infestations.

Infestation in early lettuce seedlings can lead to curling, silvering and wilting of leaves (Napier 2004). Established lettuce plants can tolerate moderate levels of infestation without loss provided TSWV is not present or thrips present are not vectors (plague thrips is not a virus vector). However, early infestation in seedlings can lead to physical blemishing and wilting, resulting in reduced growth rates while late infestations may lead to rejection by supermarkets. In practice, therefore, thrips are not tolerated by growers.

Consultants in Australia report varying thrips thresholds across a range of crops, and some of these thresholds seem extremely low. Given that these thresholds are mostly based on thrips presence rather than accurate pest thrips species identification it is an area where some further work is warranted. Internationally, thresholds for onion thrips in onions are variable and generally higher in moist conditions, lower in dry. Quartey (1982) estimated that onions with 5, 8, 10 and 12 leaves should tolerate 0.05, 5, 29 and 59 thrips per plant without yield reduction. Edelson *et al.* (1989) in Texas, USA, recommended an economic threshold of 2.2 thrips per plant in a semi-dry year and 0.9 thrips per plant in drought. 0.9 thrips per leaf was only useful in drought years: in any other year control cost would have exceeded benefit. Similar levels were recommended by Fournier *et al.* (1995).

Thrips as vectors of plant pathogens

The most serious problems with thrips arise from the transmission of plant pathogens by the very mobile adult stage in the insects' lifecycle. As described above, thrips are important vectors of 3 tospoviruses in Australia: Tomato spotted wilt virus (TSWV), Capsicum chlorosis virus (CaCV) and Iris yellow spot virus (IYSV).

The biology, detection, distribution and control of tospoviruses in Australia have been recently and comprehensively reviewed by Persley *et al.* (2006) .This document is attached as Appendix A at the end of the thrips section.

Only young nymphs can acquire TSWV and may become infected with only 5 minutes of feeding on an infected plant. Once infected as a larva, virus replicates in the thrips and the insect is infected for life (Best 1968, reviewed in Persley *et al.* 2006). Only the adults transmit the virus, but being highly mobile can rapidly spread the virus. Over 900 species of crops and weeds are hosts for TSWV (Broughton *et al.* 2004), with weeds being reservoirs for both TSWV and the thrips vectors.

WFT and tomato thrips are efficient vectors of TSWV, though WFT is less mobile, whereas onion thrips is variable in competency as a vector. In Queensland, the most abundant and highly mobile vectors of TSWV in vegetables are tomato thrips. WFT is currently a significant pest in some areas with the potential to spread and become a very serious pest and disease vector of Australian fruit and vegetables. Onion thrips is an important vector in Southern Australia and the only vector of TSWV in Tasmania (Clift and Tesoriero 2002).

The crops most severely affected by TSWV in Australia are capsicum, lettuce, tomato and potato. Currently TSWV is a major problem in lettuce in the Sydney basin, and capsicum on the north Adelaide plain. In Western Australia, TSWV can lead to 100% crop loss in lettuce, tomato and capsicum (Broughton *et al.* 2004). TSWV symptoms include: distinctive light green (immature fruit), orange or yellow concentric rings in tomatoes, irregular necrotic spots on leaves, black or purple stem streaks, chlorosis or necrotic ring spots, leaf distortion and deformation, leaf drop and bud shedding, dieback and leaf collapse, stripes on petals and plant death from wilting (Broughton *et al.* 2004, Zitter *et al.* 1989).

Capsicum chlorosis virus (CaCV) was first reported in the Bundaberg area affecting capsicum, chilli and tomatoes (McMichael *et al*. 2002). CaCv affects all capsicum production areas in Queensland and can reach epidemic proportions, though infection is more typically around 5 to 10% (Sharman *et al.* 2007). It can also be found in NSW and Western Australia (Sharman *et al.* 2007). The usual vector is melon thrips, but it is also transmitted by *F.schultzei* though not by WFT (Sharman *et al.* 2007).

Iris yellow spot virus (IYSV) is vectored by onion thrips and was first found in Australia in 2003 infecting bulb and seed onions, spring onions and leeks (Coutts *et al.* 2003). It is found in three states including the onion seed production areas of the Riverina in NSW, metropolitan Perth (WA) and Swan Hill district of Victoria. This is a serious pathogen of onions in the USA, though a different strain from the Australian virus (Pappu *et al.* 2007). It is of some concern for Australian onion growers.

The presence of tospoviruses in a susceptible crop leads to very low tolerance for vector thrips. The two key concerns are TSWV and CaCV in Queensland. Lettuce is highly susceptible to TSWV and vectors are poorly tolerated. The economic threshold in processing tomato in southern Australia to prevent an increase in disease incidence in field tomatoes is 0.33 larvae per flower since only the larval stage can acquire the virus (McDougal 2004). The objective of this threshold was to prevent polycyclic development - i.e. transmission of TSWV from infected adults to susceptible tomato plants to uninfected larvae – of disease in the tomato fields. This is much lower than the economic injury level of WFT on field tomato (0.5 adults per flower) or the economic threshold (0.33 total thrips per flower).

Indicator plants (varieties of petunia and faba beans) can be used to determine if thrips are carrying TSWV (Broughton *et al.* 2004). Petunias do not transmit virus to thrips larvae or act as a reservoir for adjacent crop plants, however faba beans do and affected indicator plants must be removed to avoid risk of systemic infection and transmission to surrounding crops.

Specialist lab tests can be used to detect and identify tospoviruses. Growers should consider that positive lab tests are indeed confirmation of the virus, but that negative lab tests may only reflect an inability to detect other tospovirus species.

Tobacco streak virus (TSV) has recently emerged as a major pathogen of sunflower and some grain legumes in central Queensland (Sharman *et al.* 2008) The virus can be transmitted by a range of thrips species as they forage on virus infected pollen deposited on susceptible host plants. This mechanical transmission is a distinctly different process than the complex circulative, propagation mode of transmission occurring with tospoviruses. TSV has the potential to become an issue for the vegetable industry if alternative virus hosts become established in production areas. (Sharman *et al.* 2008).

Packing and market access issues:

Thrips are an injurious pest, so any consignment for international export cannot be issued with a phytosanitary certificate if thrips are present. A number of thrips are notifiable pests in some states: WFT in Northern Territories, South Australia, Tasmania and Victoria, and melon thrips in South Australia, Tasmania, and Western Australia. Post harvest fumigation may be the only option in these cases.

Tolerance for thrips in packing is typically low. Thrips under leaves in cabbage and in green onions can be difficult to control if not managed well before packing. Thrips in sweet corn can prevent export and reduce acceptability if cobs are ‘gappy’. Consumer demands for low levels of insect contaminants will continue to enforce low thrips thresholds even in late season when no blemishing or yield loss is expected.

Thrips management

Management of thrips faces some significant constraints, including, difficulty to detect or identify thrips, the pathogens they vector, their rapid rate of increase or migration, and very little validated data on threshold levels. Threshold levels need to be very low if the crop is susceptible to viral infection.

Insecticide resistance is a serious threat, and any management strategy must include actions to reduce over-reliance on a single class of chemicals. Management of thrips also needs to be considered within the context of management of other pests such as *Helicoverpa* sp., silverleaf whitefly and other sucking pests. New biopesticides for *Helicoverpa* sp. management have removed the need for early broad spectrum chemical applications and may lead to preservation of beneficial insects in a field, while crop hygiene and good weed control may further reduce the need for chemical applications.

Johnson (1995) describes the use of a predatory mites to control 1st instar thrips in combination with resistant varieties of cucumber that have an antifeedant effect on second instars and result in reduced fecundity and survival of second instars.

Persley *et al.* (2007) also recommend an integrated strategy to manage tospovirus based on farm hygiene to remove sources of infection, and thrips vectors from old crops and weeds, use of healthy planting stock, the use of virus resistant varieties, and chemical control of thrips. An IPM strategy therefore combines a number of different controls against key stages in the pest lifecycle to reduce overall pressure, reserving chemical control for critical applications and thus reducing selection for resistance, while maximising and maintaining beneficial insect populations.

Chemical control

Chemical control is an important tool for thrips management to be used in conjunction with a broader Integrated Pest Management strategy. However, resistance remains a key issue and all chemical use needs to be managed to preserve efficacy. Early season use of chemical against an early season thrips such as plague thrips is particularly disruptive to beneficial insects, may lead to repeat applications, increased resistance, and cause the outbreak of secondary pests. Poor identification of thrips and a lack of data on actual thresholds probably result in unnecessary use of chemical insecticides.

WFT rapidly develops resistance to many chemical insecticides (Lewis 1997d) and resistance to pyrethroids, fipronil, organochlorines, organophosphates and spinosad has already been reported in Australia (Broughton & Herron 2007; Herron *et al.* 2007; Herron & Gullick 2001; Herron & James 2005). Spinosad is still largely effective, though occasional control failure has been reported (Broughton & Herron 2007). Resistance has so far not been reported to abamectin (a mixture of avermectins), pyrazophos (organophosphate) or chlofenapyr (Pyrrole) (Herron *et al.* (2007). Resistance by *T. tabaci* to pyrethroids was reported in populations in South Australia and Tasmania in 2006 and occasional control failure has been reported (Herron 2006). No resistance to pyrethroids has yet been reported in the Riverina or Lockyer Valley.

Herron *et al.* 2007 'WFT insecticide resistance management plan' contains a comprehensive list of chemicals registered in Australia for thrips by crop, as well as guidelines on general WFT management. Resistance management strategies for thrips in Australia promote the rotation of different classes of insecticide (Broughton & Herron 2007; Herron *et al.* 2007; Herron 2006). Broughton & Herron (2007) describe the use of a three-spray strategy combined with rotation of chemical classes, with each class of insecticide used for 3 consecutive sprays over a period roughly equivalent to one generation of thrips (15-35 days) before switching to another class.

A two or three week break with no insecticide application is recommended between the use of two classes of insecticide (Herron *et al.* 2007). They confirmed the need for 3 sequential sprays to reduce populations of both adults and larvae (Herron *et al.* 2007). In many vegetable crops a very limited number of insecticide classes are available for rotation. This impacts on effective thrips management and has implications for resistance development.

Herron (2006) notes that the number of insecticides available to onion growers for *T. tabaci* control is limited, and is potentially more limited with the review of registration of methamidophos, endosulphan and dimethoate in food crops. A certain number of chemicals have been approved for off-label use by APVMA and are listed under each crop in Herron *et al.* (2007).

New systemic products expected to be registered shortly may provide some options, depending upon which crops are allowed label use. However, chemical control needs to be viewed in the context of avoiding resistance in an overall strategy. Chemicals should therefore be used as an important but ‘last resort’ tool for control of virus vectors and very damaging outbreaks in an overall management practice designed to reduce the threat of resistance.

Weed management and farm hygiene.

Thrips may breed on weeds or other vegetation and migrate into crops in large numbers. Onion thrips has been recorded in New South Wales breeding on onion re-growth from last season's crop and brassica weeds (hedge mustard, twiggy turnip, Indian hedge mustard and shepherd's purse) prior to invasion into new season onion crops (Mo 2006b). Broad leaf weeds are especially important as thrips are attracted to, and breed in their flowers.

Thrips and viruses have large and overlapping host ranges that make control especially challenging. In Australia these include white and sub clover, thistles and cape weed, ox tongue and sow thistle (Clift & Tesoriero 2002) and probably many more. Persley *et al.* (2007) list weed hosts of tospoviruses. The presence of virus-susceptible thrips host plants in and around cropping areas is a serious concern.

In a continuous cropping environment such as the tropical north, thrips populations may build to high densities and migrate between overlapping plantings as host plants age or are harvested. Where crops that are also reservoirs of tospoviruses, such as peanuts and legumes, are used as break crops in sugar around vegetable crops, there is potential for a serious build up of both disease and vectors. No models of thrips vector movement and vegetation patterns have yet been developed in Australia.

Weed removal is frequently recommended to reduce initial thrips infestations moving into crops. Weed removal is costly and timing may be important as clearing weeds at the wrong part of the crop cycle may cause thrips migration into the crop. The effective distance around the field that needs to be cleared is not well defined and efficacy of clearing has not been well proven as some thrips are highly mobile and may migrate over long distances, though WFT is less mobile than others.

Permanent replacement of weeds with native vegetation may help to reduce both thrips and tospovirus incidence. Taverner & Wood (2006) found significantly fewer thrips vectors on native plants in South Australia and recommended replacement of weeds in field margins with native species that do not harbour TSWV vector thrips, an extension of 'mixed plantings' to the field margins and surrounding vegetation.

Tolerant / resistant varieties.

Some plant varieties resistant or tolerant to thrips are available, including cucumber, eggplant, cabbage, potato, peppers and onions, though commercial agronomic acceptance of these lines is unknown (Mellema *et al.* 1995, Lewis 1997b, Westmore *et al.* 2007).

Modelling of WFT movement indicates that each plant acts as a stepping-stone in the diffusion process. This suggests that interplanting or sequential planting with plants of different suitability to WFT may reduce dispersal.

Planting of varieties that are less preferred by WFT may also help to reduce transmission of TSWV (Peters *et al.* 2007; Westmore *et al.* 2007). Though not resistant to the virus, the plants impede the spread of tospoviruses by lower infection success, a lower acceptance rate of the plants by the thrips and a decrease in population development.

Some cultivars of tomato and capsicum have been developed with a resistance gene to TSWV. More recent crosses have produced stable, resistant lines in capsicum that are resistant to both TSWV and CaCV, while the Sw-5 gene for resistance to TSWV in tomato has been incorporated into elite tropically adapted lines (Persley *et al.* 2007). Capsicum lines resistant to both CaCv and TSWV are being developed in Queensland (Persley *et al.* 2007).

South Australia greenhouse capsicum growers report that a capsicum line initially resistant to TSWV is no longer effective after only two years of commercial use.

This highlights the point that resistant varieties should only be used as part of an integrated management strategy! Reliance on resistance alone can lead to the rapid spread of virus strains able to overcome resistance, as has occurred in Virginia S.A. following the introduction of this TSWV resistant capsicum (Sharman and Persley 2006).

Biopesticides.

Many of the characteristics that make thrips a difficult target for other controls also make control with biopesticides difficult. Sucking feeding practically eliminates ingestion of pathogens sprayed on leaf surfaces, and no effective protozoan or bacterial pathogens of thrips are known. *Bacillus thuringiensis* and baculoviruses are used in Australia against Lepidoptera but must be ingested, and have no known activity against or occurrence in thrips. Some viral pathogens of thrips do exist but are not practical for use as a biopesticide.

Entomopathogenic fungi, particularly *Metarhizium*, *Verticillium*, *Beauveria* and other Hyphomycetes are a potential option and are reviewed in Butt & Brownbridge (1997). Entomopthorales have been recovered from thrips but mass culture is still prohibitively difficult for commercial biopesticide production.

Fungal spores germinate on contact with the insect cuticle and initiate infection. Hyphomycetes can be mass-produced, can kill a high proportion of targets, and can be used as soil or foliar applications with little impact on beneficial insects. *Metarhizium anisopliae* has been tested against WFT pupae in potting soil (Ansari *et al.* 2007) and against WFT in chrysanthemums (Maniania *et al.* 2001).

Biopesticides against *Helicoverpa* have demonstrated effective use in early season control in broad acre crops, delaying the use of broader spectrum chemical insecticides and thus reducing the threat of resistance while maintaining beneficial insect populations. *Metarhizium* has been shown to be very 'soft' on beneficial insect populations in Australian broad acre crops (Knight & Hauxwell, unpublished reports to GRDC and CRDC).

As with chemical controls, improving application and coverage will be pivotal to the success of biopesticides. Delivering spores to thrips in flowers or folded leaves is very challenging. Oil formulations are known to be stable in dry conditions, but high volume water emulsion applications are more likely to reach cryptic feeding sites. Further work is needed to improve formulation and timing of applications to increase target acquisition. Techniques such as targeting early season leaf-feeding populations, applying soil treatments against pupating stages, and manipulating pest position by combination with aggregation pheromones could all enhance future control options.

Nematodes are known to be natural enemies of thrips. *Thripinema nicklewoodi* (Tylenchida: Allantonematidae (reviewed in Loomans *et al.* 1997) is an obligate parasite and therefore must be produced *in vivo*, with significant consequences for production and thus use in practice (Arthurs & Heinz 2002). It is also unlikely to be approved for release in Australia. The heterorhabditid nematode *Steinernema feltiae* is a generalist and much easier to mass produce. It is registered (as 'Nemasys F'®) for thrips control in Europe and produced by Becker Underwood, a company with facilities in Australia. Bennison *et al.* (2007) reported good control by weekly foliar applications of Nemasys against WFT and reduction of TSWV severity in glasshouses. However, the cost of Nemasys may be prohibitively high for field control.

Mulches.

Coloured and metallised UV-reflective mulches can repel thrips and reduce migration between plants and soil by larvae. UV-reflective mulches significantly reduced the early season abundance of adult thrips and incidence of TSWV and significantly increase yield compared with standard black plastic mulch (Reitz *et al.* 2003).

Metallised mulches can be significantly more expensive than conventional mulch: up to 3 times the cost of traditional black mulch (Olson *et al.* 2007). However, there are significant benefits that deserve further investigation.

Combination of metallised mulch with Actigard (acibenzolar-S-methyl) were highly effective in reducing the primary spread of TSWV in field grown tomatoes, and both in combination with insecticides reduced TSWV by as much as 81% (Olsen *et al.* 2007). Jensen *et al.* (2003) reported that combined straw mulch, spinosad and azadirachtin achieved significantly higher yields and gross returns than standard practice in the production of dry bulb onions in the arid US.

Natural enemies.

International research on control by predators has been reviewed by Sabelis & Van Rijn (1997) and on parasitoids by Loomans *et al.* (1997). Predators have been used frequently in glasshouse crops as biological controls, usually by release of generalist predators such as *Amblyseius* spp. and *Orius* spp. Predatory mites and flower bugs are mass reared and commercially distributed for inundative release in glasshouses. Even so, repeated releases may be necessary when the intrinsic rate of increase of the thrips is higher than that of the predator.

The predatory mite *Transeius montdorensis*, or commonly known in the industry as Monties, were discovered and developed by the NSW Department of Primary Industries at the Gosford Horticultural Institute. Monties are currently commercially available from the Beneficial Bug Company in Richmond and are highly efficient predators of a number of key pests in several crops. Significantly, Monties are predators of WFT, and provide excellent levels of controls in several crops including cucumbers and tomatoes. Monties also manage populations of other thrips that are present in crops and are often used in conjunction with other predatory mites such as *Neoseiulus cucumeris* and *Stratiolaelaps scimitus* (Hypoaspis) in greenhouse production.

Monties are quite hardy predators and are able to be released into a crop as a preventative inoculation against the arrival of key pests. They sustain low population numbers feeding on available insects and pollen within the crop. Once pest populations within the crop increase, the population of Monties can rapidly increase in size and manage the growing pest problem. Monties are released, at management levels, at 10 individuals per square metre. They are sent to the grower in a suspension of vermiculite that has a food source contained within it so that they survive the freight.
Whilst Monties are commercially available, work is underway to further develop their rearing potential so that the market may be expanded for their use. Research is also being undertaken examining their role as predators of many other pests in greenhouse horticulture (pers.comm. Dr Leigh Pilkington NSW DPI).

Action thresholds in glasshouses are very low and biological control is feasible and often the first line of defence, so growers like to introduce beneficials at first sign of detection, or even as a prophylactic. However, costs are high and efficacy may not be sufficient to justify releases in field crops.

Conservation of predators and parasites in the field may have some benefit. Although numerous predators and parasites of thrips have been recorded in Australia, their impact has not been investigated to any great extent.

Field control is likely to rely on naturally-occurring predators and parasites such as *Orius* spp., lacewings (*Mallada* spp. and *Micromus* spp.) and predatory mites (*Transeius* (syn: Typhlodromips) *montdorensis*) (Broughton *et al.* 2004). *Orius* species are important naturally-occuring predators of thrips and are relatively common generalist predators in Australian agricultural crops.

O. armatus has a significant impact on WFT in carnations in Western Australia (Cook *et al.* 1996), with the greatest impact on WFT larvae.

More research is needed on predators and parasites in Australia, and in particular on beneficial insects that attack life stages other than those causing damage such as pupae and pre-pupae in soil. For example, Mesostigmatid mites (*Lasioseius subrraneus* Chant and *Hypoaspis aculeifer* (Canestrini) prey on melon thrips in soil and prey on both larvae an pupal stages in laboratory cultures, however no field data are available.

Orius abundance is highest close to adjacent native bush land, and is reduced in plants sprayed with insecticide to control thrips. Cook *et al.* (1996) report that sprayed crops had reduced *O. armatus* abundance and twice the level of WFT as unsprayed crops close to bushland. Thus replacement of weeds around field margins with selected native plants may encourage beneficial insects.

Semiochemcials.

Sticky traps are useful in detecting early signs of infestation, and may be improved with new designs of sticky traps. A number of additives have been used to enhance traps, including anisaldehyde and ethyl nicotinate (reviewed in Lewis 1997b) and an unnamed 'volatile compound' increased numbers of thrips in traps (Davidson & Teulon 2007).

Kirk (2007) has noted that an exciting area of thrips semiochemistry is opening up using alarm pheromones, aggregation pheromones and plant volatiles. Semiochemicals offer a range of opportunities in management, either to improve trapping for monitoring, or to enhance chemical controls in conventional sprays or in baited applications. Semiochemicals are used as lures in insecticide applications for heliothis moths ('Magnet' ™). Application of a semiochemical baited insecticide to field margins, non-susceptible crops, or inter row areas may be a tool that could reduce infestations.

Van Tol *et al.* (2007) reported that the essential oil from *Orius majorana* is a thrips repellent and suggest that repellents could be applied on crop hosts in combination with an attractant applied to a trap crop or trap in a 'push-pull' control strategy.

Conclusions.

Management of thrips is a significant challenge for vegetable growers. More data are needed on thresholds and practical monitoring methods for growers and consultants. New chemical options may provide some relief, but overreliance on the few chemicals available could lead to rapid loss of efficacy through resistance.

An integrated strategy that avoids repeat applications of insecticides and reduces infestation through cultural and biological methods would fit well with management strategies for a range of other pests. Good farm hygiene practices are an integral part of preventing and minimizing the spread of viral pathogens. Care should be taken to prevent virus infected plants or transplants being brought into the farming area. Infected plants identified on farm should be physically removed from the field and destroyed. This physical removal of affected plants reduces the background virus infection source available to resident thrips. Weed removal and replacement with native vegetation that both encourages beneficial insects, and reduces the number of thrips and tospoviruses should further reduce the need for chemical control. Work to identify suitable native plants for northern states would be a useful tool in reducing thrips presence. Reflective mulches may have significant benefits that deserve further investigations, and biopesticides may also be an option after further work on formulation and application issues.

Improved, cost effective detection and identification is needed to allow growers and consultants to accurately identify the thrips species present and so make better management decisions. Insects are easier to find and identify on traps, and research on improved traps and their relationship to damage will help to improve control. Trapping also provides a visual measure of the level of the background thrips population.

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Tospoviruses—an Australian perspective

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Abstract. The detection, distribution, molecular and biological properties, vector relations and control of tospoviruses present in Australia, including *Tomato spotted wilt virus* (TSWV), Capsicum chlorosis virus (CaCV) and Iris yellow spot virus (IYSV), are reviewed. TS\VV occurs throughout Australia where it has caused serious sporadic epidemics since it was first described in the 1920s. The frequency and distribution of outbreaks has increased in the 1990s, with the arrival and dispersal of the western flower thrips *(Frankliniella occidentalis)* being one factor favouring this situation. The crops most frequently and severely affected are capsicum, lettuce, tomato, potato and several species of ornamentals. Minimal differences were found between the nucleocapsid (N) gene amino acid sequences of Australian isolates and these were most closely related to a clade of northern European isolates. CaCV was first detected in Australia in 1999 and is most closely related to *Watermelon silver mottle vu its,* a serogroup IV tospovirus. The natural hosts include capsicum, tomato, peanut and *Hoya* spp. The virus also occurs in Thailand and Taiwan. IYSV was first found in Australia in 2003, infecting onion and leek, with the distribution in three States suggesting that the virus has been present for some time.

Introduction

Tospoviruses are among the most damaging and widespread of the plant viruses, causing major losses in a broad range of food and ornamental crops throughout the world, both in field-grown crops and in glasshouse cropping situations (Mumford *et* *al.* 1996a). One or more tospoviruses have been recorded from over 50 different countries, representing six continents (Mumford *et al.* l996a). In recent years, several species have caused major crop losses in tropical and sub tropical regions (Jam *eta?.* 2002; Jan *et al.* 2003; Wongkaew 2002).

The genus name *Tospovirus* is derived from the type species, *Tomato spotted wilt virus* (TSWV), which was first found and described from Australia around 1920 (Samuel *et al.* 1930). All tospoviruses are transmitted by thrips in a propagative manner and the international dispersal of the efficient vector of TS\VV, *Frankliniella occidentalis* (western flower thrips), has been a major factor in the increased importance and increased research effort into tospoviruses in the last decade. This review provides an overview of current information on the biology, detection, transmission and control of tospoviruses, with an Australian perspective. Several recent reviews provide more extensive information on various aspects of tospovirus biology and management (German *et al.* 1992; Mumford *et al.* 1996a; Adkins 2000; Sherwood *et al.* 2000; Jan *et a?.* 2003; Peters 2003; Whitfield *et a?.* 2005b).

Tomato spotted wilt disease was first reported from Victoria (Australia) in 1915 and described by Brittlebank (1919). The disease was found in all Australian States during the 1920s (Best 1968) and was soon regarded as the most serious disease in tomato crops in all southern States, causing enormous losses in production in some years (Samuel *et al.* 1930). The causal agent was shown by Samuel *eta?.* (1930) to be a virus and named *Tomato spotted wilt virus.* These early workers demonstrated transmission by thrips, they transferred the virus with difficulty by sap inoculation and reported resistance in *Lycopersicum pimpinellifolium.* The first record of the disease outside of Australia was from the United Kingdom (Smith 1931) with subsequent reports from many countries of Europe, the America, Africa and Asia during the l930s (Best 1968).

Considerable research was undertaken on TSWV at the Waite Agricultural Research Institute, University of Adelaide and other centres over almost four decades (reviewed by Best 1968). These studies included a demonstration of the importance of pH and electrolyte concentration in maintaining virus infectivity, recognition of the symptom variability of TSWV and the role of genetic recombination in the development of strains (Norris 1946; Best 1954), and detailed work on the physical and biochemical properties of the virus (Best 1968). In Western Australia, Finlay (1952, 1953) undertook detailed studies on the inheritance of TSWV resistance in tomato.

For about 50 years following its discovery, TSWV was thought to be the only member of the TSWV group of plant viruses (Matthews 1982). It was first suggested in 1984 that TSWV could be a member of the *Bunyaviridae* (Mime and Francki 1984) and the *Tospovirus* genus was subsequently established with TSWV as the type member

(Francki *et a!.* 1991). *Impatiens necrotic spat virus* (INSV), previously TSWV-1, was included as a second member in this genus, based on distinct serological differences between it and TSWV (Law *et al.* 1991). The family *Bunyaviridae* is divided into five genera, based on similarities in molecular structure of their genomes, biological properties and physical aspects of proteins and virion morphology. The genus *Tospovirus* contains the viruses that infect plants. The four other genera, *Bunya virus, Hantavirus, Nairovirus* and *Phlebovirus,* contain over 300 viruses that infect animals. Members of the *Hantavirus* genus are spread by aerosols of saliva and animal excrement while members of the other four genera have specific relationships with arthropod vectors, in which they also replicate (Nichol *et a)'.* 2005).

There are currently 16 ICTV-recognised or proposed tospovirus species, listed together with their acronyms in Table 1. These species are delineated on the basis of amino acid sequence of the nucleocapsid protein, serology, by vector specificity and host range (de Avila *et al.* 1993; Elliott *et al.* 2000; McMichael *et al.* 2002; Yeh and Chang 1995). Viruses with an amino acid sequence identity less than 90% in the N protein are considered to represent different species (Moyer 1999). The species can also be serologically differentiated using antisera to the N protein, and are classified into serogroups. Some serogroups are monotypic, for example serogroup I (TSWV) and serogroup III (INSV), while others contain more than one member that cross-react serologically. TCSV and GRSV comprise serogroup 11, while serogroup IV or the Watermelon silver mottle group consists of GBNV, \VBNV, WSMoV and CaCV (de Avila *et al.* 1993; Jam *et al.* 1998; McMichael *et al.* 2002). Several other serologically distinct viruses are recognised, including IYSV ZLCV, CSNV (Bezerra *et al.* 1999) and MYSV (Cortez *et al.* 2001). The recently discovered Tomato yellow fruit ring virus (syn: Tomato yellow ring virus) (Table 1) shares an N gene amino acid sequence identity of 74% with IYSV (Ghotbi *etal.* 2005; 1-lassani-Mebraban *et al.* 2005).

The morphology of tospoviruses is typical of members of the *Bunyaviridae* (Elliot 1990). Tospoviruses form pleomorphic, spherical particles, 80—l2Onm in diameter, that are surrounded by a lipid envelope with two surface glycoprotein *(ON* and Cc) projections, enclosing three nucleocapsids. The nucleocapsids contain three single-stranded, linear RNA segments denoted L (large), M (medium) and S (small), each associated with many copies of the virus-encoded N (nucleocapsid) protein and a few copies of RNA-dependent RNA polymerase (RdRp) (Mumford *et al.* I 996a; Sherwood *et al.* 2000). The 3' and 5' termini of all three RNA segments contain relatively long inverted complementary sequences that are involved in the formation of the panhandle structure of the nucleocapsids found in mature virions and infected cells. The complementary ends are thought to be important signals for transcription and replication (Sherwood *et al.* 2000). The L RNA is negative sense and encodes the RdRp. The M and S RNAs have an ambisense coding strategy and encode the two envelope glycoproteins and a non-structural protein (NSm), and the N protein and a non-structural (NSs) protein, respectively. The NSm protein is present in infected plants and thrips, and has been proposed as a possible virus movement protein in plants (Kormelink *et al.* 1994; Ullman *et al.* 1995; Soelliek *et al.* 2000). The NSs protein has RNA silencing suppressor activity (Takeda *et al.* 2002).

Tospoviruses in Australia

Four tospovirus species have been found in Australia; TS\VV, CaCV (McMichael *et al.* 2002), IYSV (Coutts *et al.* 2003b) and an uncharacterised tospovirus from-the native orchid *Pterosty!is* (Gibbs *et al.* 2000).
TSWV remains the most widespread and damaging of the viruses in Australia (Fig. 1). Infection by TSWV results in a wide range of symptoms in its various hosts. These include mottling, chlorosis, ringspots, necrotic spots and streaks and stunting (Campbell *et al.* 2003; Kormelink *et al.* 1998; Latham and Jones 1997). The virus caused serious losses in all Australian States during the I920s and 1930s, particularly in tomato crops, with the 1928/29 growing season appearing to be particularly severe (Noble 1928; Samuel *et al.* 1930; Clift and Tesoriero 2001). Serious outbreaks occurred in potato crops in NSW and Victoria in 1945—46 and 1946—47 (Conroy *et al.* 1949; Norris 1951) with disease incidence up to 60% and the rejection of3I% of crops examined for seed certification in NSW (Norris 1951). The virus still remains one of the most widespread and damaging plant viruses in Australia. The incidence of TSWV began to steadily increase in most States in the early 1990s (Latham and Jones 1996; Wilson *et al.* 2000; Clift and Tesoriero 2001; Wilson 2001) and continued to do so into the 21st century (Coutts and Jones 2002a, *2002b;* Clift 2003; Jericho and Wilson 2003). The crops most frequently and severely affected are tomato, capsicum, lettuce, potato and several ornamental species e.g. aster, calendula, chrysanthemum. Several particularly severe epidemics occurred in the Virginia area north of Adelaide in 2000 with estimated losses of S7OM in vegetable crops (Anon. 2000) and in the Perth metropolitan area in 2001/02 with the -complete loss of many tomato, capsicum and lettuce crops (Coutts and Jones 2002a). A major reason for the increased losses from TSWV has been the incursion and wide dispersal since 1993 of *Frankiniella occidentalis* (western flower thrips) Malipatil *et al.* 1993), an efficient vector of TSWV (Ullman *et al.* 1997). Although western flower thrips has been implicated in several major epidemics, other vector species, such as *F. schultzei* and *Thrips tabaci,* have also been shown to play a significant role in recent TSWV outbreaks in Australia (Wilson 1998; Clift and Tesoriero 2001).

Table 1. Geographical distribution, natural hosts and vector species of the recognised and proposed tospovirus species

Tospovirus species[A] and acronyms	Geographical distribution	Hosts	Vector species	Reference
Groundnut (peanut) bud necrosis virus (GBNV)	India, South-east Asia	Peanut (groundnut), other grain legumes, tomato, capsicum, weed species	*Thrips palmi*	Reddy *et al.* (1992)
Groundnut ringspot virus (GRSV)	South America, South Africa	Peanut (groundnut), tomato	*Frankliniella occidentalis*, *F. schultzei*	de Ávila *et al.* (1993)
Impatiens necrotic spot virus (INSV)	USA, West and South Europe, New Zealand, Japan	Ornamentals, peanut, capsicum, potato, weed species	*F. occidentalis*	Law *et al.* (1991)
Groundnut (peanut) yellow spot virus (GYSV)	India, Thailand	Peanut	?[B]	Satyanarayana *et al.* (1996)
Tomato chlorotic spot virus (TCSV)	South America	Tomato, sweet pepper	*F. intonsa*, *F. occidentalis*, *F. schultzei*	de Ávila *et al.* (1993)
Tomato spotted wilt virus (TSWV)	Worldwide	Many hosts among crop, weed and ornamental species	*F. bispinosa*, *F. fusca*, *F. intonsa*, *F. occidentalis*, *F. schultzei*, *T. palmi*	Sherwood *et al.* (2000)
Watermelon silver mottle virus (WSMoV)	Japan, Taiwan	Watermelon, other cucurbits, tomato	*T. palmi*	Yeh and Chang (1995)
Zucchini lethal chlorotic virus (ZLCV)	Brazil	Zucchini (*Cucurbita pepo*)	*F. zucchini*?	Bezerra *et al.* (1999)
Capsicum chlorosis virus (CaCV)	Australia, Thailand, Taiwan	Capsicum, tomato, peanut, *Hoya australis*, gloxinia	*T. palmi*, *Ceratothripoides claratris F. schultzei*	McMichael *et al.* (2002), Premachandra *et al.* (2005), M Sharman, D Persley and J Thomas, unpublished data
Chrysanthemum stem necrosis virus (CNSV)	Brazil	Chrysanthemum	*F. occidentalis*, *F. schultzei*	Bezerra *et al.* (1999)
Iris yellow spot virus (IYSV)	Australia, Brazil, Israel, Japan, the Netherlands, USA	Iris, leek, onion	*T. tabaci*	Cortês *et al.* (1998)
Melon yellow spot virus (MYSV)	Taiwan, Japan	Melon	*T. palmi*	Kato *et al.* (2000)
Groundnut (peanut) chlorotic fan-spot virus (GCFV)	Taiwan	Peanut	?	Chu *et al.* (2001*b*)
Watermelon bud necrosis virus (WBNV)	India	Watermelon	*T. palmi*	Jain *et al.* (1998)
Tomato yellow fruit ring virus (Syn: tomato yellow ring virus)	Iran	Tomato	?	Ghotbi *et al.* (2005), Hassani-Mehraban *et al.* (2005)
Calla lily chlorotic spot virus (CCSV)	Taiwan	Calla lilies (*Zantedeschia* spp.)	*T. palmi*	Lin *et al.* (2005)

[A] Species recognised by the ICTV are in italics, those proposed are in Roman typeface.

[B] Unknown.

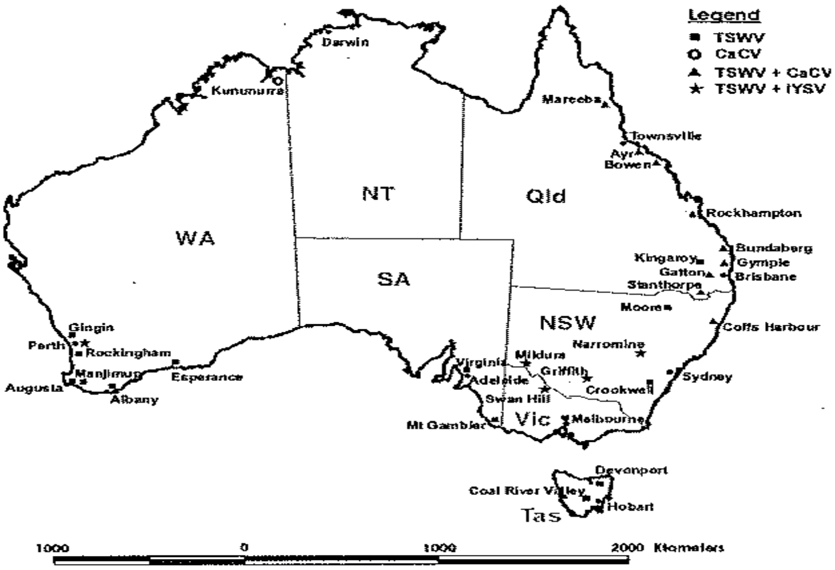


Fig. 1. Distribution of selected isolates of tospoviruses from Australia that have been identified by serological assays or PCR since the 1990s. See text for further details.

CaCV was first found in capsicum and tomato in Queensland in 1999 (McMichael *et al.* 2000, 2002). The other known natural hosts are peanut and *Hoya* spp. (M Sharman, DM Persley, JE Thomas and LA McMichael, unpublished data). Recently, an archived culture of a virus obtained from peanut grown on the Atherton Tablelands of north Queensland in 1992 was examined. It reacted with serogroup IV antiserum and had an N gene amino acid sequence identity of >98% with other Australian CaCV isolates, indicating the presence of the virus some 7 years before its formal description. CaCV has now been detected in all coastal vegetable growing areas of Queensland, in the Lockyer Valley and at Stanthorpe, an elevated summer vegetable production area near the Queensland / NSW border. The virus has recently (2004) been found in capsicum plants at Kununurra in the Kimberley region of Western Australia (Jones and Sharman 2005) and in tomato at Coffs Harbour on the central coast of NS\V (L Tesoriero, M Sharman, JE Thomas, unpublished). Although infecting three diverse families, the natural host range appears much smaller than that of TSWV. As evidence for this, surveys over 6 years have failed to find CaCV in a large number of common weed species, whereas in similar situations, TSVV was detected in a range of weeds including *Bidens pilosa, Solanum* spp. and *Sonchus oleraceus* (D Persley and M Sharman, unpublished).

The symptoms caused by CaCV resemble those induced by *TSWV,* but have several distinct features (McMichael *et al.* 2002; Persley 2003). In capsicum, marginal chlorosis and interveinal chlorosis develop on young leaves, which often become narrow and curled, with a strap-like appearance. Older leaves become chlorotic, and ringspots and line patterns may develop. The fruit on infected plants is small, distorted and frequently marked with dark necrotic lesions and scarring over the surface. Although CaCV is widely distributed in capsicum production areas, the incidence in crops is usually from 1% to 10%, although levels exceeding 60% have been found. Infected tomato plants develop chlorotic spots and blotches on leaves, which may become chlorotic and mottled, with purple ringspotting and sometimes necrotic rings (Persley 2003; Pongsapich and Cluemsombat 2002). *Hoya* spp. display symptoms of ringspots, linepatterns, chlorotic blotches and necrotic etching. Infected peanut plants develop chlorotic spots, blotches and ringspots on the leaves. Internodes are reduced in length and new leaves reduced in size. Leaves and terminal growth may develop necrosis and become flaccid and wilt. These symptoms are similar to those described for groundnut bud necrosis disease (Ghanekar *et* al. 1979).

IYSV (Cortês *et al.* 1998) was first reported in 2003 from three States, New South Wales, Victoria and 'Western Australia (Coutts *et al.* 2003b). The virus was identified using IYSV-specific antisera, reverse transcription polymerase chain reaction (RT—PCR) with 1YSV-specific primers (Pozzer *et al.* 1999) and N gene sequence comparisons, which showed 91% to 96% identity at the nucleotide level to sequences of IYSV isolates from the Netherlands and Israel (Coutts *et al.* 2003b). Symptoms in-onion plants were chlorotic and necrotic eye-like or diamond-shaped lesions on the leaves and seed stalk, which often bent at the lesion and developed extensive chlorosis (Coutts *et al.* 2003b). The virus was also found in leeks in 'Western Australia and confirmed in an archived sample from onion in Victoria in 1998, indicating the presence of IYSV in Australia for some years (Coutts *et al.* 2003b). IYSV is of increasing importance in onion seed and bulb crops in the USA and elsewhere (Gent *et al.* 2004) and its distribution and effect in Australian onion crops needs to be monitored. A tospovirus has been found in species of the native orchid *Pterostylis* with chlorotic blotch symptoms in the ACT and inland NSW and Victoria (Gibbs *et al.* 2000). Evidence by RT—PCR and serology suggest that the virus is novel (Gibbs *et al.* 2000), and further characterisation of this virus is in progress (LA McMichael, unpublished data).

Hosts of tospoviruses

TSWV has an extremely wide host range with over 1000 different plant species recorded as natural or experimental hosts (Best 1968; Campbell *et al.* 2003; Peters 2003). Almost half of the susceptible species belong to the families Solanaceae and Asteraceae (Peters 2003). The broad host range of TSWV is not characteristic of the genus, with the natural and experimental host ranges of other tospovirus species being less extensive. Although the known host range of INSV was once largely confined to plant species used as ornamentals, this was probably due to propagation through the nursery trade, where large numbers of different plant species and large numbers of thrips vectors coincided. The known host range of INSV now includes field and vegetable crops and weed species (Culbreath *et al.* 2003; Martinez-Ochoa *et al.* 2003; Perry *et al.* 2005). By contrast, the host range of IYSV seems confined to plant species in Liliaceae and Iridaceae (Cortês *et al.* 1998; Kritzman *et al.* 2000). The host ranges of recently described virus species will no doubt continue to expand as has been the case for CaCV.

The natural host ranges of the three tospoviruses found in Australia are given in Table 2 and clearly demonstrate the broad host range of TSWV compared with CaCV and IYSV. Weed species that may have an important role as alternative hosts for TSWV differ between climatic or geographic zones (Cho *et al.* 1986; Groves *et al.* 2002). In the Mediterranean climatic area near Perth in Western Australia, the weed species with the highest incidence of TSWV were *Aictotheca calendula* (capeweed) and *Sonchus asper* (sowthistle) (Latham and Jones 1997). On lettuce farms in southern Tasmania, capeweed, *Sonchus oleraceus, Malva sylvestris, Brassica rapa, Erodiun1 n1oschatun?* and *Trifolium* sp. were found to be important sources of TSWV (Wilson 1998). In sub-tropical and tropical Queensland, *Bidens pilosa* is frequently infected with TSWV. Snakeweed *(Stachytarpheta jamaicensis),* a common perennial herb in over-grazed pasture land in coastal Queensland, is also commonly infected by TSWV and may have an important role in virus survival in tropical north Queensland during the hot summer period when susceptible vegetable crops are seldom grown and few alternative herbaceous hosts are present (Abbott 2002, DM Persley and M Sharman unpublished data).

There is little evidence from the natural host range of *TSWV* to support the hypothesis that the virus, although first found and described from Australia, actually evolved on this continent. Latham and Jones (1997) found only one infected plant of the native species *Calectasia cyanea* among 1590 samples from 42 native species tested by ELISA in Western Australia. The only other recorded native hosts of TSWV are Kangaroo paw *Anigozanthos* hybrids) and *Bracteantha bracteata* (everlasting daisy), which were infected in nurseries (Hill and Moran 1996; Tesoriero and Lidbetter 2001).

Thrips transmission

Natural transmission of tospoviruses is by thrips *(Thysanoptera: Thripidae),* minute insects that generally feed on either plants or fungi. Some species are predatory and a few feed on mosses and detritus. Plant-feeding thrips feed on the contents of epidermal and mesophyll cells, using maxillary stylets and drawing the contents through a hole pierced by the mandible (Lewis 1997; Mound 2005). The general life cycle of thrips begins with eggs laid in the lamina of a host plant, followed by two active, feeding, larval stages, then two non-feeding, pupal stages (propupa and pupa) and finally the active, feeding, adult stage. The life cycle is dependent on temperature, and can last from 10 to 30 days, with adult survival for a similar duration (Lewis 1997). The first record of tospovirus transmission by thrips was by Pittman (1927) who showed that T *tabaci* transmitted TSWV. Subsequently, Samuel *et al,* (1930) showed that F *Schultzei* was also a vector. Worldwide, 11 species of thrips are now recorded as vectors of tospoviruses (Premachandra *et al.* 2005; Ullman *et al.* 2002), although there is some doubt as to the vector status of *Scirothrips dorsalis* (Mound 1996). None of these insect vectors are native to Australia but five species, F *occidentalis* (western flower thrips), F *schultzei* (tomato thrips), T *palmi* (melon thrips), T *tabaci* (onion thrips) and *S. dorsalis,* have become established (Mound 2004). Two of these are recent introductions and represent significant threats to plant production due to the fact that they are particularly effective tospovirus vectors. F *occidentalis* is thought to have originated in the western USA (Mound 1997) and efficiently transmits at least five tospoviruses, including TSWV (Ullman *et al.* 2002). The first record of F *occidentalis* in Australia was in 1993 from Western Australia (Malipatil *et al.* 1993) and it has subsequently been found throughout Australia. 7 *palmi* is thought to have originated in south-east Asia (Mound 2001) and is recorded as a vector of at least three tospoviruses, including members of serogroup IV (Ullman *et al.* 2002). In Australia, *T palmi* was first recorded in the Northern Territory in 1989 (Houston *et al.* 1991), and is now widespread in Australia (Anon. 2004).

It was first noted in 1931 (Bald and Samuel 1931) that the transmission process of tospoviruses by thrips is unusual, as only when the larval stages acquire the virus can the adults (or rarely, second instar larvae) transmit the virus. This is thought to occur due to the close developmental association between the brain, the salivary glands, midgut and visceral muscle cells in the first instar, allowing transmission of the virus across these tissues. As the second instar develops, these close contacts are lost, and further movement of ingested virions into the salivary glands is prevented (Moritz *et al.* 2004). Tospoviruses replicate in their thrips vectors (Mumford *et al.* 1996a) and the thrips remain viruliferous for life, on average 30—40 days (Best 1968). Inoculation feeds of as little as 5 min can result in transmission (Sakimura 1963). Recent molecular studies have shown that although the G_N and/or G_C virion glycoproteins may not be necessary for replication of TSWV in plants, they are required for transmission by thrips (Sin *et al.* 2005), The G_N has a role in virus binding and/or entry into the insect midgut while the G_C protein appears to function as a fusion protein mediating virus entry into thrips vector cells, including a role in pH-dependent endocytosis (Whitfield *et al.* 2005a, *2005b).*

Table 2. Natural hosts in Australia of *Tomato spotted wilt virus*, Capsicum chlorosis virus and *Iris yellow spot virus*[A]

TSWV

- Amaranthaceae
  - *Amaranthus hybridus* (Slim amaranth)
- Amaryllidaceae
  - *Agapanthus praecox* subsp. *Orientalis* (Common agapanthus)
- Apiaceae
  - *Ammi majus* (Bishop's weed)
  - *Apium graveolens* (Celery)
- Asteraceae
  - *Acanthospermum hispidum* (Starburr)
  - *Arctotheca calendula* (Capeweed)
  - *Bidens pilosa* (Cobbler's pegs)
  - *Bracteantha bracteata* (Yellow everlasting daisy)
  - *Calendula officinalis* (Calendula)
  - *Callistephus chinensis* (Chinese aster)
  - *Chrysanthemum morifolium* (Chrysanthemum)
  - *Conyza bonariensis* (Fleabane)
  - *Cosmos bipinnatus* (Cosmos)
  - *Cynara scolymus* (Globe artichoke)
  - *Dahlia hybrida* (Dahlia)
  - *Lactuca sativa* (Lettuce)
  - *Tagetes minuta* (Stinking Roger)
  - *Tanacetum cineariifolium* (Pyrethrum)
  - *Senecio vulgaris* (Common groundsel)
  - *Sigesbeckia orientalis* (Indian weed)
  - *Sonchus asper* (Rough sowthistle)
  - *Sonchus oleraceus* (Common sowthistle)
- Boraginaceae
  - *Echium plantagineum* (Paterson's curse)
- Brassicaceae
  - *Brassica rapa* (Wild turnip)
  - *Capsella bursa-pastoris* (Shepherd's purse)
  - *Diplotaxis muralis* (Wall rocket)
- Caryophyllaceae
  - *Spergula arvensis* (Cornspurry)
  - *Stellaria media* (Chickweed)
- Chenopodiaceae
  - *Chenopodium album* (Fat hen)
  - *C. pumilio* (Clammy goosefoot)
- Dasypogonaceae
  - *Calectasia cyanea* (Blue tinsel lily)
- Fabaceae
  - *Arachis hypogaea* (Peanut)
  - *Cicer arietinum* (Chickpea)
  - *Medicago polymorpha* (Burr medic)
  - *Pisum sativum* (Pea)
  - *Trifolium* spp. (Clovers)
  - *Vicia faba* (Broad bean)
- Fumariaceae
  - *Fumaria muralis* (Wall fumitory)
- Geraniaceae
  - *Erodium moschatum* (Musky storksbill)
  - *Gladiolus* × *grandiflorus* (Gladiolus)
- Haemodoraceae
  - *Anigozanthos* × hybrids (Kangaroo paw)
- Iridaceae
  - *Freesia hybrida* (Freesia)
- Lamiaceae
  - *Marrubium vulgare* (Horehound)
  - *Ocimum basilicum* (Sweet basil)
  - *Stachys arvensis* (Stagger weed)
- Liliaceae
  - *Alstroemeria hybrida* (Alstromeria)
- Malvaceae
  - *Malva parviflora* (Small-flowered mallow)
  - *Malva sylvestris* (Tall mallow)
  - *Hibiscus trionum* (Bladder ketmia)
- Plumbaginaceae
  - *Limonium vulgare* (Statice)
- Polygonaceae
  - *Polygonum aviculare* (Knotweed)
  - *Rumex* spp. (Dock)
- Portulaceae
  - *Portulaca oleracea* (Pigweed or purslane)
- Primulaceae
  - *Anagallis arvensis* (Blue pimpernel)
- Ranunculaceae
  - *Delphinium hybridium* (Delphinium)
- Scophulariaceae
  - *Antirrhinum majus* (Snapdragon)
- Solanaceae
  - *Capsicum annuum* (Capsicum, Chilli)
  - *Datura* spp. (Thornapples)
  - *Duboisia leichhardtii* (Duboisia)
  - *Lycopersicon esculentum* (Tomato)
  - *Nicandra physalodes* (Apple of Peru)
  - *Nicotiana tabacum* (Tobacco)
  - *Physalis* spp. (Wild gooseberries)
  - *Solanum americanum* sub sp. *nodiflorum* (Glossy nightshade)
  - *S. melongena* (Eggplant)
  - *S. nodiflorum* (Nightshade)
  - *S. trifolium* (Treeflower nightshade)
  - *S .tuberosum* (Potato)
  - *S. villosum* (Woolly nightshade)
- Verbenaceae
  - *Stachytarpheta jamaicensis*

CaCV

- Asclepiadaceae
  - *Hoya australis* (Native hoya)
- Fabaceae
  - *Arachis hypogaea* (Peanut)
- Solanaceae
  - *Lycopersicon esculentum*
  - *Capsicum annuum*

IYSV

- Liliaceae
  - *Allium cepa*
  - *A. porrum*

[A] Listed hosts are recent Australian records, verified by serological and molecular means. Sources of data: Coutts *et al.* (2003*b*), Greber and McCarthy (1977), Jericho and Wilson (2003), Latham and Jones (1997), McMichael *et al.* (2002), Pethybridge and Wilson (2004), Tesoriero and Lidbetter (2001), Wilson (1998), Wilson *et al.* (2000), Sharman, Persley, Thomas and McMichael, unpublished data.

Despite the groundbreaking research on thrips transmission conducted in Australia in these early years, most recent work was focused on vector identification and association of thrips species with diseased plants during field outbreaks (Clift and Tesoriero 2001). It is likely that the resurgence in the importance of TSWV in recent years is partly due to the presence of F *occidentalis* (Latham and Jones 1997), though T *tabaci* and *F schultzei* also appear to be associated with a significant number of recent outbreaks in Australia (Latham and Jones 1997; Clift and Tesoriero 2001; Coutts *at* a!. 2004). Caution is required in implicating vector species, as individual tospoviruses or isolates may not be transmitted by all vector species or clones of these species (Ullman et al. 2002; Nagata *at* a!. 2004) In addition, changes in the relationship between tospoviruses and their thrips vectors over time have been noticed. For example T *tabaci,* once an efficient vector of TSWV worldwide, now does not transmit several current isolates of TSWV (Ullman *et al.* 2002; Nagata *et al.* 2004). Research at the Department of Primary Industries and Fisheries, Queensland (M Sharman, unpublished) has shown that Australian isolates of TSWV were transmitted by E *occidentalis, F schultzei* (yellow form) and *T palmi* and that CaCV was transmitted by *T palmi* and *F schultzei.* In these experiments, *F occidentalis* failed to transmit CaCV This appears to be the first confirmed record of transmission of TSWV by 71 *palmi.* Although Fujisawa *et al.* (1988) reported transmission of TSWV by 71 *palmi,* their evidence was not conclusive. Several studies have failed to confirm the transmission (Murai 2001; Nagata *et al.* 2004) and the possibility cannot be excluded that the earlier workers were using another tospovirus (e.g. *Watermelon silver mottle virus),* at a time when different tospovirus species were not recognised. The transmission of CaCV by T *palmi* and *F schultzei* under experimental conditions is in general agreement with thrips-trapping studies over several years in capsicum crops in southern and northern Queensland (Abbott 2002; Walsh pers. comm.; Persley, Sharman and Clift, unpublished data). Both *F schultzei* and *T palmi* were regularly found in traps at Bundaberg in south Queensland where CaCV has been the dominant tospovirus detected in capsicum crops since 2000. Although T *palmi* has a restricted distribution in capsicum production areas in north Queensland, *F schultzei* has been an important pest of solanaceous crops in the region for several decades. In Queensland, the actual thrips species involved in field transmission of CaCV remains equivocal. In Thailand, the thrips *Ceratothripoides claratris* is a serious pest of tomato (Murai et al. 2000) and was recently shown to be a vector of CaCV (Premachandra *et al.* 2005). This thrips species is not known to occur in Australia. Interestingly, this is the first record of a tospovirus vector species outside of the genera *Thrips* and *Frankliniella.*

Detection and identification of tospoviruses

The detection and identification of tospoviruses can be achieved in a number of ways including observation of disease symptoms and host reactions as a preliminary indication, followed by electron microscopy (EM), serological or nucleic acid-based assays.

Tospoviruses produce a wide range of symptoms, often cause similar symptoms in common hosts and can be difficult to transmit. Despite these issues, there are a number of plant species which can be used as general indicators, including petunia *(Petunia hybrida), Nicotiana benthamiana* and *Emiliasonchfolia* (Moyer at a!. 1999; Mumford et al. 1996a; Peters 2003). *N benthamiana* is a very susceptible diagnostic host for most tospoviruses, but is a poor propagation host, as it survives for only a short time following symptom expression. Tospoviruses are unstable *in vitro,* and care must be taken with mechanical transmissions, including the use of reducing agents in the inoculating buffer. It can also be advantageous to subject plants to a period of darkness before and after inoculation (Best 1968; Mumford *et al.* 1996a).

Host range studies with CaCV were difficult when capsicum was used as a source of inoculum for test species other than capsicum. However, when *N benthamiana* was used as inoculum source, extracts prepared in cold 0.1 M phosphate buffer with 0.1% sodium sulphite, using a cold mortar and pestle, and the abrasives carborundum and celite added to the inoculum, reliable transmission was possible (DM Persley and M Sharman, unpublished), Nevertheless, to ensure reliable transmission, especially for resistance screening, it is advisable to repeat the inoculations after a few days.

Though a relatively simple process, EM of plant sap preparations of tospoviruses can be unreliable, as the membrane-bound particles are easily degraded unless fixed, and can be confused with other membranous structures. Immunosorbent electron microscopy has been successfully applied, and can be enhanced by gold labeling (Kitajima *et al.* 1992).

The lack of widely available, good quality antisera and unawareness of the extent of tospovirus diversity precluded the general use of serological assays for the detection and identification of these viruses for many years (Francki and Hatta 1981). Now, many antisera are available to a wide range of tospoviruses. Polyclonal antisera have been prepared to purified whole virions or nucleocapsids (e.g. Gonsalves and Trujillo 1986;

de Avila *et al.* 1993; Cortez et al. 2001), to *in vitro* expressed viral proteins (Sherwood *at* a!. 1995) and to synthesised peptides from the NSs protein (Heinze *at* al. 2000). Monoclonal antibodies (Sherwood *et al.* 1989) and recombinant single chain variable fragment antibodies (Griep *at* a!. 2000) have also been produced.

With the availability of a range of good antisera to various tospoviruses, ELISA (Gonsalves and Trujillo 1986; de Avila *et al.* 1993) and other serologically-based assays, such as lateral flow devices or 'dip-sticks' (Lopez Lambertini *et al.* 2003), have become the standard diagnostic method. For example, in extensive surveys in Australia for tospoviruses in ornamental and vegetable crops, and native plants, commercial ELISA kits were employed (I-Jill and Moran 1996; Latham and Jones 1997). Cross reactivity within 'serogroups' has allowed the use of ELISA kits specific for other serogroup IV members in surveys for CaCV when no specific antiserum was available (McMichael *et al.* 2002); Tissue blot assays are also effective (Hsu and Lawson 1991), and have been applied to surveys for TSWV in chickpea (M. Schwinghamer and M. Schilg, personal communication).

The first report of a RT—PCR for a tospovirus (TSWV) was by Mumford *et al.* (1994), who used primers specific for L gene sequences. These authors (Mumford *at al. 1996b)* later described a tospovirus genus-specific primer pair UNIV SI and UNIV 52, specific for conserved sequences in the N gene and 3' untranslated region, respectively. These primers were used successfully to detect TSWV, TCSV, INSV and GRSV, the known tospoviruses at the time. Concurrently, Dewey *et al.* (1996a) described a similar PCR, with Primer I essentially equivalent to UNIV 52 of Mumford *at al.* (I *996b)* and Primer 2 targeted to another conserved region in the N gene. These latter regions have since been used by others in designing tospovirus genus-specific primers (Weekes *et a?.* 1996; Bezerra *eta?.* 1999; Eiras *et al.* 2001; Okuda and Hanada 2001), with modifications being made as sequences of additional tospoviruses have become available. Such primers have assisted in the detection and identification of previously unrecogaised or unidentified tospoviruses (e.g. Dewey *at a?.* 1996a; Bezerra *at a?.* 1999; Okuda and Hanada 2001). McMichael *et al.* (2002) used primers to the S RNA serogroup IV tospoviruses (Jam *eta?.* 1998) to characterise CaCV, a novel virus previously identified by ELISA as a member of this serogroup. A novel approach was used by Cortez *eta?.* (2001), once again using a primer targeted to the conserved sequence at the 3' end of the S RNA (the complement of which is present at the 5' end of the S RNA), together with a primer to the tracts of adenosine bases (and complementary uridine bases) present in the highly homologous sequences of the intergenic region. Using this approach with Physalis severe moffle virus (syn. MYSV), either the whole S RNA, or the N and NSs genes separately, could be amplified.

A one-step RT—PCR system for the simultaneous detection and identification of multiple tospoviruses in plants has recently been described (Uga and Tsuda 2005).

The L RNA is the most conserved of the tospovirus genome components and includes the conserved motifs of RNA dependent RNA polymerases. Chit *et al.* (2001a) designed two pairs of genus-specific RT—PCR primers which allowed amplification of tospoviruses from five different serogroups. They have also been shown to work with IYSV (LA McMichael, personal communication). Real-time RT—PCR has also been developed and shown to be a sensitive and reliable method of detection of TSWV in field samples from a range of plant species (Roberts *et a?.* 2000; Dietzgen *et al.* 2005) and thrips vectors (Boonham *eta?.* 2002).

Virus diversity

TSWV is recognised as one of the most variable plant viruses and exists in nature as a heterogeneous population of isolates with the capacity to generate new variants (phenotypes) more readily than most other plant viruses (Moyer and Qiu 1996; Sherwood *at al.* 2000). This biological diversity was evident during early work in Australia. Norris (1946) described five strains selected from field-collected isolates while Best and Gallus (1953) isolated several stable variants from a single thrips inoculation site, which suggested that TS\VV occurred naturally as a heterogeneous complex population of genetic variants (Moyer and Qiu 1996). The inheritance of resistance to four TSWV strains in tomato, *Lycopersicon pimpinellifilium* and *L. peruvianum* was investigated by Finlay (1952, 1953). Both Finlay and Best (1954) developed hypotheses to explain the diversity of phenotypes observed in their work, with Best (1961) making the perceptive conclusion that new strains may have arisen ‘by some process of genetic hybridisation and that the nucleic acid determined the virus-specific protein on the one hand and the biological behaviour on the other’. It is now recognised that genomic reassortment or recombination is an important mechanism for the development of new strains of TS\VV, including adaptation of the virus to resistant hosts (Qiu *eta?.* 1998; Qui and Moyer 1999).

A major consequence of the biological diversity of TSWV is an enhanced capacity to rapidly develop variants that overcome resistance genes deployed for virus control (Moyer and Qiu 1996). In Australia, Latham and Jones (1998) and Thomas-Carroll and Jones (2003) isolated and maintained stable variants that were able to overcome the TSWV resistance genes in tomato *(Sw-5)* and capsicum *(Tsw)* following serial passage of isolates from diverse sources through resistant genotypes by sap inoculation. Field isolates virulent on capsicum cultivars with the *Tsw* resistance gene were identified from the Virginia vegetable production area of South Australia, '-'12 months after the introduction of TSWV-resistant cultivars to combat a major virus problem in glasshouse-grown capsicum crops. The N gene sequence of two resistance-breaking isolates was determined (GenBank AY818320 and AY818321) and found to have high sequence identity to standard TSWV isolates (Persley *at al.* 2002; Sharman and Persley 2005). A Tsw-resistance breaking strain has also been reported from Italy (Roggero *et al.* 2002). Both the Australian and Italian field isolates and those generated through serial sap transmission overcame *only the* resistance source *(Tsw or Sw-S* gene) used to generate the variants. Although there are phenotypic and genetic similarities between TSWV resistance in capsicum and tomato, the *Tsw* and *Sw-S* genes are distinct. The ability of TS\VV isolates to overcome resistance conferred by the *Tsw* gene was mapped to the S RNA and for the *Sw-S* gene to the M RNA (Hoffmann *et al.* 2001; Jahn *et al.* 2000).

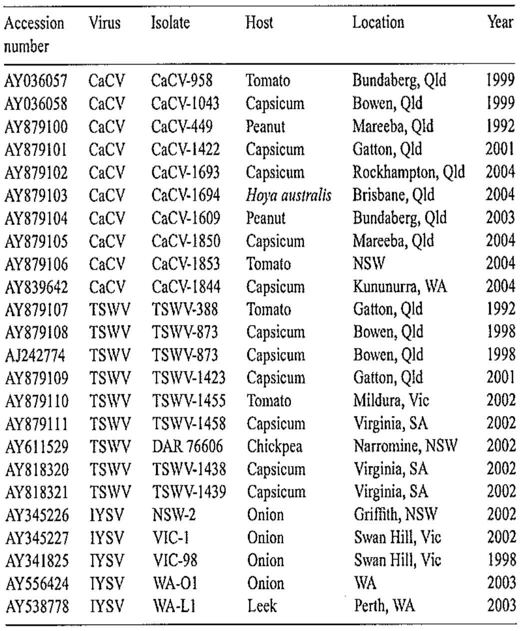
Until recently, only limited tospovirus sequence data, all from the N gene, has been reported for Australian isolates. This includes five isolates of IYSV (Coutts *et al. 2003b* and GenEank AY556424, AY538778), two of CaCV (McMichael *et al.* 2002) and one of TSWV (Roberts *et a?.* 2000 and GenBank AY879108—same isolate). This has, however, been extended by recent work with complete N gene sequences of eight additional isolates of CaCV and seven of TSWV (Table 3; M Sharman, unpublished data), and 29 partial N gene sequences of TSWV (Dietzgen *et a?.* 2005). The complete N gene amino acid sequences of eight Australian isolates of TSWV, from a range of hosts and geographical areas and collected over 10 years, and including Tsw-resistance breaking strains, were >98% identical. When these comparisons were extended to include overseas isolates analysed by Tsompana *et al.* (2005), similar geographical groupings were evident (Fig. 2). All Australian isolates grouped on a branch that contained Tsompana et *al.'s* clade of northern European isolates. Their clade contained 10/13 isolates from northern Europe, two from North Carolina (US) and one from South Africa, the latter three implying gene flow from Europe (Tsompana *et a?.* 2005). Our extended analysis adds the eight Australian isolates and one Korean isolate to this clade. This could suggest that TSWV in Australia originated from the importation of plant material from Europe in the early days of European colonisation. Dietzgen *et al.* (2005) also examined isolates from diverse crops and geographical locations, including &v-S and *Tsw* resistance-breaking strains. These showed a maximum of only 4.3% nucleotide sequence difference, and phylogenetic analysis revealed no obvious groupings of isolates according to host species or geographic origin within Australia.

Isolates of CaCV from capsicum, tomato, peanut and *Hoya* in Australia appear to be genetically fairly uniform, with N gene amino acid identities >96.5% in a comparison of 10 isolates. Interestingly, it is now apparent that CaCV also occurs overseas, in Thailand, Taiwan and possibly the USA. By serial passage and culture at elevated temperatures, a serogroup *TV* tospovirus was isolated from a gloxinia *(Sinningia speciosa)* plant, initially thought to contain only a defective form of 1NSV (Lawson *et al.* 1993, 1994). Further serological and molecular characterisation showed the virus to be a novel member of serogroup IV and it was designated gloxinia HT-1 tospovirus (Hsu *et al,* 2000). Serogroup IV tospoviruses have been isolated from tomato (Pongsapich and Chiemsombat 2002, Genl3ank AY626762, AF134400, AY846366) and peanut (GenBank AY661553, DQ022745) in Thailand. The N gene of these isolates and a further gloxinia isolate from Taiwan (Gloxinia ringspot virus, AY312061) are 91—99% identical to that of CaCV-958 at the amino acid level and, thus should be considered isolates of the same virus (Fig. 3). The appropriate name for this virus is somewhat problematic. The molecular characterisation of CaCV and gloxinia HT-I tospovirus was carried out independently, at approximately the same time. As noted by Hsu *et al.* (2000), gloxinia HT-I tospovirus 'was recognised and identified as a laboratory isolate only after propagation at elevated temperatures from INSV inoculum, originally obtained from gloxinia'. We suggest that the name 'Capsicum chlorosis virus' is preferred, as it describes field symptoms in plants naturally-infected with this virus only. When isolates from Australia, Thailand and USA were compared, all were closely related, except for one from Thailand from tomato (AF134400), which formed a separate sister clade on the phylogenetic tree. Nevertheless, this latter virus would still be considered an isolate of CaCV, as according to current guidelines of the International Committee for the Taxonomy of Viruses, N gene amino acid identities of ≥90% imply isolates of the same tospovirus (Nichol *et al.* 2005).

The origin of CaCV is unclear, but is unlikely to be Australia. The vector species confirmed so far are *Ceratothripoides claratris, Thrips palmi* and *Frankliniella schultzei,* two of which are native to Southeast Asia. Though found in field plants in Australia and Thailand, most known natural hosts, i.e. tomato, capsicum, chilli and peanut, are all of Central and/or South American origin. Only the *Hoya* spp. are endemic Australian species. Interestingly, though gloxinia has a worldwide distribution due to the floriculture industry, it also originated in Brazil. However, despite extensive research on tospoviruses in Argentina and Brazil (Bezerra *et al.* 1999; de Avila *et al.* 1993; Dewey *et al.* 1996b; Gracia *et al.* 1999; Pozzer *et al.* 1999), CaCV has not been detected there.

When a phylogenetic analysis was done on the amino acid sequences of the N gene of all available IYSV isolates, those from Australia were all practically identical (Fig. 4), despite originating in three different States. This may indicate a single or very limited recent introduction into Australia, followed by minimal divergence.

Table 3. **Tospovirus sequences from Australia detailing GenBank accession code, virus acronym, isolate name, original host, collection location (see Fig. 1 for map) and collection year**



Accession number	Virus	Isolate	Host	Location	Year
AY036057	CaCV	CaCV-958	Tomato	Bundaberg, Qld	1999
AY036058	CaCV	CaCV-1043	Capsicum	Bowen, Qld	1999
AY879100	CaCV	CaCV-449	Peanut	Mareeba, Qld	1992
AY879101	CaCV	CaCV-1422	Capsicum	Gatton, Qld	2001
AY879102	CaCV	CaCV-1693	Capsicum	Rockhampton, Qld	2004
AY879103	CaCV	CaCV-1694	*Hoya australis*	Brisbane, Qld	2004
AY879104	CaCV	CaCV-1609	Peanut	Bundaberg, Qld	2003
AY879105	CaCV	CaCV-1850	Capsicum	Mareeba, Qld	2004
AY879106	CaCV	CaCV-1853	Tomato	NSW	2004
AY839642	CaCV	CaCV-1844	Capsicum	Kununurra, WA	2004
AY879107	TSWV	TSWV-388	Tomato	Gatton, Qld	1992
AY879108	TSWV	TSWV-873	Capsicum	Bowen, Qld	1998
AJ242774	TSWV	TSWV-873	Capsicum	Bowen, Qld	1998
AY879109	TSWV	TSWV-1423	Capsicum	Gatton, Qld	2001
AY879110	TSWV	TSWV-1455	Tomato	Mildura, Vic	2002
AY879111	TSWV	TSWV-1458	Capsicum	Virginia, SA	2002
AY611529	TSWV	DAR 76606	Chickpea	Narromine, NSW	2002
AY818320	TSWV	TSWV-1438	Capsicum	Virginia, SA	2002
AY818321	TSWV	TSWV-1439	Capsicum	Virginia, SA	2002
AY345226	IYSV	NSW-2	Onion	Griffith, NSW	2002
AY345227	IYSV	VIC-1	Onion	Swan Hill, Vic	2002
AY341825	IYSV	VIC-98	Onion	Swan Hill, Vic	1998
AY556424	IYSV	WA-O1	Onion	WA	2003
AY538778	IYSV	WA-L1	Leek	Perth, WA	2003

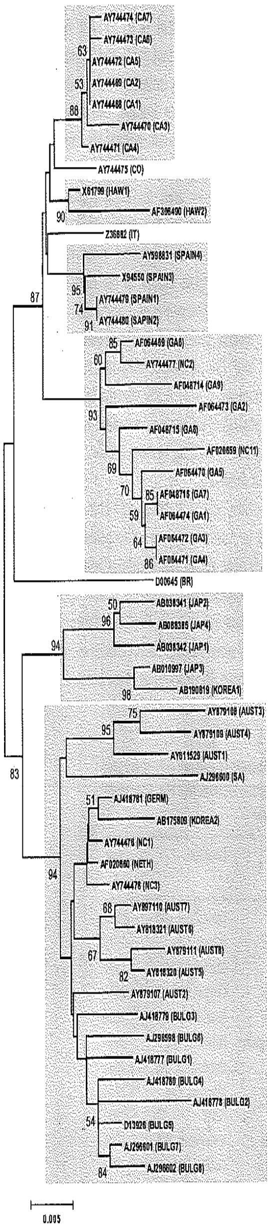


Fig. 2. Cladogram showing the relationship between TSWV N gene nucleotide sequences. GenBank accession numbers are shown for all. Abbreviations for location of origin adapted from (Tsompana *et al.* 2005) are: CA, California, CO, Colorado, HAW, Hawaii, GA, Georgia, NC, North Carolina, USA; IT, Italy; BR, Brazil; JAP, Japan; AUST, Australia; GERM, Germany; NETH, Netherlands; and BULG, Bulgaria. Five grey-shaded boxes indicate geographical sub-populations adapted from Tsompana *et al.* (2005) with an additional box for the Hawaiian isolates (see text for further details). Bootstrap values greater than 50% are indicated, scale bar indicates nucleotide substitutions per site (M Sharman, unpublished data).

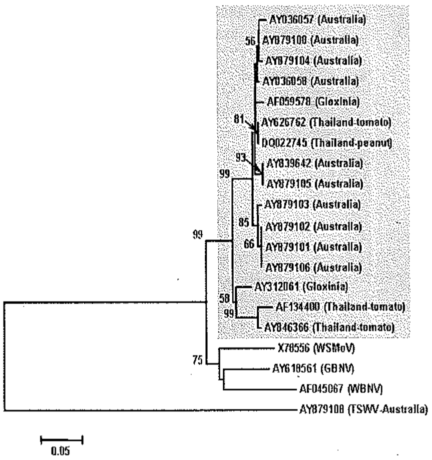


Fig. 3. Cladogram showing the relationship between the amino acid sequences of the N gene of CaCV isolates, shown in the shaded box with country of origin listed, and other serogroup IV members. GenBank accession codes are shown for all. TSWV is used as an outgroup. Bootstrap values greater than 50% are indicated, scale bar indicates amino acid substitutions per site (M Sharman, unpublished data).

Control

Despite considerable research and extension over the past decade on control measures for TSWV and other tospoviruses, these viruses continue to cause serious losses worldwide with the capacity to develop devastating outbreaks. The reasons for the difficulty in controlling tospoviruses include the wide host range of TSWV, the most widespread member of the genus, thus providing a very large number of alternative weed and crop hosts. Several different thrips species efficiently transmit tospoviruses, particularly the western flower thrips, which is widely distributed in both temperate and sub-tropical regions and has the capacity to rapidly develop resistance to many insecticides.

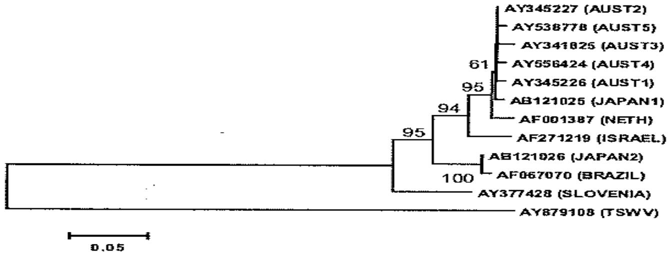


Fig. 4. Cladogram showing the relationship between the amino acid sequences of the N gene of IYSV isolates. GenBank accession code and country of origin are shown for all. Abbreviations: AUST1 to AUST5 are Australian isolates and NETH is from the Netherlands. TSWV is used as an outgroup. Bootstrap values greater than 50% are indicated, scale bar indicates amino acid substitutions per site (M Sharman, unpublished data).

Control through resistant cultivars has been hampered by the lack of resistance to tospoviruses among many important crop hosts and the ineffectiveness or lack of durability of some sources when used (Boiteux and Nagata 1993; Cho *et al.* 1996).

To be effective, control measures should be based on sound epidemiological principles (Jones 2004). There is a considerable body of information on the complex interactions between tospoviruses, their hosts and vectors, particularly for TSWV. The following information can be used as a basis for designing integrated disease management practices.

Tospoviruses are not seed borne nor spread by contact, but are transmitted through vegetative propagules such as tubers, corms, cuttings etc and seedling plants can be infected shortly after germination (Adkins 2003; Wilson 2001). TSWV has a very wide host range among crop, weed and ornamental species, thus providing many potential sources of inoculum. Most other tospovirus species, however, seem to have narrower host ranges and the role of alternative hosts in their epidemiology is not as clear.

Several vector species, for example, the western flower thrips, also have a broad host range which often overlaps with hosts of TSWV, allowing vectors to both breed and acquire virus for spread into, and within, crops (Ullman *et al.* 2002). Thrips vectors acquire virus in the first and early second larval stages and remain infected for life, allowing multiple transmissions by adult insects (Sherwood *et al.* 2000. Tospoviruses are persistent in thrips vectors and only relatively short feeding periods are necessary for transmission to the effect that many plants can be infected as a viruliferous thrips migrates through a crop.

Tospovirus spread in crops is often monocyclic with vectors introducing the virus into crops from outside sources, rather than establishing foci within crops with subsequent secondary spread (Coutts *et al.* 2004). This situation often leads to steep gradients of disease within crops with disease levels decreasing sharply as distance from external inoculum sources increases.

Crop species are most vulnerable to virus infection in the early growth stage and prevention of seedling infection is vital. This can be achieved by raising seedlings distant from the production areas in nurseries with a high standard of hygiene and, if applicable, in structures protected by thrips-proof netting or in tunnel houses (Jones 2004). Applying insecticides either directly to the soil or as a seedling drench prior to transplanting has shown considerable promise in reducing TSWV incidence, particularly during the early stages of crop growth. In Western Australia, Coutts *et al.* (2003a) and Coutts and Jones (2005) demonstrated significant reduction in TSWV levels in lettuce when seedling plants were drenched with the neonicotinyl insecticides thiomethoxam and imidacloprid that are effective against the early larval stage of thrips.

In field situations, a reduction in the rate of virus spread can be achieved through a range of cultural and agronomic measures. Separating plantings of susceptible crops by non- host barriers or fallow ground decreased the levels of TSWV in lettuce and capsicum in Western Australia, allowing calculation of safe planting distances for susceptible crops to reduce virus spread (Coutts *et al.* 2004). As expected, the highest rates of spread occurred when successive plantings of susceptible hosts were made side by side. The work of Coutts *et al.* (2004) suggests that a non-host barrier may be more effective than fallow ground between crops as some viruliferous thrips will land and colonise the non-host species rather than continue migration to the susceptible host. Other agronomic practices that decrease virus spread are planting crops up wind from inoculum sources and removal of virus-source plants; for example, harvested crops with virus infection or areas of infected alternative hosts (Wilson 1998; Coutts *et al.* 2004; Jones 2004). TSWV is a major problem in peanuts in south-eastern USA and virus incidence is influenced by agronomic practices such as plant population, planting date, row pattern and tillage systems with minimum tillage generally resulting in lower levels of TSWV compared with conventional tillage (Culbreath *et al.* 2003; Lanier *et al.* 2004).

Although thrips are vectors of all tospoviruses, the application of conventional insecticides as the sole or primary means of control is seldom effective (Cho *et al.* 1989; Ullman *et al.* 1997; Momol *et al.* 2004). Reasons for this include the short feeding periods required for transmission, the ability of adult viruliferous thrips to transmit throughout their life, the monocyclic nature of many epidemics with migrating thrips from outside a crop having a major role in spread, and the difficulty of insecticides in reaching the target insects in protected plant parts and pupating larvae in the soil. The rapid development of resistance to insecticides, especially by the western flower thrips, is also a contributing factor to the failure of conventional, foliar-applied insecticides in tospovirus control (Zhao *et al.* 1995). Recently developed chemicals such as the microbial insecticide Spinosad, a natural macrocyclic lactone with a unique mode of action and low mammalian toxicity, offer greater promise as part of integrated management strategies (Eger *et al.* 1998). The in-furrow application of the organophosphate insecticide phorate at planting has reduced TSWV levels in peanuts in the United States (Culbreath *et al.* 2003) and it is thought that the chemical may induce a host defense response or inhibit virus replication or movement (Gallo-Meagher *et al.* 2001). Acibenzolar-S-methyl (Aetigard) induces systemic acquired resistance against a broad range of pathogens and has reduced TSWV incidence in tobacco and tomato while giving in consistent results with peanut(Culbreath et al. 2003; Momol *et al.* 2004).

Alternative means of modifying thrips behaviour include UV reflective mulch in row crops such as capsicum and tomato (Terry 1997; Greer and Dole 2003) and the application of horticultural oils and film-forming products to plants (Allen *et al.* 1993). In intensive protected cropping situations, thrips exclusion netting has been used successfully. Biological control of vector species has also had some success; for example, the Montdorensis predatory mite *(Thyphlodremips montdorensis)* has successfully controlled T *tabaci* and F. *occidental is* in protected cropping situations in Australia (Steiner *et al.* 2003).

Resistant cultivars have had only a limited effect on the control of tospoviruses. The main reasons for this are the lack of resistant germplasm among many major hosts and the capacity of TSWV, in particular, to overcome resistance sources soon after their deployment (Moyer and Qiu 1996; Mumford *et al.* 1996a). Resistant cultivars are currently part of the control strategies for TSWV in capsicum, peanut and tomato (Cho *et al.* 1996; Roggero *et al.* 2002; Culbreath *et* a!. 2003). In peanut, a range of cultivars and breeding lines with varying levels of field resistance to TSWV are being increasingly used as part of an integrated disease management strategy in the south-eastern United States (Brown *et al.* 2005; Culbreath *et al.* 2003).

A significant amount of early work on the development of TSWV-resistant tomato cultivars was undertaken in Australia. Finlay (1953) designated two dominant genes and three recessive genes for resistance in *Lycopersicon pimpinellifolium,* while Hutton and Peak (1953) studied the development of TSWV in *L. pimpinellifolium,* the source of resistance in the Hawaiian resistant cv. 'Pearl Harbour' and in the L. *esculentum* cv. 'Rey de los Tempranos'. These workers considered the latter a more promising parent for the development of TSWV-resistant cultivars. Cho *et al.* (1998) has suggested several factors in the development of this material, including the lack of sensitive virus detection assays, the use of mechanical inoculations for screening, often with defective TSWV mutants, and the presence of many resistance-breaking virus strains, that contributed to the inconsistent performance of these lines and cultivars in Australia and elsewhere.

Stevens *et al.* (1994) also identified several sources of resistance in different *Lycopersicon* species. Of these, the *Sw-S* gene is more durable and specific than previously used genes, and is now the most widely used source (Stevens *et al.* 1992; Spassova *et al.* 2001). This gene was derived from L. *peruvianum* and introgressed into the fresh market cv. Stevens (Stevens *et al.* 1992). Resistance operates as a hypersensitive response preventing systemic movement of the virus within the host plant tissue. The *St'-S* gene is closely linked to the RLFP markers CT 220 and CT 71 and is located near the telomere of chromosome 9 of tomato (Stevens *et al.* 1995). The gene consists of two homologues and encodes a coiled-coil, nucleotide-binding leucine-rich repeat class (CC-NBS-LRR) resistance protein (Spassova *et a!.* 2001). The *Sw-5* locus has been shown to be a homologue of the root-knot nematode resistance gene *Mi* (Brommonschenkel *et al* 2000). The *Sw-S* locus is effective against many TSWV isolates (Cho *at a!.* 1996; Roselló *et al.* 1996) and also provides resistance against two other tospoviruses infecting tomato, *Groundnut ringspot virus* and *Tomato chlorotic spot virus* (Boiteux and Giordano 1993; Brommonschenkel *et al.* 2000).

Although useful resistance to TSWV has not been found in *Capsicum annuum* germplasm, resistance operating as a hypersensitive response and controlled by the single dominant gene *Tm',* has been found in the *C. chinense* accessions P1 152225 and P1 159236 (Black *et a!.* 1991; Boiteux 1995; Moury *et al.* 1997; Soler *et al.* 1999). The *Tsw* gene has been mapped to the distal portion of chromosome 10 (Jahn *et al.* 2000). Genetic studies have indicated that despite phenotypic and genetic similarities of resistance to TSWV in capsicum and tomato, distinct viral products control the outcome of infection in plants having the *Tsw* and Sw-S genes and the two genes do not appear to share a recent common evolutionary ancestor (Jahn *et al.* 2000). Capsicum cultivars incorporating this resistance are currently grown in several countries including Australia. The *Tsw* gene is not effective against several other tospoviruses, including CaCV (McMichael *et al.* 2002). However, resistance to CaCV has been found in several *C. chinense* accessions, including P1 290972, from which sub-lines were obtained by self-pollination of the original material and were resistant to several field isolates of CaCV. One of the sub-lines was resistant to both CaCV and TSWV, with the sources of resistance segregating independently (M Sharman, DM Persley and DJ McGrath, unpublished data). This TSWV resistance is overcome by a *Tsw* resistance- breaking strain, indicating that the source may in fact be *Tsw.* Both resistance sources have been transferred to elite bell capsicum lines with a third backcross generation now being produced (DJ McGrath, M Sharman and DM Persley, unpublished data).

The efficiency of selection for CaCV resistance in capsicum and TSWV resistance in tomato and capsicum has been enhanced by using molecular markers (Garland *et al.* 2005; Langella *et al.* 2004; Moury *et al.* 2000). In Queensland, a PCR-based marker specific for the *Sw-S* gene has been developed and successfully applied to the selection of TSWV-resistant individuals within a tomato breeding population (Garland *et al.* 2005).

It is recognised that TSWV can adapt and overcome resistance genes relatively easily (Qui and Moyer 1999), including the Sit'-S and *Tsw* genes (Aramburu and Marti 2003; Thomas-Carroll and Jones 2003; M Sharman and DM Persley, unpublished data). These resistances, however, can still have an important role in virus control if used as part of integrated disease management systems where excessive pressure is not applied by relying solely on resistance for virus control (Aramburu and Marti 2003; Jones 2004; Sharman and Persley 2005). There is an urgent need to identify new sources of resistance to TSWV and other tospoviruses in crops such as capsicum and tomato with a view to broadening the genetic base through gene pyramiding and other strategies. Cebolla-Cornejo *et al.* (2003) have also reported sources of resistance in capsicum, but information on the relationship to the *Tsw* gene is not available.

An alternative or complementary resistance strategy is through host resistance to thrips. Reduced spread of GBNV in the peanut cultivar Robut 33—1 was attributed to lower numbers of thrips infesting plants of this cultivar (Reddy *et al* 1983). Varying levels of resistance to western flower thrips was found among *Capsicum* lines and correlated with a reduction in TSWV spread in resistant accessions (Mans *et a!.* 2003). The potato cv. Bismark expresses field resistance to TSWV through resistance to thrips feeding, but is susceptible following sap inoculation (Jericho and Wilson 2003).

Genetic transformation of plants with the nucleocapsid (N) gene or NSm gene has been achieved in several important hosts of TSWV, including tobacco, tomato and peanut (Culbreath *et al.* 2003; Gubba *et al.* 2002; Herrero *et al.* 2000; Jan *et a!.* 2003). Although there appears to be limited field testing of transformed plants, tomato hybrids developed from a transformed line were highly resistant to TSWV when tested in Italy (Accotto *et al.* 2005). With the aim of reducing the high specificity of RNA-mediated resistance, Jan *et al.* (2003) demonstrated resistance to several tospoviruses by transforming plants with a chimeric construct containing segments of different viral genes that were linked to a universal silencer DNA. Broad spectrum resistance to tospoviruses has recently been achieved in transgenic tobacco carrying the conserved region of the L protein of WSMoV (Yeh *et al.* 2005).

The application of plantibody-mediated resistance may also be a practical future means of control with Prins *et al.* (2005) conferring resistance to TSWV with the stable and high expression of phage display-derived single-chain antibodies in *Nicotiana benthanilana.*

These approaches should provide greater opportunity to develop durable resistance to tospoviruses, particularly in the many hosts where conventional resistance genes have not been found.

Control measures are aimed at preventing the entry of virus or reducing spread of virus within a crop. The strategies offering most success aim to integrate a range of phytosanitary, cultural resistance and chemical methods to target vulnerable stages of the virus/vector/crop cycle (Jones 2004).

Discussion and future research

Four tospoviruses have been found in Australia; TSWV, CaCV, IYSV and a tospovirus from the native orchid *Pterostylis.* TSWV, first described from Australia (Samuel *et al.* 1930), remains the most widespread and damaging with sporadic major epidemics inmost States during recent years, The crops at most risk are capsicum, lettuce, tomato and potato. However, the recent report of the virus as a cause of chickpea dieback in Queensland and NSW (Thomas *et a!.* 2004), and the increasing incidence of TSWV in peanuts in south Queensland suggest that the virus may become increasingly important in grain legume crops over a wide geographic range. Therefore, these crops should be monitored on a regular basis for the presence of TSWV and preventative measures put in place to reduce potential crop losses.

CaCV first found in Queensland in 1999 (McMichael *et al.* 2000), is now present in all vegetable production areas of the State, where it infects capsicum and tomato. The virus has been detected in peanut crops at Bundaberg over three seasons and has the potential to become a significant disease in the expanding areas of this crop in the region. CaCV has recently been found at two diverse locations outside of Queensland, Kununurra in the East Kimberley region of Western Australia and the central coast of NSW. These records suggest that the virus maybe present throughout northern Australia and along the eastern seaboard of Queensland and much of NSW The virus is also present in Thailand and Taiwan and, as a member of the Eurasian cluster of tospoviruses (Hassani-Mehraban *et al. 2005),* it most likely has a much broader distribution in crops such as capsicums, tomato and peanut in southeast Asia. The known vectors are *T palmi* and F *schultzei* in Australia and *C, calartris* in Thailand and the distribution of the virus may well overlap the natural range of these vector species.

Further work is required to determine other possible vector species for CaCV.

IYSV has recently been detected from onion crops at several locations in Western Australia, Victoria and New South Wales, suggesting a wide distribution in all Australian onion production areas (Coutts *et al. 2003b).* The virus has probably been present for some years with symptoms sometimes attributed to factors such as iron chlorosis or nutrient deficiencies. Given the increasing importance of IYSV in USA, Israel and South America, the distribution and effect of the virus needs to be monitored in Australia in both onion bulb and seed crops and in other *Allianz* species.

Although there has been considerable work in the last decade in Australia on the control of tospovirus insect vectors such as the V/FT and other species using insecticides and other means, often supported through the National Strategy for the Management of Western Flower Thrips and TSWV, little experimental work has been done for several decades on demonstrating transmission of tospoviruses by particular species and in confirming observations made concerning the presence of vector species during virus outbreaks by transmission experiments. In work with Australian tospovirus isolates, and local vector populations, Sharman (unpublished data) has demonstrated transmission of TSWV by *F occidentalis, F schultzei* and T *palmi.* Transmission of CaCV by T *palmi* and *F schultzei* has also been demonstrated. Although T *tabaci* has long been recorded as a vector of TSWV, the ability and efficiency of Australian populations to transmit local isolates needs to be examined. This species is the only known vector of IYSV and this requires confirmation with Australian isolates.

Excellent advances have been made in understanding the epidemiology and control of tospoviruses in Australia, and some resistance sources are available. However, with the continued spread of different thrips vector populations, increased world trade and the increased difficulty in maintaining quarantine barriers, it is likely that tospoviruses will continue to increase in importance in Australia. For example, the thrips *F intonsa,* a known tospovirus vector, is a common contaminant of nursery stock entering Australia (Mound 2002). The current knowledge of tospovirus diversity and the availability of a range of molecular and serological assays for members of this genus make it likely that more species will be found in Australia. A potential increase in the number of thrips vector species becoming established in Australia, coupled with a paucity of durable disease resistances will almost certainly pose a challenge to Australian agricultural and horticultural industries for some time to come. It will be a continuing challenge to develop and implement effective disease management strategies to reduce economic losses due to tospoviruses.

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Chapter 4

Silverleaf Whitefly

FUTURE RESEARCH DIRECTIONS – SLW.

1. DISPERSAL CONTROL.

Silverleaf whitefly (SLW) dispersal from neighbouring crops or from infested crop residues is the major source of SLW invasion in vegetable production areas.

a. Identify workable, "cost-effective' dispersal control strategies.
b. Crop hygiene /cleanup measures need to be improved – simply ploughing in residues is not sufficient. Carry out trial work to quantify the effect of spraying off SLW infested crop residue with several carefully selected knockdown insecticide and herbicide products, such as "Spray Seed®". Quantify the effect this has on dispersal, compared to simply ploughing in crop residue. Products should be chosen carefully with the cost of the treatments compared and results communicated clearly and concisely to growers.
c. Dispersal effects created by the various treatments should be measured, documented, and communicated to growers.

2. EXTENSION / EDUCATION ACTIVITIES.

Research and grower education on certain SLW insecticides remains a priority to ensure these tools deliver maximum benefit. Key candidates for this type of research and extension under Australian conditions are the IGR pyriproxyfen, and the soon-to-be-registered lipid biosynthesis inhibitor spirotetramat (Movento®). Pegasus® should also be considered – refer to point three.

3. SOFT OPTION PRODUCTS.

The unique mode of action product diafenthiuron (Syngenta: Pegasus®) is only registered for SLW and aphid control in cotton. The barriers to possible registration for use against SLW in vegetables should be discussed with the manufacturers, APVMA and industry bodies. It is an important SLW management option for vegetables.

4. FORECAST MODELS.

Develop population models based on increased use of climate/season-based risk assessments to guide deployment of prophylactic soil-applied insecticides, and guide timely application of the newer slow acting IGRs to maximise SLW control. Greater awareness of climatic factors influencing SLW risk could assist some growers to identify when prophylactic imidacloprid application could be avoided (or most needed) at planting. This would benefit resistance management, production costs and should be pursued on an area wide basis.

5. **EDUCATION and COLABORATION**.
a. Invest in relationships, structures and agreements to deliver best practice regional SLW management.
b. In some regions, a high degree of mutual understanding, co-operation and agreement will be required between competing vegetable growers and/or different commodities (e.g. melons and cotton) to effectively manage SLW populations and delay the development of insecticide resistance. Therefore significant effort and resources should be devoted to developing relationships, structures and agreements that will facilitate the best possible outcomes for all sectors. Greater co-operation between the grains/cotton and horticultural industries would be desirable in regions where cross-commodity issues are identified as significant barriers to progress in regional SLW management.

6. **VIRUS VECTOR RECOGNITION**
Recognition of SLW as a vector of begomoviruses.

Industry need to be conscious of the fact that SLW is a vector of begomoviruses which pose a significant threat to both the vegetable and field crops industries. Tomato yellow leaf curl virus is now present in Queensland and many viruses in this group are widespread throughout south east Asia.

7. **ADAPTATION OF EXISTING KNOWLEDGE**.
Adapt population growth models and the 'population management threshold' concept as used in cotton to vegetable production systems
The potential for applying and refining/validating the cotton industry's decision support models for SLW management ought to be investigated within vegetable cropping regions. A different tack may need to be taken due to multiple cropping of different crops on a continual basis in the production season. There may still be value in forecasting, or advising growers when optimum SLW breeding conditions are expected. You could possible predict a" window of maximum activity".
It must be remembered that cotton is concerned about lint contamination while many vegetable crops have physiological responses at very low densities, so thresholds etc may be very different.

Note:

a. .Integration of many of the overlapping future research area directions highlighted for each of the sucking pest groups reviewed should be encouraged in new research projects.
b. Ensure cross discipline integration in appropriate areas. The proposed IPM co-ordinator to be appointed by HAL should play a key role in this.

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Silverleaf Whitefly

Silverleaf whitefly *Bemisia tabaci* biotype B (Gennadius)
(Hemiptera: Aleyrodidae)

by: Austin McLennan

Introduction

Since its accidental introduction in the early 1990s, exotic silverleaf whitefly (*Bemisia tabaci* biotype B (Gennadius)) has become regarded as a serious pest of vegetable and other crops in northern Australia.

This review is not concerned with the other two whiteflies that can occur in Australian vegetable crops: native *Bemisia tabaci* and the greenhouse whitefly *Trialeurodes vaporariorum.* Once exotic silverleaf whitefly invades an area, it is known to displace native whitefly following an outbreak (de Barro 2006a). Greenhouse whitefly is not as concerning a field pest as exotic silverleaf whitefly because it is easily controlled by currently registered insecticides.

The international published literature uses two scientific names to refer to the biotype of exotic silverleaf whitefly found in Australia (biotype B). The Australian convention is to refer to this biotype as silverleaf whitefly (often abbreviated as SLW) or *Bemisia tabaci* biotype B *(Gennadius).* In contrast, US researchers frequently use the names sweetpotato whitefly and *Bemisia argentifolii.* This review follows the Australian usage.

SLW in Australia – early 1990s to present

Exotic SLW arrived in Australia with pre-developed resistance to many insecticide groups and a reputation for rapidly developing insecticide resistance to others. Its short generation time under hot conditions and high fecundity make it capable of rapidly producing massive outbreaks. By the early-mid 2000s, vegetable growers in Queensland had experienced several outbreaks of SLW, with significant damage to crops and increased insect control costs across a range of horticultural crops. Affected districts ranged from the Lockyer Valley in southeast Queensland to Bundaberg and Bowen districts in the north of the state.

In broad acre crops, soybean and cotton growers were also severely affected, particularly in central Queensland in 2002. In subsequent seasons there has been a problem as far south as St George and the Darling Downs. SLW is also an established pest in Western Australia in the Perth and Carnarvon areas where it is mostly of concern in protected cropping systems. It has not to date been detected in the Kimberley region. To protect the Kimberley region from SLW being introduced from other parts of WA, various plant/produce movement restrictions have been proposed (DAFWA 2008).

Recent seasons in the eastern states have caused some horticulturalists to hope that SLW has stabilised at a lower mean population since the initial outbreaks. Certainly, SLW has not been a significant problem in the Lockyer Valley, Bundaberg and Bowen horticultural areas of Queensland since about 2004-05 (as at March 2008).

Possible reasons for this reduced incidence of SLW include (B. Nolan, *pers. comm.*; R. Sequeira, CRDC SLW workshop 2006):

- A major drought that has impacted greatly on host availability (both crop and non-crop) of SLW throughout the summer period.
- The widespread prophylactic use in horticulture of imidacloprid to protect vegetable transplants, thus also limiting subsequent SLW population build up.
- The impact of various natural enemies (both native and exotic predators and parasitoids), perhaps enhanced because of a SLW population already suppressed within districts by insecticide usage, drought and climate (i.e. cooler temperatures).
- The widespread establishment of the introduced SLW parasitoid, *Eretmocerus hayati,* which has been detected parasitising at times in excess of 80-90% of SLW nymphs, in all production areas.

There is no guarantee that SLW populations will continue to persist at current low levels, particularly if rainfall driving host availability coincides with high temperatures favourable to rapid development of SLW.

For this reason, it is essential that Australian vegetable growers in areas at risk from SLW have a range of strategies available to them for avoiding and/or managing this pest should conditions favourable for its increase return.

Purpose of this review

Due to the proven ability of SLW to rapidly acquire resistance to a broad range of insecticides, SLW management strategies are highly vulnerable if they rely mainly on chemical control.

Unfortunately, this reflects the current situation in Australian vegetable crops where the prophylactic use of imidacloprid is widespread and arguably the key component of SLW management. While imidacloprid is currently effective, it is likely that its continued and widespread use will eventually render it less effective against SLW due to resistance.

Overseas experience with another SLW biotype (biotype Q) highlights the risk of relying on imidacloprid (or any chemical) should a new SLW biotype breach Australian quarantine. Specimens of Q-biotype silverleaf whitefly collected from poinsettia plants in Arizona in 2004 were characterized as being “virtually immune to the IGR pyriproxyfen, having greatly reduced susceptibility to the IGR buprofezin and a reduced susceptibility to the neonicotinoid insecticides imidacloprid, acetamiprid and thiamethoxam” (Mid Florida Research and Education Centre 2008; Dennehy 2008).

Given the need to expand our SLW management toolkit, the purpose of this review is threefold:

- To review the current level of knowledge about management options for SLW based on both the Australian experience and the published international literature.
- To identify aspects of current SLW management in the Australian context that could be improved by the integration of this knowledge.
- To identify a suite of new SLW management options/strategies for testing in the Australian context that, if proven/adopted, would have prospects for improving management of SLW in vegetable crops.

Biology, ecology and pest status

Since it is the underlying biology and ecology of a species that ultimately causes it to become an agricultural pest, understanding these attributes is the key to developing successful IPM approaches. Amongst SLW's key pest attributes are its wide host range, its ability to rapidly multiply under favourable conditions (esp. high temperatures), and its proven ability to develop resistance to many chemical insecticides.

Broad host range

Not only does SLW whitefly attack a wide variety of crop plants including various vegetable crops (Appendix A), it also develops on a number of weed species. A comprehensive draft host list of crop and weed hosts has been recently developed by WA researchers to assist in implementing quarantine measures (DAFWA 2008a).

In an Australian study, Lea & Franzman (1998) compared the development of silverleaf whitefly on conventional and transgenic (*Bt*) cotton, lucerne, pigeon pea and sowthistle. They found that sowthistle was a very good host of SLW and postulated this may be the case for other weed species common to cotton cropping areas. Pigeon pea was the least favourable host in this study.

In cotton agroecosystems, sowthistle and lucerne are prevalent over winter when other hosts may not be available, thus providing the possibility for substantial populations to persist between cropping seasons. However, these concerns may not be as relevant to northern Australian vegetable production areas where most vegetable production occurs in the winter.

Thus, in vegetable production areas, one possibility is that lucerne and winter weeds could act as a diluting influence on the overall whitefly population. A negative alternative is that they could instead be a source of SLW build-up, without the constraints imposed by chemical control. A further hypothesis is that lucerne and non-crop weed hosts could, on balance, be more important as a source of natural enemies for SLW and other pests than as a source of SLW. In the Emerald Irrigation Area of central Queensland, off-farm broadleaved weeds are considered an important stabilising component of the SLW population by providing a continuous source of beneficial insect populations, in particular the parasitoid wasps *Eretmocerus* and *Encarsia* spp. (R. Sequeira, CRDC SLW Workshop 2006).

Naranjo *et al.* (2004) have shown from their recent studies in Arizona how some of these ecological questions about the role of crop and non-crop hosts can be addressed by detailed life table studies. They determined, where possible, the relative importance of natural enemy, chemical and abiotic causes of SLW mortality for the various host plants. Sauvion *et al*. (2005), while looking at the potential impact of aphid resistance genes in melons on SLW rate of increase, describe a statistical method that may be useful in such life table studies.

Naranjo *et al.* (2004) contend that, because SLW is a multiple-crop pest, the development of sustainable, ecologically-based management strategies depends on a mechanistic understanding of the factors governing pest population development in the mosaic of host crops and wild hosts available throughout the year. An important conclusion of this work is that the relative survival of SLW on various hosts (and thus the relative importance of these hosts in driving SLW abundance) will vary from region to region.

Rapid population growth

The key role of temperature in driving population increase of the desert-loving SLW is reasonably well understood. This means that growers, advisors and researchers have some ability to predict their SLW risk in a given climate scenario.

The key factors that temperature drives are;

- The number of generations per year, and thus the potential for exponential population increase.
- The length of longest generation, and thus overwintering mortality.

(de Barro 2006a)

With temperature the primary driver of SLW population growth and rate of increase, risk assessments have been provided for a range of horticultural and cotton/grain production areas for SLW. The SLW risk is generally highest in areas that are hottest.

Under present climate conditions there is a nil-low risk of SLW outbreaks in southern Australia horticultural areas, i.e. from approximately central NSW – south. The exception to this is greenhouse production systems where temperatures are artificially raised, thus increasing SLW risk. Therefore, in the Sydney basin, SLW populations in field–grown vegetables are not regarded as high and of concern, though they are noted to increase in the field over summer and can be of concern in greenhouse production (DPI&F Vegetable sucking pest workshop participants, *pers. comm.* 2007).

SLW risk modelling suggests that those areas with an average of at least 9-10 generations per year and the shortest 'longest generation' (i.e. warmest winters) are predicted to have the highest risk of SLW outbreaks (de Barro 2002).

Table 1 below highlights these regional differences as applied to the Australian situation, as does Table 2 with some updated predictions, additions and omissions.

Predicted climate change over the coming decades will increase the southerly geographical range of SLW, and thus the likelihood of outbreaks further south. An anticipated 1-2^{o}C increase over the next 40-50 years is predicted to produce an extra 1-2 generations per year: i.e. one extra generation per year per degree Celsius rise in temperature (de Barro 2006a).

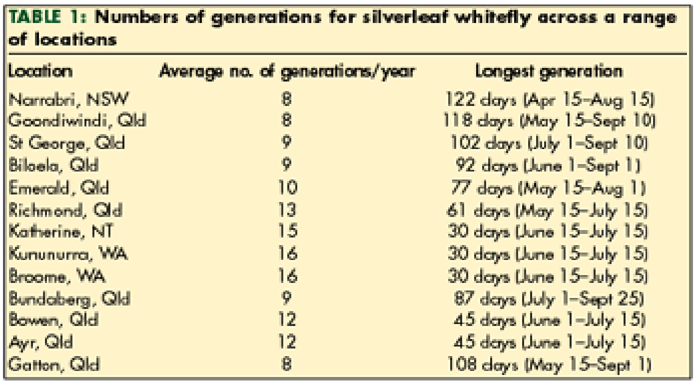

TABLE 1: Numbers of generations for silverleaf whitefly across a range of locations

Location	Average no. of generations/year	Longest generation
Narrabri, NSW	8	122 days (Apr 15–Aug 15)
Goondiwindi, Qld	8	118 days (May 15–Sept 10)
St George, Qld	9	102 days (July 1–Sept 10)
Biloela, Qld	9	92 days (June 1–Sept 1)
Emerald, Qld	10	77 days (May 15–Aug 1)
Richmond, Qld	13	61 days (May 15–July 15)
Katherine, NT	15	30 days (June 15–July 15)
Kununurra, WA	16	30 days (June 15–July 15)
Broome, WA	16	30 days (June 15–July 15)
Bundaberg, Qld	9	87 days (July 1–Sept 25)
Bowen, Qld	12	45 days (June 1–July 15)
Ayr, Qld	12	45 days (June 1–July 15)
Gatton, Qld	8	108 days (May 15–Sept 1)

From de Barro, The Australian Cotton Grower (2002).

Table 2. Numbers of generations for *B. tabaci* biotype B across a range of locations. From de Barro 2006a.

Location	**Generations, Oct – Mar* Mar – Oct ** Mar –Dec*****	**Generations per Year**	**Longest Generation (days, approx)**	
Narrabri*	4-7 (6)	6-9 (8)	122 days	15 Apr - 15 Aug
Goondiwindi*	5-8 (6)	7-10 (8)	118 days	15 May - 10 Sept
Gatton***	4-7 (6)	7-10 (9)	108 days	15 May – 1 Sept
St George*	5-8 (7)	7-11 (9)	102 days	1 Jun - 10 Sept
Biloela*	6-8 (7)	7-11 (9)	92 days	1 Jun - 1 Sept
Bundaberg***	5-7 (6)	7-11 (9)	87 days	1 Jul – 25 Sept
Emerald*	6-8 (7)	9-12 (10)	77 days	15 May - 1 Aug
Bowen***	7-11 (9)	10-14 (12)	45 days	1 Jun – 15 Jul
Ayr***	7-11 (9)	10-14 (12)	45 days	1 Jun – 15 Jul

However, while this model predicts the likelihood of SLW outbreaks based on climatic factors, it doesn't take into account how timing of the maximum predicted whitefly population relates to maximum crop risk and host availability.

For example, the prediction that Katherine in the Northern Territory would experience 15 whitefly generations in an average year means that outbreaks should be an almost annual occurrence. The reality is that susceptible crops at Katherine are grown in the dry season, or the cooler part of the year, when whitefly populations are at their lowest. Thus, it is typically only at the beginning of the cropping season (i.e. coming out of summer) or the end (i.e. as temperatures are increasing coming into summer) when SLW numbers may be of concern in such a region (B. Thistleton, *pers. comm.*).

Rapid development of insecticide resistance

The ability of SLW to develop resistance to many chemical insecticides is well documented. SLW arrived in Australia with resistance to synthetic pyrethroids, organophosphates, carbamates and insect growth regulators. Since its arrival, SLW in horticulture has developed measurable resistance to endosulfan, amitraz, bifenthrin and imidacloprid (R. Gunning, CRDC SLW workshop 2006). Dr Gunning also advises that the rate of resistance development in SLW is rapid, and that two consecutive sprays of the same product can be sufficient to increase resistance factors (CRDC SLW workshop 2006).

Such is this ability of SLW to develop resistance that even relatively new compounds like the insect growth regulator pyriproxyfen (Admiral®) are at risk. US researchers have concluded that rapid evolution of resistance to pyriproxyfen could occur if individuals in field populations with traits similar to those of their laboratory-selected strain were treated intensively with this insecticide (Crowder *et al.* 2007). There is now a new permit for pyriproxyfen in some Australian vegetable crops (cucurbits, eggplant, tomato), but it is also the main SLW product used in cotton. Cross resistance has been demonstrated between IGRs in SLW (R. Gunning, CRDC SLW workshop 2006).

Resistance levels to pyriproxyfen in Australia have remained low to date (R. Gunning, CRDC SLW workshop 2006), but there are now unpublished data suggesting significant increases starting to occur (D. Murray, *pers. comm.* June 2008). If true, continued monitoring will confirm this situation and require a response from the local industries.

Modes of damage

Not only does silverleaf whitefly infest a wide array of broadleaf vegetable crops, but it damages crops in a variety of ways. These different modes of damage are by:

1. Direct feeding – direct stress on the plant caused by the sucking/removal of plant resources by large numbers of nymphs and adults
2. Honeydew and sooty mould contamination – also a potential result of high densities of SLW feeding.
3. Host-specific physiological reactions to toxic saliva – some vegetable crops exhibit extreme physiological reactions to SLW feeding. In particular this refers to the silverleafing that occurs in many cucurbits (Costa *et al.* 1993; Jemenez *et al.* 1995) and uneven ripening in tomatoes (McCollum *et al.* 2004).
4. Virus transmission. In Australia this is mainly an issue for tomatoes, with two geminiviruses present in the country, ATLCV (Australian Tomato Leaf Curl virus) and the recently introduced TYLCV (Tomato Yellow Leaf Curl virus). TYLCV is of most concern. Silverleaf whiteflies need to feed on infected plants for at least 15 minutes to acquire TYLCV and then feed on another host plant for 15 to 30 minutes to transmit the virus. Transmission efficiency increases as the duration of feeding times increases. Although the transmission efficiency of individual insects may be low, where enormous populations of SLW are moving within and between crops, this can result in rapid spread and high disease levels. Research results are inconclusive, but TYLCV is probably not carried from generation to generation through the SLW egg. Hosts of TYLCV include two symptomless crop hosts, capsicums and beans, plus various weed hosts (DPI&F 2007a).

Table 1 in Appendix A outlines the host range, pest status, and main types of damage inflicted by SLW for a range of key Australian vegetable crops.

These four different modes of damage have an important bearing on potential approaches to SLW control:

- In crops where the priority is to avoid direct feeding and honeydew issues, population management/suppression is the key i.e. as long as high populations are avoided, damage will not result.
- For the two types of damage where high populations are not required for crop damage to occur (physiological reactions and virus transmission), approaches

that focus on reducing the symptoms will have merit, rather than a sole focus on SLW population reduction. Such symptom-reducing strategies could include:

- *Selection for feeding tolerance in vegetable varieties.*
- *Breeding for virus resistance.*
- *Delaying time to virus infection.*

Selection for feeding tolerance
Feeding tolerance is only one aspect of host plant resistance (HPR). While HPR traits are often associated with rendering the plant a less attractive or suitable host for development, a plant with feeding tolerance to SLW may remain a suitable host, yet have a reduced sensitivity to the effects of SLW feeding, i.e. to the severe physiological reaction typically seen in cucurbit silverleafing or uneven ripening of tomatoes. Brassicas can also exhibit a physiological disorder called white streaking disorder (Brown *et al.* 1992).

Initial screening of cucurbit lines in the USA revealed genotypes that do not respond with the dramatic silverleaf disorder to the same extent and severity as non tolerant varieties, despite the different varieties carrying similar whitefly densities. (Cardoza *et al.* 1999; McAuslane *et al.* 1996). However, later studies showed that this silverleaf tolerance does not give these resistant zucchini genotypes any yield advantage under high whitefly infestation (Chen *et al.* 2004).

Resistance to SLW in some brassica lines has also been recognised, but thought to be related to the fact that SLW adults preferentially select non-glossy over glossy collard phenotypes in the field, rather than a resistance to the physiological impacts of SLW feeding itself. The indications from these studies in collards are that whiteflies only discriminate at close range or after contacting the plant (Farnham & Elsey 1995; Jackson *et al.* 2000).

This review has not determined whether research on different SLW feeding tolerances (e.g. within cucurbit lines) has been incorporated into commercial breeding programs overseas, and/or been used to influence grower's decisions on which varieties to plant. This would be worth following up in a separate review with international seed companies, given that most seed used in Australia is imported (D. Carey, *pers. comm.*)

Research into HPR traits other than feeding tolerance to SLW in key vegetable crops is discussed later in this review.

Breeding for geminivirus resistance – based heavily on the review of Lapidot & Friedmann (2002).
During the last two decades, the worldwide spread of the B biotype of *B. tabaci* has been accompanied by the emergence of whitefly-transmitted geminiviruses. Yield losses due to TYLCV in tomatoes can often reach 100% in Mediterranean areas (Pico *et al.* 1996). Under conditions of severe whitefly attack, Lapidot & Friedmann (2002) argue the best way to reduce geminivirus damage is by breeding crops resistant or tolerant to the virus, either by classical breeding or by genetic engineering. In their review they define a host plant as resistant if it can suppress the multiplication of a virus, and consequently suppress the development of disease symptoms. They further state that progress in breeding for TYLCV resistance has been slow and challenging, primarily because of:

1. the complex genetics of TYCLV resistance. In most cases, the sources of resistance to TYLCV appear to be controlled by multiple genes.
2. the need to set up a reliable screen for resistance to the virus, which is dependent on the availability of viruliferous whiteflies.

The first commercial resistant cultivar, ‘TY20’, carrying resistance derived from *Lycopersicon peruvianum*, showed delay in both symptoms and accumulation of viral DNA (Pilowsky & Cohen 1990; Rom *et al.* 1993). Thereafter, different breeding teams have produced advanced breeding lines with high levels of resistance from the following wild tomato *Lycopersicon* spp. hosts:

TYLCV resistance source	References cited in Lapidot & Friedman 2002
L. peruvianum	Lapidot *et al.*1997; Friedmann *et al.* 1998
L. chilense	Zamir *et al.* 1994; Scott *et al.* 1996
L. pimpinellifolium	Vidavsky *et al.* 1998
L. peruvianum	Vidavsky *et al.* 1998
L. hirsutum	Vidavsky & Czosnek, 1998; Hanson *et al.* 2000

These resistant lines are being used extensively to breed high quality F1 hybrids overseas (Lapidot & Friedmann 2002). In addition, a number of resistant F1 hybrids have been released for commercial production by several seed companies (Pico *et al.* 1998). Until the recent detection of TYLCV in Australia there would have been no local demand for these TYLCV resistant tomato cultivars. In turn, attempting to incorporate the various TYLCV resistances into local varieties has not been a priority. However, some TYLCV resistance genes are likely to be already present in many imported tomato varieties and parent materials (D. McGrath, *pers. comm.*).

Australian breeding programmes could potentially benefit from molecular markers linked to the resistance genes, making it simpler to incorporate the resistance from the cultivars being released overseas into locally adapted cultivars. However, these markers have not yet been widely developed.

Bean is also attacked by TYLCV and resistance to TYLCV has been observed in commercial bean varieties, but the inheritance has not yet been evaluated (Lapidot & Friedmann 2002). This report is of interest, since beans in Australia have been referred to as a symptomless host of TYCLV (CRDC SLW workshop 2006).

It is likely that combining genes from different sources of resistance can lead to superior levels of resistance to begomoviruses. For instance, Pilowsky *et al.* (1997) developed the highly TYLCV-resistant TY172 and TY197 lines by combining lines that expressed moderate levels of resistance to TYLCV.

Delaying time to TYLCV infection in tomatoes

If virus resistance cannot be easily achieved for a susceptible crop, then cultural tactics that delay the movement of virus-bearing adult SLW into a crop may have merit. For example, reduced virus infections were seen in a trial with a squash trap crop surrounding tomatoes, though even the author admitted that the practical application of this method to large scale commercial farm operations may be limited (Schuster 2004).

See the section below on cultural controls for a fuller review of cultural practices designed to reduce virus transmission, especially trap crops and row covers.

Integrating population ecology with management

SLW's pest status is high because it can build up to both very high numbers and inflict severe yield losses because of the nature of its feeding (potential virus vector plus toxic saliva). As shown above, some research has been conducted in attempts to reduce the susceptibility of the crops themselves to viruses and the SLW saliva. However, the other keys to fighting SLW focus more on SLW population dynamics.

Important mortality agents acting on the population dynamics of SLW include:

- Widespread use of chemical controls.
- Parasitism by native and introduced parasitoids. In Australia, parasitism seems to be more important than predation (CRDC SLW workshop 2006).
- Specific weather events (e.g. frosts, heavy rains etc.).

Area-wide management (AWM)

Since the widespread adoption of two chemicals – imidacloprid (Confidor®) in horticulture and pyriproxyfen (Admiral®) in cotton – both industries in Australia have been relatively successful to date in suppressing SLW. In fact, widespread deployment of these two chemical controls is regarded to have had an area-wide suppressive effect on SLW in various regions. In high SLW-risk cotton areas (i.e. central Queensland) one of the stated aims of using Admiral® is to target populations on a field-by-field basis before they reach an exponential growth phase, and so exert a level of regional control (CRDC SLW workshop 2006). Research staff sampling brassica fields for SLW in the Lockyer Valley report that it is obvious where imidacloprid has been used, due to the lack of any obvious whiteflies in the crop (M. Firrell, *pers. comm.*).

Attempts at area-wide management strategies to limit SLW build-up in horticultural areas have also been made by soybean growers around Bundaberg and Childers. The key strategy employed by these growers is to delay the use of synthetic pyrethroid sprays for green vegetable bug *Nezara viridula* and similar species for as long as possible in the soybean crop (and avoid them altogether if possible). The aim of this is to avoid flaring SLW numbers in the soybeans by preserving the parasitoids and other natural enemies in the soybean crops for as long as possible (Brier & McLennan 2006).

Another key AWM tactic is to minimise the risk of mass migrations of adults SLW from old crops to younger susceptible crops. This is discussed further below under 'cultural controls: management of crop residues to minimise mass migration.'

Monitoring and thresholds

Ellsworth & Martinez-Carrillo (2001) define 'sampling' as one of the three major keys (along with 'effective chemical use' and 'avoidance') of the SLW IPM system developed for cotton production in US desert agricultural ecosystems. They contend that without well-developed sampling tools, progress in all areas of whitefly management would be hampered.

SLW sampling in US cotton involves multi-stage, binomial methods of classifying populations. These have recently been refined by Australian researchers for use in local cotton production systems (CRDC SLW workshop 2006).In reviewing extension material provided to vegetable growers regarding SLW, there are two key monitoring methods described:

1. Sticky traps – to act as an alert to commence more thorough in-crop scouting
2. Active scouting in crops, using adult and/or nymph counts on leaves - to determine whether/when a control (i.e. insecticide) should be applied.

Sticky traps

Current recommendations for using sticky traps in SLW monitoring are to place around three to five traps in a crop of 2 to 3 ha. Place traps them level with the tops of the plants, as whiteflies are most attracted to young foliage (DPI&F 2007).

Researchers have also used sticky traps to identify and compare the relative numbers of natural enemy species in various SLW treatments, though specialised identification skills are required, especially in identifying the minute parasitic wasps *Eretmocerus* and *Encarsia* spp.

US research investigating the relationship between yellow sticky trap catches of SLW parasitoids in vegetable crops and other estimates of in-field abundance concluded that sticky traps placed within crops can be used to detect the presence of parasitoids and to estimate the general trend in parasitoid populations over time at specific locations, but more research on trap numbers, size and placement is needed in order to better gauge the size of field populations based on trap counts (Hoelmer & Simmons 2008).

In greenhouse systems, yellow sticky card traps equipped with green LEDs (light emitting diodes) have been shown to increase the capture of the silverleaf whitefly) and other pests (Simmons *et al.* 2004; Chu *et al.* 2004). As compared with the standard sticky trap, the light-modified trap increased the capture of whiteflies and fungus gnats. The capture of thrips was not affected. Also, the light-modified trap had little or no effect on the capture of two beneficial insects (a parasite and a lady beetle). This LED is reusable and is low cost. The LED-modified sticky trap may be useful for greenhouse vegetable growers to improve whitefly management with little impact on released predators and parasitoids.

Crop scouting methods

In a wide range of vegetables, crop scouts can determine the numbers of adult SLW by gently turning over young leaves and counting the adults on the underside. Adults should ideally be sampled during early morning (7 to 9 a.m.). Rapid adult migration usually occurs when infested crops are in decline or about to be destroyed (DPI&F 2007).

To assess nymph populations, sampling should focus primarily on the older leaves. A hand lens (10 x) is necessary when inspecting leaves for the presence of eggs or small nymphs. Large nymphs can be counted with the unaided eye (DPI&F 2007).

More recently there has been a switch away from nymph monitoring to adult monitoring in cotton as this was found to be easier and more reliable. This is supported by observations in brassica crops by Farnham & Elsey (1995) who concluded that adult counts were more consistent, for a variety of reasons. In cotton, adult numbers/5th node leaf from the top of the plant are the recommended sampling unit per plant. Binomial sampling systems in cotton have been developed where changes in the percentage of leaves infested are used to track the rate of population growth, and a leaf is defined as infested provided it contains at least two SLW adults (CRDC SLW workshop 2006; NSW DPI 2007).

How many samples to take?

In early work with tomatoes in Australia, checking about 20-40 plants per 5 acre block was the recommended practice for SLW monitoring (S. Subramaniam, *pers. comm.*).

No evidence has been found of industry-standard sampling plans for SLW in Australian vegetable crops. However such sampling recommendations do exist for some US crops. For example, extension material for Florida tomato production recommends examining "six feet of row (a sample) for every 2.5 acres. When plants have three or fewer true leaves, examine six plants per sample for adult whiteflies…Tentative thresholds are 0.5 pupae or nymphs per leaflet or 10 adults per plant (0-3 true leaves) or 1 adult per leaflet (over 3 true leaves)" (Florida Tomato Scouting Guide, SP 22, 2nd edition).

Compared to many pest/crop situations, relatively little research effort has been expended in Australia to determining how many samples are needed to precisely estimate SLW numbers in vegetables. This is partly because economic thresholds for SLW in vegetables are themselves not very precisely defined, owing to the low market tolerance for damage. The emphasis on monitoring SLW in both vegetables and other crops therefore tends to be on detecting when changes in the population (or rate of increase) occur, rather than on the numbers of SLW themselves.

Economic thresholds

The concept of economic thresholds based on economic injury levels is arguably less relevant for SLW in vegetables than some other crop/pest interactions. This is mainly due to the two ways that damaging SLW populations can arrive in a crop:

1. Rapid in-crop build-up, or
2. Mass migration from surrounding crops or crop residues.

In the first case, populations need to be controlled or managed *before* crop damage is evident, as once an outbreak is underway it is difficult to regain effective control. Thus the threshold used is more anticipatory of future problems than based on a known relationship between crop damage and the SLW density in the crop at that time.

In the second case where a rapid influx of SLW adults occurs, the need for control is usually obvious without resorting to a defined threshold density of SLW adults per plant.

Another factor rendering economic thresholds less applicable to SLW management in vegetables is the widespread use of imidacloprid at/prior to planting. While this currently gives good early and even season-long, protection against SLW and other sucking pests, prophylactic treatments by their very definition do not use a threshold. However, prophylactic use of imidacloprid at planting is a recipe for resistance, and reflects a zero-tolerance/risk approach to pest management.

The fact that mass migrations into a crop can occur suddenly and without warning is another reason why (a) regular monitoring is important and (b) prophylactic systemic insecticides have been widely adopted.

Nevertheless, some vegetable crops and varieties are certainly more tolerant of or resistant to SLW than others (e.g. Chu *et al.* 1995; Schuster 2004, de Barro 2006). This knowledge can provide a type of threshold – or trigger for action - in that the urgency for additional protection with insecticides will vary with crop type. Tomatoes and cucurbit crops, like zucchini for example, can tolerate only a very low SLW population before action needs to be taken due to the toxic impacts of their saliva on the crop, and consequently on fruit quality and/or yield. In contrast, eggplant can tolerate moderate numbers of SLW without major risk of yield loss or unmarketable fruit, and so intervention is less important (I. Kay, *pers. comm.*). Capsicum is known to be a poor host for SLW (nymphs not seen developing beyond 1st instar), so neither insecticides nor thresholds are likely to be warranted in this crop (de Barro 2006).

However, the need for some more explicit and available written guidelines to inform insecticide selection and timing in vegetable crops remains. This has been attempted for some crops overseas. While there are no established thresholds for whiteflies on most cucurbits, in Texas and Arizona, well-accepted thresholds have been developed and continually refined for cantaloupe (rockmelon) (Palumbo *et al.* 1994; Ellsworth & Martinez-Carillo 2001).

Population thresholds developed for SLW in cotton

In cotton, the ability for SLW to rapidly increase has lead to the concept of population thresholds. This concept emerged from cotton research in the US and has now been validated in and adapted to Australian conditions. This concept involves treating SLW populations that might not be damaging in themselves, but are identified as being at risk of growing exponentially beyond a point where crop damage will occur and effective control will become unachievable (CRDC SLW workshop 2006).

The successful deployment in cotton of the right insecticide at the right time for SLW management has demanded detailed data on typical population growth scenarios for the region of interest. To date the Australian cotton work relates to monitoring protocols developed for cotton in central Queensland by Sequeira (CRDC SLW workshop 2006), in collaboration with US colleagues. Ongoing work in southern Queensland over the 2006/07 summer sought to validate their population growth model for SLW under milder climatic conditions (M. Miles, *pers. comm.*). A full version of the current SLW decision support strategy is published in the industry's annual Cotton Pest Management Guide (NSW DPI 2007).

Cotton systems do have some advantages in predicting and managing SLW population progress that vegetable production systems do not. The long duration and relatively synchronous planting and harvesting of cotton crops in a region leads to relatively predictable patterns of SLW population growth. In contrast, any population prediction and threshold model for vegetable production regions would have to account for the risk of sudden- and presumably less predictable- population increases caused by the mass-movement of SLW between successive planting of various susceptible crops in a continuous cropping system.

Key recommendations– monitoring and thresholds:
It would be of benefit if a similarly effective model to cotton's could be developed to guide SLW sampling and control decisions in Australian vegetable production areas and systems. The research expertise from the central Queensland cotton industry is readily accessible, and in the best case scenario, the cotton model may only need refining for vegetable production areas, rather than complete reworking.

However, it is acknowledged that the data collection and modelling task is more complex for vegetables than cotton owing in part to the multiple crops involved. The convenience of at-planting systemic insecticide application in vegetables will also pose a challenge to the adoption of more complex IPM strategies which require careful monitoring, SLW risk prediction (related to day degrees and crop stage), and the precise timing of insecticides when required.

Chemical control options-

The development of robust IPM in vegetable crops has been hampered by a lack of selective chemical options for the control of sucking pests, i.e. SLW, aphids, thrips and other bugs such as green vegetable bug and Rutherglen bug.

Of all these sucking pests, SLW is arguably the most adept at developing resistance to insecticides. Fortunately, unlike the situation for the other groups of sucking pests, there are some products available that are still effective against SLW while having minimal impacts on natural enemy populations (e.g. the IGRs).

Selective organic options limited

Insecticide options for organic growers are limited and require frequent applications to be effective. Unfortunately, the organic options for SLW are also broad-spectrum and so will kill natural enemies of SLW. Research by A. Najar (current UQ PhD student) into petroleum spray oil (PSO) effects on cotton aphid is showing that suffocation is not the mode of action as originally thought. Rather, the oil is moving into the fat bodies and concentrating in the ganglia acting as a nerve toxin. This could have implications for the perceived 'softness' of PSOs towards natural enemies in the crop (CCC CRC cotton aphid management workshop 2006).

Current SLW insecticides

Appendix B contains a complete list of insecticides registered for use against SLW in Australian vegetable crops, or for which there is a permit. Currently the most important of these are the insect growth regulator pyriproxyfen (Sumitomo: Admiral®) and the neonicotinoid imidacloprid (Bayer CropScience: Confidor® and Confidor Guard®) (e.g. Palumbo 1996).

Pyriproxyfen is not known to have any adverse impacts on arthropods other than whiteflies, while some of the impact of imidacloprid on beneficial insects is reduced because of how it is applied (i.e. not as a foliar spray, but as seedling drenches, at-planting furrow treatments or through drip irrigation systems). Nevertheless, indirect non-target effects on predators from the consumption or parasitism of imidacloprid-intoxicated SLW nymphs have been shown (Walker *et al.* 2007).

Imidacloprid use is widespread and largely prophylactic so there is a strong need for alternatives for effective resistance management. Interestingly, brassica crops in California do not have a registration for the use of soil applied or seedling treated Confidor® (imidacloprid) in brassicas, whereas this is the strategy pursued in Australia (University of California 2007). In some US crops such as lettuce, granular applications of imidacloprid are known to be registered (D. Carey, *pers. comm.*).

Spirotetramat (Bayer CropScience: Movento®) is a novel mode of action (lipid biosynthesis inhibitor) product with a strong systemic activity, and is expected to be registered for a range of uses in Australian horticulture in 2009, including SLW control. When this product does become available grower education will be required to ensure it is used to maximum effect. Spirotetramat is effective and provides excellent residual control, if applied at the correct time in the pest population cycle. It can take over a week before the impacts of spirotetramat are seen, so once SLW populations are increasing exponentially it may be difficult to avoid crop damage if treatment has been delayed, even though the population may ultimately be reduced.

Accurately timing novel insecticides with low knockdown potential

The Australian cotton industry has acknowledged that applying the right SLW insecticide at the right time relies heavily on a well defined sampling strategy that links observed early population growth to (a) crop progress, and (b) modelled projections of the likelihood of SLW outbreaks in the life of the crop. Thus cotton growers are well equipped to make decisions such as whether the SLW population is sufficiently small and slow-growing to be controlled by a cheaper knockdown spray, or whether the slower-acting but much more effective IGR pyriproxyfen would be the better option. Such decisions are also informed by estimates of whether the season is likely to grow hotter or cooler over the remaining life of the crop, which impacts on the population's rate of increase (CRDC SLW workshop 2006; NSW DPI 2007).

Spray-timing is equally important for other pest specific products like pymetrozine (Chess®). This product works subtly by stopping adult feeding, resulting in premature death of adult whiteflies, but not necessarily preventing egg laying in the period between ingestion and death, and with no significant impact on developing SLW nymphs.

One of the key challenges, therefore, is to develop, test and adopt IPM strategies that make the best possible use of the chemical tools available, integrating them with other control tactics such as biological control. For example, a recent trial in Bowen, north Queensland, has been assessing the performance of several combinations of insecticide, parasitoids and variety tolerance in zucchini, bean and pumpkin crops (DPI&F 2007b).

Recommendations– more effective chemical use:

Researcher and grower education on certain SLW insecticides remains a priority to ensure these tools deliver maximum benefit. Key candidates for this type of research and extension under Australian conditions are the IGR pyriproxyfen, the feeding inhibitor pymetrozine, and the soon-to-be-registered lipid biosynthesis inhibitor spirotetramat.

Such education is important because misapprehensions about modes of action can lead to misguided insecticide strategies, and there are indications this is happening with pyriproxyfen in particular.

Verbal extension recommendations for the Australian cotton industry currently emphasise the sterilising impact of pyriproxyfen on adult females as its primary mode of action. Thus cotton growers have been told to expect that adults and nymphs will continue to be seen in the crop for at least two weeks after applying pyriproxyfen, until the population suddenly crashes, mostly as a result of only sterile eggs having been laid in the previous period. However pyriproxyfen extension material for vegetable growers indicates 'no direct mortality' on adults, and no reference to its sterilising impact, but states that is 'best' against the egg and nymph stages (DPI& 2007). Assuming the cotton information is correct, the latter recommendation appears to miss the subtleties involved in using pyriproxyfen to maximum effect, and may explain recent reports of excessive pyriproxyfen sprays by some vegetable growers within a single crop (D. Murray, *pers. comm.*). Anecdotal evidence suggests that these growers, not observing a rapid knockdown effect following pyriproxyfen application, may have used repeat sprays and consequently increased the risk of selecting for resistance to this product.

Maximum effectiveness for all products should also be sought by looking to integrate the available chemicals with other IPM tools such as natural enemies, pest risk forecasting, or cultural controls such as row covers and reflective mulches.

Recommendations - potential new chemical options:

In a review of insecticides currently used overseas or under development for SLW control, for which there are no regulatory approvals in Australia, products stood out as being of particular interest: novaluron (an IGR) and dinotefuran (a neonicotinoid). However, the likelihood of these gaining registration in Australian vegetables is probably remote. A watching brief on overseas developments with these products would be warranted.

It is unclear why the unique mode of action product diafenthiuron (Syngenta: Pegasus®) is only registered for SLW and aphid control in cotton. The barriers to possible registration for use against SLW in vegetables may be valid, but should be discussed with the manufacturers. It is an important SLW management option in Australian cotton.

Insecticide resistance management in Australia.

With the anticipated addition of spirotetramat within the next 12 months, Australian vegetable growers will have five synthetic chemistries with distinct modes of action for targeting SLW:

- IGRs (Group 17A) – Buprofezin, Pyriproxyfen
- Neonicotinoids (Group 4A) – Imidacloprid, Thiamethoxam
- Feeding inhibitor (Group 9A) – Pymetrozine
- Lipid biosynthesis inhibitor (Group 23 acaracide) – Spirotetramat
- Synergised synthetic pyrethroid (Group 3A) – Bifenthrin + piperonyl butoxide as synergist.

Further additions to this list seem unlikely in the near future. As noted earlier, a novel IGR called novaluron with no indications of cross resistance to the other IGRs appears promising on paper (Ishaaya *et al.* 2003) but no approaches have yet been made to have it registered in Australia. Palumbo (2001) comprehensively reviewed developing insecticides likely to be effective against a range of sucking pests. Despite being a

2001 article, few additional compounds effective on SLW other than spirotetramat have emerged since. Appendix C contains a table of all active ingredients known to have activity against SLW worldwide, but for which there are currently no regulatory approvals in Australia.

Local vegetable production areas in Queensland have attempted to develop insecticide resistance management plans to protect the chemistries currently used for SLW. Compliance, however, is voluntary, and the perceived high risk of not using imidacloprid by most growers is an impediment when developing specific strategies to protect this chemical.

Another challenge in devising an adequate IRMS (insecticide resistance management strategy) for vegetable industries is to ensure that there are adequate periods where entire SLW generations are not exposed to the mode of action being protected. In the cotton IRMS this is done, for example, by restricting usage of pyriproxyfen for SLW control to one spray per crop, in a system where the crop grows for about 5 months and there is only one crop per year/season (NSW DPI 2007). However, on a single vegetable farm with at least several distinct crops/plantings of each variety per season, it is easy to see how even a restriction of one spray per crop could lead to multiple generations of SLW being exposed to the same chemistry over a growing season.

Finally, any IRMS relevant to silverleaf whitefly in vegetables must attempt to ensure there is genuine rotation between groups - not merely the allocation of less effective chemistries to periods where little SLW pressure, and therefore little insecticide usage, occurs.

Cross commodity disputes about which industries should have access to certain chemistries is also a challenge. For example, cotton industry representatives have been known to state their preference that, under any proposed cross-industry IRMS, cotton would ideally have sole access to the IGR pyriproxyfen, leaving imidacloprid for horticulture.

Insecticide resistance monitoring in SLW funded by both the cotton and horticultural industries will hopefully provide sufficient warning to adjust insecticide usage as required. The literature contains information on approaches to monitoring insecticide resistance in SLW for various products such as imidacloprid (Prabhaker *et al.* 1997).

Insecticide resistance and B. tabaci biotype Q

To further complicate resistance management in SLW, a new biotype of *B. tabaci* known as biotype Q is currently undergoing a major worldwide range expansion. It is much more resistant to insecticides than even SLW. For example, biotype Q is known to already be very resistant to pyriproxyfen (Dennehy 2008). The potential incursion of biotype Q into Australia is also considered a major threat on account of any viruses it could introduce.

Despite these concerns, at least one SLW researcher has tentatively suggested that the arrival of Biotype Q need not necessarily lead to a worsening of the current SLW situation. Apparently biotype Q is adept at outcompeting and displacing biotype B, which could provide some relief in that biotype Q (minus its viruses) is considered to be less damaging in terms of its feeding impacts on crops than biotype B (P. de Barro, CRDC SLW workshop 2006).

Recommendations - resistance management:

All SLW-affected industries are heavily dependent on effective chemical options for its management. Therefore insecticide use for SLW control within and across industry sectors must be guided by sound insecticide resistance management principles so as to avoid overuse and eventual loss of the most valuable chemical tools available. Pyriproxyfen and imidacloprid are of especial concern based on current usage.

In regions where cross-commodity issues are identified as significant barriers to effective resistance management, considerable investment will be required to build understanding, relationships and agreement across sectors to develop workable, effective and adopted IRMSs. The risks of not complying with any regionally-negotiated IRMS for SLW require continual emphasis.

Once in place, a SLW IRMS should be revised on an annual basis and necessary adjustments made based on the the results from insecticide resistance monitoring programs. The Australian cotton industry has well-established processes for developing and refining annual IRMS based initially around *Helicoverpa* that may be of relevance to managing resistance in SLW across multiple industries (NSW DPI 2007).

Biological control

Most attempts to utilise biological control for SLW management in Australian field-grown crops involve natural enemy conservation through the use of selective insecticides.

Parasitoids

A number of aphelinid species are recorded as parasitising silverleaf whitefly in Australia, *Eretemocerus warrae*, *E. queenslandensis*, *E. mundus*, and 8 *Encarsia* species including *E. formosa*. All species will parasitise either *B. tabaci* or *T. vaporariorum*, or both (de Barro *et al.* 2000; Schmidt *et al.* 2001).

A number of *Eretmocerus* and *Encarsia* species were imported into the USA in the early 1990s. The strategy adopted was to source parasitoids from a variety of climatic regions to match with the range of climatic regions in the USA in which *B. tabaci* was a major pest (Hoelmer & Goolsby 2003). The experience of the USA researchers has informed the search for biocontrol agents for silverleaf whitefly in Australia. Climate matching in particular resulted in the identification of *Eretmocerus hayati* ex Pakistan as the best candidate for Australia (Goolsby *et al.* 2005).As a result of the success of the imported parasitoids in the USA, and the matching climate, *E. hayati* has been imported, evaluated and released in Bundaberg, Childers, Lockyer Valley, Fassifern, Emerald, Bowen and Ayr (de Barro 2006). In other regions, e.g. the Emerald Irrigation Area in central Queensland, where SLW is a frequent pest of cotton and melons, native species (*Eretmocerus mundus*, *Encarsia* spp.) commonly account for up to 90% of the parasitism observed in cotton and 30-40% in melons (R. Sequeira, *pers. comm.*).

Many insecticides, including the neonicotinoids, have a repellent effect on *E. formosa* (and probably other aphelinid species). However, until recently it had been thought that soil applications of the neonicotinoid imidacloprid had little impact. New techniques to evaluate the long-term influence of neonicotinoids have recently been developed. This research has shown that soil applied imidacloprid has a long-lasting repellent and lethal effect on *E. formosa*. Acetamiprid had a minor effect on *E. formosa*, and thiacloprid showed no persistent effect (Richter 2006).

Prabhaker *et al.* (2007) used laboratory studies to compare the impacts of several foliar insecticides on SLW parasitoids (*Eretmocerus eremicus* Rose & Zolnerowich and *Encarsia formosa* Gahan). Their trials included acetamiprid (neonicotinoid); chlorpyrifos (organophosphate); bifenthrin, cyfluthrin, and fenpropathrin (pyrethroids); and buprofezin and pyriproxyfen (insect growth regulators-IGRs). Chlorpyrifos was consistently the most toxic, followed by the neonicotinoid and pyrethroids, followed by the IGRs. Some variation was found among the three pyrethroids, with fenpropathrin usually less toxic than cyfluthrin and bifenthrin, except on *E. formosa* where fenpropathrin was of similar toxicity to bifenthrin. Acetamiprid was generally less toxic than bifenthrin. Impacts on female fecundity were not tested.

Some weather events may reduce parasitoid effectiveness. In the 2007/08 Australian cotton season there was very little parasitism recorded from samples taken from cotton in St George, the Darling Downs and central Queensland. One researcher's interpretation was that wet weather and high humidity had a negative impact on the parasitoids (Sequeira 2008).

Different parasitism rates have been observed on various host plants in the same region and could have implications for the regional ecology of both pest and parasitoids. As reported and discussed by Gruenhagen & Perring (2001), in California's Imperial Valley, the proportion of SLW parasitised varied seasonally among a suite of crop and weedy whitefly host plants and choice tests involving velvetleaf, *Abutilon threophrasti,* a weed with dense glandular trichomes on its leaves, and melons showed that velvetleaf was clearly the less preferred host of SLW. However, SLW on velvetleaf suffered less exposure to parasitism from the natural enemy *Eretmocerus eremicus* and around 30% of the parasitoids released on velvetleaf in an experimental study were entrapped and killed in glandular trichomes. These observations suggest that, if sufficiently abundant, velvetleaf could be an important refuge for SLW in California. Perhaps weeds performing a similar role to velvetleaf in the Australian landscape should be preferentially targeted for control over weed hosts where SLW parasitism is higher.

Recommendations- parasitoids:

Eretmocerus hayati and other native parasitoids have been shown to play a potentially key role in limiting SLW build-up, both in and outside crops. Any control strategies adopted should therefore aim to maximise and incorporate, not disrupt the potential for these parasitoids to exert significant biological control of SLW.

Research to determine the impacts of insecticides on natural enemies should strongly consider the need to screen for the potential of long-term repellent and lethal effects of soil-applied insecticides on parasitoids, given their important role in SLW management. In some cases, less disruptive alternatives may be available.

Detailed life table studies of SLW on a variety of crop and non-crop hosts would grow our understanding of the role of important weed and non-crop hosts in sustaining SLW parasitoids in local vegetable producing regions. Without this knowledge, farm hygiene practices could be working competitively, not synergistically, with the role of weeds in sustaining natural enemy populations.

Predators

In the USA, four whitefly predators have been imported: three coccinellids, *Serangium parcesetosum* Sicard, *Serangium* sp. nov., and *Clitostethus arcuatus* (Rossi), and the drosophilid *Acletoxenus formosus* (Loew). Of these species, only one has been released, *S. parcesetosum*, in Arizona and California where it did not establish (Hoelmer and Goolsby 2003).

In Australian cotton, SLW nymphs are predated on by bigeyed bugs (*Geocoris lubra* Kirkaldy), Neuroptera larvae, and coccinellids (Cotton Catchment Communities CRC 2007).

A native coccinellid, *Delphastus catalinae*, was inundatively released into Californian cotton as field experiment but was not effective at reducing SLW numbers, perhaps partly due to observed predation of all *D. catalinae* life stages by other predatory invertebrates in the crop. However, no adverse interactions between *D. catalinae* and indigenous whitefly parasitoids were detected, in line with other studies that concluded *Delphastus* adults avoid or are unable to feed on parasitized whiteflies in advanced stages of development (Heinz *et al.* 1999).

In Australia, there was recent interest in mass-rearing the polyphagous ladybird *Hippodamia variegata* for use as an inundative release biological control agent for SLW, particularly within glasshouse systems. However, preliminary research into the effectiveness of this predator in brassicas showed this species found it difficult to search the plants for SLW nymphs because the ladybird larvae readily fell off the plants (B. Nolan, *pers. comm.*). This accords with other findings that three predatory insect species – a hemipteran pirate bug, a lacewing larva and a coccinellid beetle – all spent less time walking/searching and more time in ‘scrambling’ (ineffective forward locomotion) when placed on leaves of the standard non-glossy cabbage variety than on non-standard glossy leaves (Eigenbrode *et al.* 1996).

Pathogens

The entomopathogenic fungus, *Paecilomyces fumosoroseus,* was found on the lower leaves of cabbage in French Polynesia (Tahiti). This can be a highly effective insect pathogen, but is limited by a requirement for high humidity (de Barro 1996).

Akey & Henneberry (1998) trialled *Beauveria* and *Paecilomyces* in Arizona cotton and reported the trials as effective, though no subsequent registration was achieved in USA cotton. The following reference is a clue to the possible conclusion of the *Paecilomyces* work, and confirms the high humidity/efficacy relationship referred to by de Barro (1996).

According to the “*Paecilomyces fumosoroseus* Apopka Strain 97 (115002) Fact Sheet” (USA EPA 2007), this pathogen is only approved for indoor and glasshouse use on non-food crops. Before EPA could approve additional uses, especially outdoor uses, the Agency would require additional data to determine whether there were harmful effects to beneficial insects and other non-target organisms. The product is sprayed on the leaves of the plant… It works best at temperatures between 22°C and 30°C and requires high humidity."

Setting aside the regulatory hurdles associated with introducing and registering an exotic insect pathogen in Australia, the climatic requirements of *Paecilomyces* would in any case restrict its likely application to glasshouse vegetable production. The only outdoor situation where its use could be considered in Australian vegetable production is warm, humid North Queensland.

A new whitefly pathogenic fungus, *Isaria (=Paecilomyces) poprawskii*, was isolated in 2001 in the USA from infected whiteflies feeding in eggplants. Key promising attributes of this pathogen are its natural establishment in a semi-arid region where temperatures reach 42°C, its persistence in the absence of hosts, and its high spore production, enabling ease of production. It also attacks the glassy-winged sharpshooter *Homalodisca vitripennis* (Flores 2007).

Recommendations– biopesticides:
While a biopesticide option for Australian field conditions would be desirable for SLW, the current lack of such an option is not as concerning for SLW where selective options are available, as it is for other sucking pests such as Rutherglen bug and green vegetable bug for which there are no selective chemical options.

Cultural control

Hilje *et al.* (2001) published a relatively recent review on research efforts, field utilization, and the potential of cultural practices to manage whiteflies and associated viral diseases.

They concluded that certain practices such as crop-free periods, altering planting dates, crop rotation, and weed and crop residue disposal, perform well only if used on a regional scale, and therefore are difficult to test or demonstrate experimentally. Furthermore, they stated that growers may be reluctant to adopt cultural practices such as living barriers, high planting densities, floating row covers, mulches, and trap crops, that require significant changes in conventional cropping practices.

Nonetheless, there has been adoption of some cultural practices to manage whiteflies, such as crop planning that includes host-free periods, and various forms of screened exclusion (Hilje *et al.* 2001).

Hilje *et al.* (2001) also proposed a useful system for classifying SLW cultural control tactics based on underlying biological and ecological mechanisms and the scale on which the practice is expected to operate: regional, local (i.e. field level) or individual plants. Thus, practices intended to remove or decrease inoculum sources over an entire area can be categorised as 'regional', while practices intended to manage whiteflies in a single field can be classified as 'local'. Fertilization regimes or host plant resistance traits, although applied over an entire field, are intended to alter the suitability or susceptibility of individual plants and so can be characterized as individual (Hilje *et al.* 2001; see Table 3).

Table 3. Classification of cultural practices to deal with *B. tabaci*, according to the biological and ecological mechanisms underlying them, as well as the scale on which practices are expected to operate. From Hilje *et al.* 2001.

Ecological/biological mechanism	Scale	Examples
Avoidance in time	Regional	Crop-free periods, rotations and planting dates
Avoidance in space	Local (i.e. single fields)	Screenhouses, floating row covers and high plant densities
Behavioural manipulation	Local	Intercropping and mulching
Host suitability	Individual (i.e. individual plants	Fertilization, irrigation
Removal	Individual	Overhead irrigation

Here we will consider the following cultural control options for SLW in terms of the published literature and possibilities for incorporation into Australian vegetable production systems:

- Crop free periods
- Altering planting dates
- Weed and crop residue disposal
- Living barriers
- High planting densities
- Floating row covers and other forms of screened exclusion
- Mulches – reflective and living
- Trap crops
- Greenhouse screening materials

Crop free periods

Crop-free periods, or area-wide production breaks, have been used to successfully combat other vegetable pests in Australia. Most notably, brassica growers in the Lockyer Valley over the last decade instigated a summer production break for brassica crops as a means of combating population build up and insecticide resistance in the diamondback moth, *Plutella xylostella* (K. Niemeyer, *pers. comm.*).

However, in that case the pest had a host range restricted to brassicaceous crop and weed hosts. While summer cropping breaks are typical for many vegetable commodities in northern Australian production areas, a complete break in host availability is probably unrealistic due to the likelihood that SLW can utilise a broader range of weed hosts than *P. xylostella.* As such, good weed control and farm hygiene over any summer production break would be expected to play a key role in keeping SLW to manageable levels over summer. However, summer weed control strategies should be guided by an improved understanding of their role in driving SLW ecology, including its natural enemies. It is currently suspected, but not confirmed for many regions, that weeds hosts also play a key role in sustaining SLW parasitoids. While it seems unlikely, we would not want an over-aggressive approach to weed control to undermine other natural controls of SLW operating in the landscape.

SLW is typically a pest in hotter regions, where summer vegetable production is challenging, if it happens at all. Therefore, winter cropping breaks are not generally feasible in these regions due to the economic dependence upon winter production. In some horticultural areas, even though production of SLW-susceptible vegetable crops may cease for a period over summer, potential host-gaps may be filled by other summer crops, e.g. cotton or soybeans. This can lead to perceived conflicts of interest between neighbouring industries.

Recommendation – regional coordination:
In some regions, a high degree of mutual understanding, cooperation and agreement will be required between competing vegetable growers and/or different commodities (e.g. melons and cotton) to effectively manage SLW populations and delay the development of insecticide resistance. Regional cooperation is therefore relevant if area wide management strategies such as voluntary production-breaks or focussed weed-host reduction programs are to be considered.

It is a key recommendation of this review that significant effort and resources be devoted to developing cross-industry relationships, extension structures and agreements that will facilitate the best possible outcome for all sectors in terms of SLW population and resistance management. While this is not a research recommendation per se, such agreements should be underpinned by science, not simplistic perceptions (e.g. 'that soybeans/melons/cotton are the problem'). Greater cooperation and communication in regional SLW management by the grains/cotton and horticultural industries would be desirable in regions where cross-commodity issues are identified as significant barriers to progress.

Recommendation – role of weed hosts in crop-free periods:
Research is needed to better understand the role of important weed and non-crop hosts in sustaining SLW parasitoids. This would help ensure that farm hygiene practices work synergistically, not competitively, with the role of weeds in sustaining natural enemy populations, especially during any crop-free periods.

Altering planting dates
In Australian cotton production areas – particularly central Queensland - the threat of SLW has placed a renewed emphasis on area wide co-ordination to ensure that all cotton crops in an area are planted and defoliated (harvested) at similar times. It is known that once defoliation of the cotton starts, SLW adults will begin migrating and concentrating *en masse* into the remaining attractive crops in the area (CRDC SLW workshop 2006).

Unfortunately, vegetable industries rely on successive plantings and harvests to ensure continuous production so, unlike cotton, there is no opportunity to synchronise plantings and harvests. Therefore the emphasis in vegetables is not on synchronised planting dates to reduce the impact of migrations into late plantings, but on harvest/crop residue management tactics to reduce the risk of triggering SLW dispersal from harvested or senescing vegetable crops into younger plantings.

Weed and crop residue disposal
Unlike cotton or grain crops, such as soybean, that senesce prior to harvest, vegetable crop residues contain fresh leaf tissue and can continue to remain attractive to SLW for a period after harvest. At harvest any systemic insecticides have typically been depleted and are at low levels, so not only can crop residues continue to act as a host for SLW , but when they senesce or are destroyed by a plough out operation, mass migrations of SLW adults onto nearby younger crops can be triggered.

Immediate mechanical removal of residues is one tactic to reduce post-harvest colonisation and build-up on the residues themselves. However, if there are significant numbers of SLW on the residues at the time of destruction, it can pose a risk to neighbouring plantings when any adults take flight. Therefore residue removal may also need to be used in combination with another method (typically chemical control) that quickly reduces the SLW around harvest and/or just prior to residue destruction. While not highly effective due to resistance, bifenthrin is sometimes used in Queensland to knock down populations on crop residues just prior to or immediately after harvest (B. Nolan, *pers. comm.*). The advantage of a synthetic pyrethroid (SP) in this situation is its short withholding periods and low cost. Its disadvantages, however, are low efficacy due to high resistance levels and harsh impacts on natural enemies that could be present in the crop residues.

The poor efficacy of a synthetic pyrethroid can now be somewhat overcome by the use of a synergist available on permit from APVMA. PBO (piperonyl-butoxide) acts by interfering with the resistance mechanisms/enzymes that SLW uses to overcome pyrethroids. The recommendation to apply PBO five hours prior to applying the pyrethroid is to give the PBO time to act on the SLW resistance enzymes so that the insects are at maximum susceptibility when they encounter the SP. To achieve similar results with a single spray application, research has also shown that microencapsulation technologies can deliver an initial dose of PBO, followed by a delayed release of the SP insecticide (Bingham *et al.* 2007). Some recent trials in Bowen suggest that acceptable results can still be achieved by combining the PBO plus bifenthrin in a single tank mix without encapsulation (DPI&F 2007b).

Another option for avoiding build up of SLW on crop residues could be to ensure that crops are fully protected by systemic insecticide until the point of residue destruction. A ‘top-up’ SLW control with spirotetramat (Movento®) or similar chemical may serve this purpose. Movento® is a systemically-acting product about to be released in Australia by Bayer CropScience. However, withholding periods and MRLs (maximum residue levels) may not be compatible with such a strategy unless the product was applied after harvest, in which case residues may not be sufficiently actively-growing for translocation of the active ingredient to take place. The cost: benefit ratio of an after harvest spray would also be questionable.

Chemical destruction of crop residues with a contact desiccant herbicide such as Sprayseed® (paraquat/diquat) could also be considered as an alternative to mechanical destruction. While they are registered as herbicides, paraquat and diquat are also highly toxic to insects (and humans). Post harvest applications would desiccate crop residue ready for plough in and should kill many of the whitefly present on those residues.

Key recommendation – crop residue disposal:
Further demonstration and refining of the full range of practical dispersal management options discussed above is required, and is currently happening to some degree in the Australian vegetable industry.

Prior to harvest/residue destruction, growers should consider the risk of SLW migration onto nearby plantings and, if the risk is deemed high, they may be able to provide additional protection to the nearby crops via a range of existing methods such as crop desiccants, row covers or selective chemistry applications.

Trap crops

The published international literature strongly suggests that, in commercial-scale vegetable production systems, trap crops show little promise for protecting crops from SLW attack when used alone (Hilje *et al.* 2001). Such systems also often require complex management decisions and techniques, since a different trap crop species to the main crop often requires different herbicide inputs and may be killed by herbicides used in the main crop. They often also have different crop length, flowering cycles, and agronomic requirements, as well as being susceptible to different disease pressures.

Schuster (2004) observed a greater cumulative proportion of plants with symptoms of TYLCV on tomato plants surrounded by tomato compared to tomato plants surrounded by squash, and greater cumulative numbers of whitefly adults and nymphs were observed on tomato plants surrounded by tomato than on tomato plants surrounded by squash. Therefore, the author concluded that growing squash as a trap crop could be a useful cultural manipulation in managing the silverleaf whitefly and TYLCV on tomato, although more applicable to small-scale farm operations. In this trial, the attractiveness and longevity of the squash trap crop was maintained by weekly harvests to promote flowering and weekly fungicide applications for preventive control of fungal pathogens. In another study, cucumber intercropped with tomato resulted in decreased incidence of TYLCV on tomato (Al-Musa 1982).

Eggplant planted adjacent to tomato resulted in reduced numbers of whiteflies on the adjacent tomatoes, but only when the eggplant was treated at transplanting with a soil drench of imidacloprid (Stansly *et al.* 1998). Insecticide-treated trap crops could therefore be an avenue of investigation, especially if protecting the trap crop enabled it to produce some marketable product. However, this practice was not recommended by the authors (Stansly *et al.* 1998) who considered the insecticide was more efficiently used directly on the crop rather than on the trap crop.

Against these slightly positive examples of trap crops stand several studies showing no benefit or negative impacts of trap crop/intercropping tactics when used alone against SLW. A key reason for this seems to be that the attractiveness of the trap crop (often a cucurbit species) wanes over the crop cycle due to maturity, senescence, or a high pest population, changing the trap crop from a whitefly sink to a source (see references and discussion in Hilje *et al.* 2001).

As further evidence against trap crops for commercial-scale SLW management, Castle (2006) confirmed an up-to 10 fold preference of SLW adults for settling and retention on rockmelons (cantaloupes) over cotton, which formed the basis for field experiments examining the potential of rockmelons to serve as a trap crop protecting cotton in Arizona. The cotton was completely surrounded by the rockmelon trap crop, but although SLW densities in the protected cotton were reduced relative to unprotected cotton, the managed trap crop was unable to prevent economic thresholds from being exceeded in the protected cotton.

The ideal SLW trap crop must be more attractive to SLW adults than the plant being protected, and if protecting tomato, would not be susceptible to TYLCV. It would also be cropped for a period as long as the protected crop so as not to serve as a source of whitefly adults as the trap crop reaches senescence, and would ideally be a poor reproductive host for SLW. One conclusion might be that the ideal trap crop candidate has not yet been detected for SLW. However oviposition preference studies, as summarised by Schuster (2004), consistently find cucurbits to be generally more attractive to *Bemisia* spp. adults than other crops, including alfalfa (*Medicago sativa* L.), broccoli (*Brassica oleracea* var. botrytis L.), carrots (*Daucus carota* L.), cotton (*Gossypium hirsutum* L.), lettuce (*Lactuca sativa* L.), sugar beet (*Beta vulgaris* L.) and tomato (*Lycopersicon esculentum*). Cucurbits have also been favoured as potential trap crops because they do not host TYLCV. However cucurbits are generally good reproductive hosts for SLW.

Simmons (2002) investigated another method of screening host plant suitability (but not oviposition preference) and concluded that collard (*Brassica oleracea* ssp. *acephala* de Condolle) was a better host of SLW than cantaloupe (*Cucumis melo* L.), cowpea (*Vigna unguiculata* (L.) Walpers), pepper (*Capsicum annuum* L.) and tomato (*Lycopersicon esculentum* Miller), inferred from the observation that the first instar crawlers travelled for less time on collard before settling.

Bellotti & Arias (2001) summarised the results from several studies related to host preferences, and therefore trap crop suitability, in Table 4 below.

However, even if adequate trap crop species were available, the complexity of managing two crops simultaneously would be too challenging for many commercial settings. A further limitation of trap crops is the cost in setting aside land and resources for a crop that may not be easy to utilize or market. Hilje *et al.* (2001) concluded that trap crops have not proven to be a reliable approach to deal with whiteflies and whitefly transmitted viruses.

Table 4. Studies evaluating the *B. tabaci* species complex: oviposition/feeding preference on different crop species. Reproduced without full references from Bellotti & Arias (2001).

Crops compared	**Observations**	**References***
Cotton, broccoli, cantaloupes, lettuce	Highest population of eggs on cantaloupes, followed by cotton; broccoli least preferred	Chu *et al.* (1995)
Zucchini, cantaloupes, cotton, Pumpkins, lettuce, tomatoes	Zucchini highest whitefly survival; tomatoes lowest	✳
Soybeans vs. groundnuts	Fewer eggs laid on groundnuts in field, trap-crop experiments	✳
Cotton vs. poinsettias	No significant differences in whitefly development time & longevity	✳
Brassica oleraceae	Cabbage & broccoli less infested than kale, collards & brussel Sprouts	Elsey & Farnham (1994)
Squash vs. zucchini	Squash supported larger whitefly populations	McAuslane et al. (1996)
Zucchini, cabbage, sugar beets	Zucchini preferred over other hosts	✳

- *Unless provided, the original references cited in Bellotti & Arias (2001), and marked '✳', were not consulted for this review. See Bellotti and Arias (2001) for citations.*

Recommendation – trap crops:
The devotion of resources to investigating trap crops as a management option for SLW is not recommended.

Row covers and other physical barriers

Spun-bonded polyethylene floating row covers can effectively protect cucurbits from many foliar pests including aphids, whiteflies, and the pathogens these insects transmit during the early stages of crop development (see references in Hilje *et al.* 2001). With cucurbits, however, row-cover material must be removed after flowering to allow proper pollination and harvesting.

The use of spun-bonded row covers would be most applicable in relatively short-term crops such as zucchini, for which even a short delay in insect infestation may allow fruit to mature before insect populations or plant diseases develop to damaging levels. This review has not identified any Australian growers currently using floating row covers to exclude SLW from vegetable crops.

One zucchini grower in the Burdekin area is known to have used floating row covers for a range of insect pests (helicoverpa, green vegetable bug and SLW) during the 2005 season. It would be worthwhile following up his recent experiences. A small-scale grower at Bowen also tried row covers two years ago but he was not very successful, with increased powdery mildew and mite problems (I. Kay and S. Subramaniam, *pers. comm.*).

In Australia, Qureshi *et al.* (2007) compared floating row covers in zucchinis up until flowering against open plots treated with pyriproxyfen, with and without the introduction of silverleaf whitefly into both open and covered plots. Floating row covers increased temperature and humidity compared with the uncovered treatments. Average fruit weight and percentage of marketable fruit was less for the row cover plus introduced SLW treatments. This result indicates that the use of either row covers or IGR controls whiteflies, reduces fruit damage and increases the size, weight, and quality of fruit and may also control other sap-sucking insects. However, if SLW are already present on plants, use of floating row covers may reduce predation and favour build up of SLW.

In zucchinis, Costa *et al.* (1994) found, under conditions of low silverleaf incidence in Hawaii (<25% of plants with symptoms), that row-cover treatments reduced the incidence of silverleaf symptoms, although no significant increase in yield per plant was found, and no relationship between silverleaf incidence and yield was found. However, under high levels of silverleaf (>50% of plants with symptoms), there was a significantly higher total marketable yield per plant in row-cover treated plots than in pesticide-treated or untreated plots. In addition, increased yields were correlated with lower ratings of silverleaf severity and lower proportions of plants with silverleaf. In this trial, row-cover material was draped loosely over each row and held in place with soil.

Singh *et al.* (2006) tested enclosures covered with various nylon mesh nets for the protection of sweet peppers from Leaf Curl Virus (LCV). Sweet pepper grown under a 50 x 50 holes cm^{-1} mesh net had the lowest LCV incidence (16.8%), followed by the 40 x 40 holes cm^{-1} (22.7%) and the 30 x 30 holes cm^{-1} (55.2%) mesh nets. Control plants with no netting had the highest LCV incidence (95.1%). Plants grown under mesh nets had similar fruit yields, which were higher than plants grown without nets. It was concluded that use of net screens could reduce the need for application of insecticides.

According to references cited by Holt *et al.* (2008), an alternative barrier design developed and tested in tomato production systems in India involved partial row covers/barriers. These insect-proof cloth fences were erected around tomato plots to reduce immigration of whiteflies most of which fly close to the ground, but without a cover. These fences incorporated an inward facing yellow-coloured insecticide treated strip to increase the mortality of any whiteflies that circumvented the barrier. These barriers were effective in reducing infection by tomato leaf curl virus and allowed TYLCV-susceptible tomato varieties to be grown successfully. Virus incidence in a susceptible tomato crop was reduced to 23–50% compared with 100% incidence in the control.

Holt *et al.* (2008) used a similar barrier design to reduce the entry viruliferous SLW to tomato plots. The barriers erected around the crop were of insect-proof cloth fences, 1.5 m in height with a deltamethrin treated, insect-attracting strip facing inwards. In the second experiment the barrier was used but with no insecticide-treated strip. A mathematical model was fitted to the symptom data which suggested that the barriers reduced vector immigration by approximately 12-fold but that *B. tabaci* retention within the plots was also increased slightly despite the mortality caused by the insecticide-treated strips. In particular, more rapid virus disease progress was observed in the second experiment where barriers were deployed without insecticide-treated strips, explained by a large increase in *B. tabaci* retention within the barriers. The conclusion was that partial insect barriers can be worse than none because sufficient whiteflies can enter to establish a population and, at the same time, large numbers are retained in the barrier plot, with the net effect being a more rapid population increase than in the absence of barriers (Holt *et al.* 2008).

An alternative to mesh fences or enclosures is the use of living vegetation barriers. Holt *et al.* (2008) summarise how such vegetation barriers have been used with mixed results in attempts to exclude SLW and limit whitefly-borne virus diseases in the field. Maize was used as a barrier to protect common bean in trials in Florida, but this was not effective even when combined with the use of eggplant as a trap crop (Smith & McSorley 2000). Sorghum barriers placed around tomato fields were reported to have reduced adult whitefly numbers and increased natural enemy abundance in Brazil, although it is not clear whether this led to lower disease incidence (Hilje *et al.* 2001). A limitation of live barriers is that they generally need to be planted some time in advance of the main crop in the field and it is not always easy to utilize or market the produce from them.

A further limitation of partial barriers, living or non-living, is that they were originally based on imperfect assumptions about SLW behaviour. Earlier work suggested that the majority of *B. tabaci* adults normally fly 0-2m from the ground, but it is now known that SLW adults may be trapped as high as 7.2m above the ground adjacent to source fields (see references in Holt *et al.* 2008). This may partially explain the inconsistent effect of partial barriers on whitefly population levels and virus incidence in some studies.

Recommendations – physical barriers:
The potential of floating row covers to protect especially young crops in Australia is uncertain. Presumably economics and complexity of handling the material have limited their adoption to date, particularly by large-scale growers. However, it seems they could be a cost-effective low or no-chemical option to protect young plantings at an especially high risk of invasion by nearby SLW adults from senescing crops or crop residues. Mechanised handling of the row covers would be desirable. The practical experiences of Australian growers who have tried floating row covers should be documented to determine any issues limiting their practicability prior to commissioning any research in this area.

Reflective mulches

As summarised by Hilje *et al.* (2001), the aim when using reflective mulches to manage whiteflies is to reduce the insect's ability to find the crop. The mode of action of inert ground covers such as plastics, sawdust, and various mulches has been attributed to interference with visual host-finding or suicidal attraction to the sun-heated mulch.

Coloured plastic mulches in a variety of colours, including aluminium, silver, transparent, white and yellow have been shown to be somewhat effective against SLW (e.g. Csizinszky *et al.* 1997; Smith *et al.* 2000). USA extension material frequently states that coloured plastic mulches may be effective in reducing whitefly populations and geminivirus incidence. For example, in Florida, tomato plants mulched with yellow or aluminium plastic mulches yielded more and had less tomato mottle virus infection than those planted on white or black plastic mulches (McAuslane 2007). Californian extension material states that adult silverleaf whiteflies are repelled by silver-or aluminium-coloured mulches, and growers can use them to significantly reduce rate of colonization by whiteflies and delay the build-up of damaging numbers of whiteflies by 4 to 6 weeks. This delay in infestation can be especially important if virus transmission is a major concern. The mulches lose their effectiveness when more than 60% of the surface is covered by foliage. Therefore, they are effective only for the first few weeks after seedling emergence or transplanting of either spring or fall tomatoes (University of California 2008).

In a US study, reduced colonization by SLW adults resulted in reduced populations of nymphs and a delay and reduction in the incidence of silverleaf in pumpkin and zucchini squash, and the reflective mulch treatments were as effective at reducing nymphal SLW populations as a pre-plant soil application of imidacloprid (Summers & Stapleton 2002).

In the Australian industry, plastic mulches are used by some growers, though primarily for weed suppression and soil temperature modification rather than insect pest management. Thus black plastic mulches that absorb UV radiation are used in cooler months, and white or light-coloured mulches used in the summer/warmer periods.

Despite the data from overseas, there is currently little enthusiasm for the use of reflective/coloured mulches for SLW management in Australian vegetable crops. One reason is that reflective mulches had already been trialled for aphid reduction in the past, especially around Bundaberg. According to one former crop consultant, people were not happy with the results and the reflective mulches were rapidly abandoned (G. Artlett, *pers. comm.*).

Recommendation – reflective mulches:
Given the overseas data's consensus that reflective mulches can reduce SLW infestations, and that the previous Queensland experiences with them were prior to the introduction of exotic SLW, perhaps there is scope to reassess their local potential in sucking pest management.

While the results may have been disappointing with aphids, perhaps the benefits of reflective mulches may be more obvious in a farming system containing SLW. The past practical experiences of Australian growers and consultants with reflective mulches should be more fully explored, as it is possible that either:

a) a useful practice for sucking pest management has been too hastily discarded, or
b) the mulches, while somewhat effective at reducing aphid numbers, were primarily abandoned because they were uneconomic, unpractical or had a poor fit with the farming system. Such disadvantages would most likely persist, even in a cropping system that now includes SLW.

Living mulches

Low-growing living mulches or ground covers are a potentially low-cost alternative to plastic mulches without the environmental liability. Living mulches are of particular interest because they could have two pest management functions:

1. Reducing the ability of pests to find the crop
2. Acting as a refuge for natural enemies.

However, do living mulches, in fact, reduce pest encounters with the crop, resulting in lower pest numbers, reduced damage symptoms (e.g. virus or physiological damage such as silverleafing) and increased marketable yield of vegetables and profits?

Hooks *et al.* (1998) in Hawaii compared living mulches of buckwheat (*Fagopyrum esculentum* Moench) and yellow mustard (*Sinapis alba* L.) with a bare ground treatment for the reduction of various pests and viruses in zucchini, most notably aphids, but also SLW. The severity of squash silverleaf disorder was significantly higher in bareground zucchini compared with living mulch-diversified zucchini during both experiments. The yellow mustard mulch died out early in one trial and was allowed to regrow with natural weed infestation. Melon fly infestations affected yield loss more than aphids and whiteflies.

In Florida, two living mulches, buckwheat, *Fagopyrum esculentum* Moench, and white clover, *Trifolium repens* L., and two synthetic mulches (reflective and white) were evaluated during the autumn of 2002 and 2003 for control of SLW and aphids in zucchini (Frank & Liburd 2005). Reflective and buckwheat mulches consistently had fewer adult SLW and aphids compared with the standard white mulch treatments. The white clover did not establish well in Florida conditions. Living mulch treatments had higher natural enemy populations than synthetic mulch and bare-ground treatments. Despite some inconsistency in results between years, the two living mulches were clearly effective at reducing SLW numbers in the year when SLW numbers were highest (i.e. 5.9 adult SLW per plant in buckwheat vs. 12.6 adults SLW per plant on the white mulch. The bare ground treatment had 8.9 adult SLW per plant). Despite these somewhat encouraging results, Frank & Liburd (2005) concluded the net gains with respect to the suppression of whiteflies and aphids with living mulches were erased in

Florida when the additional upkeep and management of the living ground covers were taken into consideration.

However, in small Costa Rican farms several living ground covers have been effective in reducing the number of incoming whitefly adults, delaying virus dissemination, decreasing viral disease severity, and providing high yields and, importantly, net profits (Hilje & Stansly 2008). USA extension material states that in Costa Rica, living mulches (e.g. perennial peanut and cilantro) may reduce somewhat the spread of geminivirus within tomato fields (McAuslane 2007). Several plants species, including perennial peanuts (*Arachis pintoi*, Fabaceae), ‘‘cinquillo’’ (*Drymaria cordata*, Caryophyllaceae) and coriander (*Coriandrum sativum*, Apiaceae), have been evaluated as living mulches for tomato production in Costa Rica (Hilje & Stansly 2008).

Research in Australian vegetable production systems has previously investigated living mulches. However, the impetus for that work was related to chemical-free weed suppression and the provision of ground cover, not insect pest management. Researchers at the time did not notice any profound impacts of the ground cover crops on pest management (C. Henderson, *pers. comm.*). Nor have these living mulches been adopted into conventional vegetable production systems, largely because of the more intensive management required.

Recommendation – living mulches:
Unless some particularly compelling and multiple reasons emerge for incorporating living mulches into our current vegetable production systems, it seems unlikely that Australian growers would consider them for the relatively mild insect pest management benefit they may offer. Thus, no local research is currently recommended into living mulches for SLW management.

Overhead sprinklers
Online extension material on SLW management in lettuce in California states: “Present research indicates sprinklers may reduce whitefly populations and virus incidence (University of California 2007a)”. Interestingly, this site does not refer to sprinklers under SLW cultural controls for crops other than lettuce.

In the early 1990s, Castle *et al.* (1996) conducted field experiments to evaluate SLW infestations in both sprinkler and furrow irrigated rockmelon and cotton plots under conditions of intense whitefly pressure in the Imperial Valley, California. Their consistent finding was that densities of immature whiteflies were significantly reduced in sprinkler irrigation plots, and most reduced in sprinkler irrigated rockmelon plots also treated with the insecticide imidacloprid. Results from their first rockmelon trial indicated that sprinkler irrigation on a daily schedule resulted in consistently lower whitefly infestations compared to a biweekly schedule (Castle *et al.* 1996).

However, their cotton trials revealed yields were significantly higher in the furrow irrigated plots compared to the sprinkler irrigated plots, despite being more heavily infested with whiteflies. Thus, while sprinklers may have reduced SLW numbers, it is a crop’s water requirements that should determine the irrigation methods and timing selected, not SLW. The mechanism of whitefly suppression by sprinklers was not examined by Castle *et al*. (1996) but was thought to involve a disruptive effect on adult whiteflies and their feeding, mating and oviposition behaviours.

Genscoylu & Sezgin (2003) also tested the effect of sprinklers against a ground-level watering treatment ('border irrigation') on populations of SLW in cotton in Turkey. Densities of SLW were lower in sprinkler-irrigated plots in both years, but not significantly reduced in one of these. They reported no impact on the effect of irrigation method on natural enemy numbers of SLW, though parasitoid wasps - which are considered the most effective group of SLW natural enemies in the Australian context - were not common in these trials.

Various researchers have noted the negative impact of rainfall on populations of whiteflies, but some have also suggested that rainfall (and presumably sprinklers) may also reduce populations and/or the effectiveness of small parasitic wasps such as *Eretmocerus* and *Encarsia spp* (Sequeira 2008).

The other potential impact of irrigation on SLW populations is in relation to honeydew production and whether the crop is water-stressed. Despite occasional suggestions that honeydew production by feeding SLW is increased on water-stressed plants, research from cotton showed that SLW produced more honeydew when feeding on well-watered cotton in the field than on water-stressed cotton (Henneberry *et al.* 2002).

Recommendations- overhead irrigation:
While sprinklers may reduce SLW numbers and/or activity, crop water requirements are what should primarily determine irrigation methods and timing. Sprinkler irrigation impacts on SLW may be of general interest to industry.

Screened exclusion (greenhouses)
While the focus of this review is on SLW in field-grown vegetables, non-chemical cultural controls are also important in protected cropping systems.

Israeli researchers have had success with the use of barriers to keep viruliferous SLW from invading greenhouses and they have been widely adopted as a cost-effective disease control solution for protected tomato production (Taylor *et al.* 2001). These greenhouses are screened with very fine mesh plastic screen. Ventilation must be increased however, to reduce the likelihood of infection by plant pathogens. Whitefly infestations have also been reduced with the use of UV-absorbing greenhouse plastic films. Whiteflies do not enter greenhouses or areas covered with this type of plastic as frequently as they do greenhouses covered in non-UV-absorbing material (McAuslane 2007).

Bell & Baker (2000) tested twenty-eight greenhouse screening materials with predetermined airflow resistance values for exclusion of SLW and thrips from a mixed-species population. Seventeen screens excluded more silverleaf whitefly than did the window screen control, whereas only seven excluded more thrips. One material differentially excluded whitefly over thrips; many more differentially excluded thrips over whitefly. Airflow resistance, indicative of mesh hole size, did not necessarily correspond with degree of exclusion. Not all materials characterized as highly resistant to airflow provided significant exclusion. Exclusion of both types of pests was attained with several moderate- and one low-resistance screen. Another low-resistance screen excluded silverleaf whitefly only.

As referred to by Holt *et al.* (2008), various forms of protected cultivation are increasingly used worldwide. Most commonly greenhouses are constructed from insect-proof mesh or polythene or other materials. These have frequently proved to be effective in reducing virus disease but such structures are costly and may not be economically feasible, especially in developing countries.

Recommendation – screened exclusion (greenhouses)
It is recommended that the above research results be made available to SLW-affected greenhouse producers in Australia for local adaptation.

Host plant resistance

There have been numerous studies into mechanisms of host plant resistance (HPR) to silverleaf whitefly. HPR offers the promise of a low-cost, practical, long-term solution for maintaining lower whitefly populations and reducing crop losses. Unfortunately, the quest for HPR to SLW has so far delivered little to commercial vegetable producers in developed economies like Australia.

Bellotti & Arias (2001) conducted a review of worldwide progress in whitefly HPR research with emphasis on cassava as a case study. Some of their general conclusions were that:

- Whitefly HPR research has increased in recent years, primarily on the *B. tabaci species* complex.
- There is a limited number of related wild species being evaluated or used as a source of whitefly resistance for breeding programs.
- There is limited research being done to combine resistance to crop viruses and whiteflies in the same genotype.

Furthermore, one of the reasons given by Bellotti & Arias (2001) for this relative lack of progress is that host plant resistance to SLW is rare in cultivated plants.

Large-scale screening of an extensive collection of cultivars and breeding materials for whitefly resistance has been limited. Table 5 shows that, apart from alfalfa (lucerne) where initial selections were made from an extensive pool, the selection of genotypes for other crop types has been less systematic and sometimes resulted in very low numbers of lines being tested. However, even where the number of genotypes tested is relatively high, there is no guarantee of finding resistance (e.g. groundnuts).
In many cases the range of germplasm evaluated has been too limited to understand or obtain the diversity of whitefly resistance genes that may be available in a given crop species. While crops with genotypes ‘resistant’ to the *B. tabaci* species complex are mentioned in the literature, Bellotti & Arias (2001) determined that in most cases these were not cultivars developed for whitefly resistance; rather they are cultivars or breeding lines that happen to contain resistance and were selected during field or greenhouse trials.

Table 5. Examples of HPR screening or evaluations of crop germplasm for resistance to *B. tabaci* species complex. Reproduced without full references from Bellotti & Arias (2001).

Crop	**Country**	**Genotypes**		**References***
		Evaluated	**Selected**	
Alfalfa	USA	73 Plants from 10,000 1/2sib (F)	2 Families with resistance	✳
Brassica oleraceae	USA	64 (F, C)	Glossy leaves associated with Resistance (non-attractiveness)	Farnham & Elsey (1995)
Common beans	Puerto Rico	41 (F)	?	✳
Common beans	Puerto Rico	4 (G)	2 Genotypes less preferred	✳
Cotton	Turkey	19 (F)	3	✳
Cotton	Israel	3 (F)	1 (Glabrous)	Navon *et al.* (1991)
Cotton & wild relatives	USA	19 (F)	1 (Wild species)	✳
Gossypium spp.	USA	24 (F, G)	4 Genotypes low eggs/nymphs	✳
Groundnuts	USA	150 (F)	0 (No resistance)	McAuslane *et al.* (1995)
Melons	USA	31 (G)	8 (Less damage)	✳
Melons	Venezuela	8 (F)	2	✳
Soybeans	USA	14 (F)	3	✳
Soybeans	USA	36 (F)	7	McPherson (1996)
Summer squash	USA	19 (F)	Differences in susceptibility	✳
Tomatoes	India	1200 (F)	3	✳
Tomatoes-commercial	USA	20 (L)	(Ovipositional differences)	✳
Wild tomatoes	USA	7 (L)	2	✳

a (F)=field, (G)=greenhouse, (L)=laboratory, (C)=cages

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The alfalfa example is noteworthy because it represents a comprehensive breeding effort to develop high-yielding, whitefly resistant cultivars from first-principles, and based on specific selection criteria such as the absence of whitefly and leaf stickiness (e.g. Jiang *et al.* 2003).

Perhaps of more immediate interest to the Australian situation, the USA alfalfa breeding program has actually released a cultivar UC Impalo WF, resistant to the silverleaf whitefly and presently being grown on 4800–6100 hectares in the San Joaquin and Imperial Valleys of California, as reported in Bellotti & Arias (2001).
Given that lucerne is a crop that often features in Queensland vegetable production areas like the Lockyer valley, perhaps there is scope to reduce/eliminate altogether lucerne's role as a potential source of SLW population by introducing SLW resistant lucerne cultivars. However it should be noted that lucerne is not currently considered a major SLW source, so the advantages to be gained from pursuing such a strategy may be slight.

Host plant resistance mechanisms

Table 6 outlines the HPR mechanisms Bellotti & Arias (2001) encountered in their review relevant to SLW. Interestingly, it does not contain any reports of HPR in beans nor does it record any examples of antibiosis (i.e. lethal impacts on developing SLW immatures following oviposition). Yet, in Australia, mungbeans have been observed to support substantial SLW adult populations and oviposition, yet nymphal populations fail to establish (H. Brier, *pers. comm.*). Capsicum is another crop plant where similar effects have been observed (de Barro 2006).

Table 6. Crops with genotypes reported showing some resistance to the *B. tabaci* species complex. Reproduced without full references from Bellotti & Arias (2001).

Crop	**Resistance**		**References ***
	Country	**Mechanism/factor**	
Zucchini	USA	Tolerance	Cardoza *et al.* (1999)
Zucchini	USA	Tolerance – reduced silverleafing, but not associated with any yield advantage under high SLW pressure	✳
Melons	Venezuela	Antixenosis	✳
Soybeans	USA	Antixenosis	✳
Tomatoes	India	Antixenosis (thrichomes)	✳
Tomatoes	USA	Trichome density	✳
Lettuce	USA	Latex (entrapment)	✳
Tomatoes (wild)	USA	Acylsugars	✳
Cotton	USA	Not indicated	✳
Cotton	Spain	Tolerance (varietal release)	✳
Soybeans	USA	Glabrousness	✳
Broccoli	USA	Glossy foliage	Farnham & Elsey (1995)
Melons	USA	Glabrousness	✳

** Unless provided, the original references cited in Bellotti & Arias (2001), and marked '✳', were not consulted for this review. See Bellotti and Arias (2001) for citations.*

When tolerance doesn't work

Adding further to the challenges raised by Bellotti & Arias (2001), one of the most active USA researchers into host plant resistance for SLW recently concluded that, "Host plant resistance offers limited hope for whitefly management" (McAuslane 2007).

Some of this pessimism no doubt stems from many years' of studying and selecting cucurbit (esp. zucchini) breeding lines with reduced sensitivity to silverleaf disorder (e.g. McAuslane *et al.* 1996), only to confirm recently that reduced silverleafing in zucchini makes no difference to the timing, yield and quality of the final harvest (Chen *et al.* 2004). These studies showed that varieties with high resistance to silverleafing still produce the same delayed, smaller and pale fruit under conditions of high SLW pressure, as do non-silverleaf resistant lines. Furthermore, the same research team also found that tolerance to silverleaf disorder does not prevent stunting in zucchini seedlings, nor does it protect against the systemic loss of photosynthetic and protoprotectant pigments induced by feeding of SLW (McAuslane *et al.* 2004).

Antixenosis (non-preference or avoidance) based on physical plant structures

McAuslane (2007) continues; "No varieties of host plants have been found to be highly resistant to whiteflies themselves; however, some plant factors are not preferred by whiteflies. For example, smooth-leaved varieties of cotton and soybean are less preferred by ovipositing female *Bemisia* than hairy-leaved varieties Glossy (less waxy) crucifers, such as broccoli and collard, are less acceptable for oviposition than are varieties with a normal wax layer" (e.g. Chu *et al.* 1995, 2000; Farnham & Elsey 1995; McPherson 1996); Navon *et al.* 1991).

There is an unfortunate aspect to HPR traits based on non-preference, such as or glossy leaves in brassicas or lack of leaf pubescence/trichomes. While these traits may operate well in choice-test screening trials, they tend to work less well when deployed in commercial field situations. This is because SLW adults, when faced with a field of non-preferred hosts, may remain and cause damage because their urge to reproduce and feed, even is stronger than their non-preference reaction. Thus, for example, in a no-choice test involving two identical melon lines (PMR 45, one with non-glandular trichomes, one lacking trichomes entirely), the number of SLW eggs laid on each melon isoline did not differ significantly (Gruenhagen & Perring 2001).

Antixenosis based on plant exudates

Not all cases of non-preference of SLW adults for oviposition are related to physical plant structures. Trichomes (leaf hairs) that are specialised to produce glandular secretions are known to have insect-defensive functions in plants. Such trichome-mediated host plant resistance secretions have been of especial interest in wild *Lycopersicon* (tomato) lines.

In a major study, no-choice experiments showed fewer adults settled on leaflets of wild *Lycopersicon* species and deposited 75–100% fewer eggs than on the cultivated tomato, *L. esculentum.* Adult mortality ranged from 77–100% on the wild hosts but was only 1% on *L. esculentum*, with most dead adults trapped in glandular trichome exudates. When leaves from the wild species were appressed against the leaves of the cultivated crop, some of these resistant effects were transferred, indicating that a chemical exudate from the trichomes was responsible (Muigai *et al.* 2002).

Laboratory studies then evaluated the repellent, fumigant and residual toxic effects of identified trichome exudates on SLW. These indicated that 2-tridecanone had low levels of repellent and residual toxicity activity; that 2-undecanone had high levels of repellent and fumigant activity; and that ginger oil (composed, in part, of sesquiterpene hydrocarbons) had high levels of repellent and residual toxicity activity; and that multi-factor resistance is therefore likely in wild tomato germplasm (Muigai *et al.* 2002).While such results suggest possibilities for tomato breeders seeking genetic sources of SLW resistance, they also suggested that some of these plant exudates such as ginger oils could be rapidly commercialised into repellent and/or toxic sprays for application across a range of crops.

Follow-up studies on ginger oil unfortunately revealed that there were significant challenges in getting it to work. For example, the low-molecular weight terpenes involved in repellence to SLW evaporated quickly, meaning that adequate coverage on the plant was not achieved. Phytotoxicity involving severe wilting and death was observed to be a problem on tomato seedlings at relatively low ginger oil concentrations of 0.5-1.0% (Zhang *et al.* 2004). To work, ginger oil formulations need to be improved, with lower phytotoxicity, longer residual time and combined with complete coverage and adequate droplet deposition for repelling whiteflies.

DPI&F researchers are currently investigating formulations of cypress oil and are aware of similar challenges associated with phytotoxicity (M. Firrell, *pers. comm.*).

Current research in the cotton industry is looking at derivatives from a species known as ‘Plant X’, as an insect protectant, though its effect has mainly been discussed in terms of helicoverpa and mirids, not SLW. The research team involved has identified two fractions from the plant which they have developed into a stable spray product with anti-feedant/repellent properties. It also deters “egg laying and is toxic to smaller stages of insects” (CRDC Spotlight 2008). Dr Robert Mensah of NSW DPI, Narrabri, leads this research. This is an example of the potential impact that as-yet-undiscovered plant extracts could play in future SLW control.

Beyond the immediate challenge of getting plant extracts such as these to perform against the target pest at economic concentrations, there is often the additional aspect that many plant-based extracts are broad spectrum in their repellence or toxicity, and so can negatively impact beneficial arthropods. Indeed, this is the case with the natural but broad-spectrum pyrethrins (plant extracts) used in organic production systems.

HPR in multi-pest situations

A further challenge of HPR mechanisms is that, while they may be effective against one pest, treatment is still required for other pests. Thus, while previous studies had shown that four aphid resistant lines of melon cultivars also showed signs of SLW resistance, Sauvion *et al.* (2005) showed that the VAT gene responsible for conferring resistance to *Aphid gossypii* in some melon cultivars has no impact on reducing the SLW intrinsic rate of increase. Thus, since both *Aphis gossypii* and SLW are targeted with some of the same chemical options in melons, to be effective in reducing insecticide usage a melon variety would require the genes conferring resistance to both species.

HPR impacts on natural enemies.

HPR traits may have negative or uncertain impacts on natural enemies. While host plant resistance and biological control are often assumed to act additively to suppress populations of agricultural pests, this assumption can be worth testing.

Since reduced trichome densities are generally associated with increased resistance to SLW in tomatoes, Heinz & Zalom (1996) questioned whether glabrous leaves combined with predatory coccinellid releases would provide greater SLW reduction than glabrous leaves alone. Their results showed a neutral relationship between trichome density and predator ability to suppress SLW numbers.

In collards monitored using sticky traps, a significantly higher ratio of parasitoids to whitefly adults was found on the nonglossy phenotype than in plots of the glossy (SLW non-preferred) phenotype suggesting that the glossy phenotype of Green Glaze had a slight, but significant, negative effect on overall parasitism (Jackson *et al.* 2000). However, in another study, McAuslane *et al.* (2000) reported that the fecundity, developmental period, and survival of *Eretmocerus* sp. (Hong Kong), an important SLW parasitoid, were not reduced by the leaf glossiness of Green Glaze collard phenotypes. Thus, the influence of the glossy leaf characteristic on parasitism of *B. tabaci* remains unclear.

Experiments comparing the performance of five Australian native *Bemisia tabaci parasitoids* showed some impact of host plant on parasitoid performance, notably that, across all five species, the total parasitism over a ten day period was less on tomato and soybean than on rockmelon, cotton and hibiscus (de Barro *et al.* 2000).

Host plant resistance – summary

Despite the volume of work and insights into SLW biology and ecology offered by HPR research, there have been limited benefits to vegetable growers despite a range of potential resistant genotypes having been discovered. The vast majority of these resistance mechanisms are due to non-preference which can break down when SLW encounters a whole field of a non-preferred variety.

The feeding tolerances to silverleafing originally identified in several cucurbit lines appear to offer no major benefit in terms of reducing damage and yield loss of the harvested product itself. To date, no progress has been recorded in breeding tomato lines where the effects of uneven ripening induced by SLW feeding are reduced. In fact, it has been suggested that the reduced fruit size seen in cucurbits may be more analogous to the uneven ripening response in tomatoes than previously considered (Chen *et al.* 2004).

Options to utilise plant extracts with repellent and/or toxic properties have to date proven difficult to deploy in formulations with sufficient residual activity and coverage, and without phytotoxic effects.

Finally while no straightforward conclusions have emerged about the impact of certain SLW-resistant on natural enemy performance, complex plant-insect interactions are often involved. It can certainly not be assumed that an HPR plus an abundant natural enemy necessary equates to greater SLW control than if either mortality agent was acting alone.

Recommendations- host plant resistance:

Certainly HPR has not yielded dramatic advantages to date in management of SLW in vegetable crops. However, there may be some benefit in a separate review to determine which of the identified resistances or tolerances from commercial breeding programs overseas have been incorporated into commercially available varieties. The most significant overseas research published with respect to HPR traits relevant to vegetable production is in zucchinis, melons, and tomatoes. Such a review would involve the international seed companies, given that most seed used in Australia is imported. While reviewing SLW resistances, it could also document forms of genetic host plant resistance to other sucking pests (e.g. aphids, thrips and viruses) identified from and/or deliberately incorporated into commercially available cultivars overseas, and of which Australian growers and researchers may be unaware.

Conclusion: Key recommendations for SLW management in Australian vegetables

There have already been several research projects directed at SLW management in the Australian cotton and horticulture industries, with the associated production of printed and online extension guidelines to facilitate successful management.

For example, in cotton, a recently concluded research project looked at silverleaf whitefly management with a focus on developing action thresholds and decision support guidelines (CRDC SLW workshop 2006).

In horticulture, two previous HAL-funded projects (VX99003 and VX02016) identified, developed and delivered a range of IPM strategies for SLW in tomato, melons, eggplant and zucchini. A current project (VGO5050) is focussed on developing, validating and implementing integrated pest management (IPM) strategies for silverleaf whitefly in brassicas, beans, sweetpotato and pumpkin.

The recommendations of this review support the conclusions of de Barro et al (2006 – HAL Final Report for VX02016, p. 104) for further RD&E work relevant to SLW management in vegetables. However current indications are that releases of the SLW parasitoid may no longer be required due to its apparent widespread establishment.

These seven recommendations of de Barro (2006) are summarised below:

1. Further evaluation and releases of the parasitoid *Eretmocerus hayati.*
2. While adequate control was at that time being achieved with current new insecticides, inappropriate use and over-reliance on limited new chemistries will lead to resistance.
3. Linked to the above point, insecticide resistance is a particular concern with SLW. Effective management of new insecticides is needed to preserve their longevity in vegetable production systems.
4. Especially in north Queensland, SLW migration across commodities was considered a major issue with movement form older crops/crop residues the primary source of infestation in young crops. Workable and practical SLW dispersal control strategies are needed combined with general farm-hygiene practices.
5. Area-wide adoption of IPM components – i.e. individual tactics will become more effective if deployed over larger scales, as local benefits can be diminished by whiteflies invading from nearby crops/growers.
6. While soil-applied imidacloprid, especially via trickle irrigation systems, had been broadly adopted, application challenges remained in crops where flood irrigation is used (esp. pumpkins).
7. Training and grower education to maximise the effective use of pyriproxyfen, where timing of application and careful monitoring of pest numbers are essential.

While supporting the above statements, this review further emphasises and elaborates upon the potential for RD&E in the following areas relevant to SLW management in Australian vegetable production:

1. Investigate the potential for climate/season-based risk assessments to guide deployment of prophylactic systemic insecticides.
2. Adapting population growth models and ‘population threshold’ concept (as used in CQ cotton) to vegetable production systems and regions.
3. Development of spatially explicit models to investigate the effectiveness of regional SLW management strategies and test understanding of SLW regional ecology
4. Further ecological studies where required to support #3 above.
5. Identifying and further developing ‘workable and cost-effective’ strategies to minimise SLW dispersal from crop residues.

6. Strategies and education to obtain maximum benefit from novel SLW insecticides, especially the IGR pyriproxyfen, the feeding inhibitor pymetrozine, and the soon-to-be-registered lipid biosynthesis inhibitor spirotetramat.
7. Continued development and annual revision of regional IRMS (insecticide resistance management strategies) based on annual feedback from cross-industry insecticide resistance monitoring.
8. Investment in the development of relationships, structures and agreements to minimise cross-industry conflicts and facilitate best practice SLW population and resistance management strategies at regional scales.

1. Increased use of climate/season-based risk assessments to guide deployment prophylactic soil-applied insecticides.

With temperature the primary driver of SLW population growth and rate of increase, SLW risk assessments are available for a range of horticultural and cotton/grain production areas in Australia. The key reason why imidacloprid is applied prophylactically through the soil is that this is the way the chemical works best. However it is also widely deployed without regard to the fact that some planting windows are more at risk from SLW attack than others, due to the impact of climate, and without regard to the certain risk of overuse leading to resistance.

Therefore a greater awareness of climatic factors influencing SLW risk could assist some growers to identify when prophylactic imidacloprid application could be avoided (or most needed) at planting.

In fact, this is the very approach that was taken by a large tomato growing operation in Bundaberg (at least in the 2005/06 summer). This group did not use imidacloprid for crops planted in Jan/Feb period, coming into fruit around April/May. These growers cited good parasitism by the wasp *E. hayati,* combined with a low-perceived risk for SLW at that time of year (i.e. fruiting under cooler conditions), as the basis for their decision (I. Kay, *pers. comm.*).

Could other growers be prompted to take similar calculated risks? And what information tools or resources would they need to adequately support such decisions?

2. Adapting population growth models and the ‘population management threshold’ concept as used in cotton to vegetable production systems.

In cotton, the successful deployment of the right insecticide at the right time for SLW management requires information on typical population growth scenarios for SLW within a region. This work has related to monitoring protocols developed for cotton in central Queensland by R. Sequeira (DPI&F) in collaboration with USA colleagues. This decision support model utilises population growth predictions based on historical data and, by tracking observed populations against predicted growth curves for a SLW outbreak, is able to lead the crop manager to a number of appropriate responses (e.g. IGR vs. rapid knockdown product vs. keep sampling/not of concern).

The potential for applying and refining/validating the cotton industry’s decision support models for SLW management ought to be investigated within vegetable cropping regions.

3. Developing spatially explicit models to investigate the effectiveness of regional SLW management strategies.

Given the complex nature of vegetable production systems compared with the more uniform cotton monoculture, there is scope to investigate spatially explicit models of regional SLW population dynamics that incorporate aspects such as differential mortality on different hosts and their arrangement in space and time to each other.

One of the focuses of much SLW management is to take a regional approach towards managing insecticide resistance and the build-up of SLW. However it is notoriously difficult to test and prove the effectiveness of area-wide management approaches for a pest due to the absence of an ‘untreated control’ (e.g. M. Miles *pers. comm.* on helicoverpa area-wide management). Therefore, many researchers now accept that the ideal way to assess the success of regional population management of SLW would be to develop explicit models of agricultural systems that incorporate (a) the known data about SLW population responses to a variety of treatments and host types, into (b) population predictions based on the relative areas of each type of host type/control measure acting in the landscape.

The spatially explicit part of the model allows it to accounts for differences in area of different host types and can also model assumptions about movement and migration behaviours. This is potentially very relevant to vegetable systems where dispersal of SLW adults from crop residues is a major feature of the population dynamics experienced in a cropping area.

Once constructed, spatially explicit computer models can therefore generate expected SLW population dynamics for a particular crop in the modelled landscape based on inputted spatial arrangements of surrounding crop types and mortality agents acting in that modelled landscape. Therefore, such a model enables the testing of ‘with regional management’ vs. ‘without regional management’ hypotheses. Perhaps even more importantly, these predictions can be compared with observations of SLW abundance in the real landscape being modelled, revealing important differences between our predicted and expected SLW population dynamics, and thus raising further questions about SLW relevant to its management.

Arguably the main deterrent to such modelling based approaches is the lack of sufficient computer-modelling skills amongst the entomological research community. The other challenge is to keep such modelling projects focussed on the needs of industry to manage a pest, rather than the desire of researchers to understand the pest, unconstrained by the need to manage it themselves.

4. Further ecological studies as required.

To support the development of landscape pest population models, ecological studies such as those by Naranjo *et al.* (2004) in Arizona are essential in determining the key risks and mortality factor contributing to SLW population build up from region to region. Nevertheless, much of this information is probably available.

A particular question emerging from this review is the role of various key weeds and non-crop hosts in supporting SLW over any proposed or practiced crop-free periods. Some plants/weeds may also play a more important role in preserving SLW parasitoids during these periods than others. Incorporation of such ecological information into adequate computer models of SLW population dynamics could provide feedback on whether such concerns are of minor relevance to weed management strategies, partially driven by concerns about providing hosts for SLW in the landscape.

5. Identifying 'workable and cost-effective' dispersal control strategies.

Dispersal of adults from neighbouring crops or crop residues is the major source of SLW invasion in vegetable production areas. Most dispersal control strategies are currently concerned with hygiene, in particular the use of clean-up insecticide sprays to knock down numbers before the destruction of residues by plough down. However there are a number of other strategies discussed in the body of this review that could be, and are being, further tested and developed.

6. Strategies and extension to achieve best practice chemical use.

Research and grower education on certain SLW insecticides remains a priority to ensure these tools deliver maximum benefit. Key candidates for this type of research and extension under Australian conditions are the IGR pyriproxyfen, the feeding inhibitor pymetrozine, and the soon-to-be-registered lipid biosynthesis inhibitor spirotetramat. Some particular concerns with potential overuse of pyriproxyfen have been discussed earlier in this review.

As well as education, there is the need to develop overall IPM strategies that integrate the available chemical tools with natural enemies, cultural controls and other tactics, as well as effective insecticide resistance management. For example, research could consider the prospects for integrating these new chemistries with cultural controls such as row covers and reflective mulches. It is well acknowledged that chemical controls for SLW and other pests with a low impact on natural enemy populations are vital to overall SLW management.

For vegetable growers to make informed decisions about insecticide choice and fit within a cropping system that includes SLW, they require extension material that clearly outlines the impacts of SLW insecticides on SLW- and non-SLW natural enemies, as well as the impact of non-SLW insecticides on key SLW natural enemies, especially the parasitoids. While there are currently no obvious knowledge gaps in this area, research should be undertaken to supply this information as necessary, and the information integrated into a regularly updated reference tables such as that used by the Australian cotton industry (NSW DPI 2007).

7. Recommendations for insecticide resistance management.

The continued development, annual revision and acceptance of regional IRMS (insecticide resistance management strategies) informed by data from ongoing insecticide resistance monitoring programs is vital. Vegetables and cotton should be working together to share data from resistance monitoring strategies to facilitate the development of appropriate regional IRMS that acknowledge the shared benefits of managing SLW resistance effectively.

A method of measuring compliance with these resistance management schemes on a regional basis where they are implemented would also be of value. This should involve working with resellers and producers maximise and measure awareness of, and compliance with these schemes.

8. Investing in relationships, structures and agreements to deliver best practice regional SLW population and resistance management.

The broad host range of SLW means that cross-industry misunderstandings and potential conflicts of interest can interfere with effective SLW management. Yet in most vegetable producing districts, a high degree of mutual understanding, cooperation and agreement will be required between competing vegetable growers and/or different commodities (e.g. melons and cotton) to effectively manage SLW populations and delay the development of insecticide resistance.

It is therefore suggested that significant effort and resources be devoted to developing relationships, structures and agreements that will facilitate the best possible outcomes for all sectors in terms of SLW population and resistance management. While this is not a research recommendation per se, such agreements should be underpinned by science, not simplistic perceptions (e.g. 'that soybeans/melons/cotton are the problem').

Thus greater cooperation and funding into regional SLW management by the grains, cotton and horticultural industries would be desirable in regions where cross-commodity issues are identified as significant barriers to progress.

Finally, we should acknowledge that current management of SLW in Australian vegetable crops is not in a state of crisis and significant progress has been made. However, the threat of resistance developing to the currently effective selective chemistries is of concern. Arguably the main concerns are in the future and surround the longevity of the current insecticides that, in combination with SLW's key natural enemies, are successfully delivering the current level of control.

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Appendix A: Silverleaf whitefly – Pest status and modes of damage for SLW in vegetable crops

Table 1: PEST STATUS of SLW in key vegetable crops

✓✓✓ = major issue – i.e. high densities not required for substantial impact on host plant, ✓✓ = moderate risk, ✓ = can be a problem, but only at high densities. Damage/losses relatively rare. X = no risk/reports. **HOST STATUS**: x = not a host, ✓ = poor host - adults but not support nymphal development, ✓✓ = intermediate host and/or moderate susceptibility, ✓✓✓ = good host, very susceptible

Crop		**Host status and damage susceptibility**	Direct (e.g. wilting etc. at high population levels leading to yield reduction	Honeydew contamination leading to reduced quality or other yield impacts	Injecting toxic saliva – host specific responses	Transmission of viruses
Brassicas	Broccoli	✓✓✓	✓✓ Whiteflies damage cole crops by sucking enormous quantities of sap and covering plants with sticky honeydew. Black sooty mould grows over the honeydew, lowering the photosynthetic capacity of the plant. Feeding by silverleaf whitefly stunts plant growth and development; as a result harvest may be delayed. Silverleaf whitefly feeding on broccoli causes a bleaching or whitening in stems and leaf petioles. http://www.ipm.ucdavis.edu/PMG/r108301411.html	✓✓ (accessed 30/7/08)	✓ - high populations can cause bleaching of broccoli stem	×
	Cauliflower	✓✓✓	✓	✓	×blanching in purple varieties (pers.com.. Grower/walsh)	×
	Cabbage	✓✓✓	✓ ✓	✓ ✓	× ×	× ×
Solanaceae	Capsicum	✓ - but poor host, not common-rare on capsicums. Can vary with varieties, perhaps due to smoothness of leaves (I. Kay pers. comm.). Noted that less eggs laid per plant and nymphs not developing beyond 1st instar in many varieties (De Barro et al. 2006).	✓ - these levels rarely reached due to non preference and poor nymphal development on many commercial varieties	✓ - rare, for reasons at left.	×	× - though is a host of TYLCV
	Eggplant	✓✓- is reasonably tolerant, such that light –	Light –moderate populations OK. Under heavy populations plant becomes unthrifty and less	Under heavy populations, fruits	Under heavy populations Dark fruit varieties can also lose their	×

		moderate densities show no distinctive symptoms as in tomatoes, cucurbits.	productive	can be rendered unmarketable (honeydew)	glossy black colour. . Data on marketable fruit quality in HAL VX02016 Final Report. de Barro et al. 2006	
	Potato	✓✓	✓ - can tolerate moderate numbers. US experience is that winter-harvested crops are at most risk from inundation of SLW from nearby cotton crops at defoliation (i.e. around autumn)	✓	×	×
	Tomato	✓✓✓	✓✓✓	✓✓✓	✓✓✓ (irregular ripening - internal and external symptoms)	✓✓✓ ATLCV TYLCV
Crop		**Host status and damage susceptibility**	Direct (e.g. wilting etc. at high population levels leading to yield reduction	Honeydew contamination leading to reduced quality or other yield impacts	Injecting toxic saliva – host specific responses	Transmission of viruses
Cucurbits	Zucchini /squash	✓✓✓ Squashes and rockmelons have been evaluated as highly attractive to SLW adults in field-based choice tests. This has lead to their evaluation as trap crops. (Schuster 2004; Castle 2006)	✓✓ In certain crops, economic damage caused by *B. argentifolii* is mainly expressed as late maturity and low quality of the reproductive harvestable structures (e.g., cauliflower [Natwick et al. 1996], cotton [Naranjo et al. 1996], melons [Riley and Palumbo 1995], and tomatoes [Schuster et al. 1996]). In this study, fruit from all genotypes infested with high levels of whiteflies (60 pairs or more depending on the season) were shorter 2 or 3 d after pollination than were fruit from control plants. The time that it took for fruit to grow to a harvestable size is gernally longer also longer at higher infestation levels (Chen et al. 2004)	✓✓	✓✓✓ In severe infestations fruit can become paler green/yellow (Schuster *et al.* 1991; Siva Subramanium 2000). Data on marketable fruit quality in HAL VX02016 Final Report. de Barro et al. 2006.	×
	Pumpkin and Cucumbers	✓✓✓	✓	✓✓	✓✓✓ No hard data in impact on fruit quality impacts. In severe situations, pumpkins can get paler reactions in fruit / qualitative impacts i.e. Brix/sugars (I Kay pers. Comm.)	×
Other	Green beans	✓✓?	✓✓ - Both leaves and cotyledons attacked. Leaf curling, plant stunting, paler and possibly shortened pods. SLW cause severe leaf curling of the new growth followed by stunting of the plants to a point where they fail to grow or produce many flowers. Symptoms of	✓	✓	× A symptomless host of TYLCV

			mature plants attacked late in the crop life are thought to be a stunting or shortening of the pods and paler pods of both the green and yellow beans. Silverleaf whiteflies generally are not a serious problem in beans. When present, infestations are frequently restricted to small areas and to the field edge. Infested leaves will be slightly curled and copious quantities of honeydew may be deposited on leaves, resulting in a sticky, shiny appearance Source: http://www.ipm.ucdavis.edu/PMG/r52300511.html Note: Mungbeans are a poor nymphal host.	(accessed 30/7/08)		
			Type of damage caused by SLW			

Crop		**Host status and damage susceptibility**	Direct (e.g. wilting etc. at high population levels leading to yield reduction	Honeydew contamination leading to reduced quality or other yield impacts	Injecting toxic saliva – host specific responses	Transmission of viruses
	Lettuce	✓ - can feed adults, but may be a poor host for nymph development. i.e.: Although present in very high numbers and laying large numbers of eggs, did not complete a life cycle on the plants. In fact, we were hard pressed to find any nymphs beyond the 2nd instar stage of this pest. This would suggest that lettuce is not a preferred host .for this pest, NSW DPI 2004. The Lettuce Leaf newsletter. URL: http://www.dpi.nsw.gov.au/data/assets/pdf_file/120618/issue10-0603.pdf	✓✓- Silverleaf whitefly feeding can cause a stunting and yellowing of head lettuce. SLW This pest can cause stunting of the plants if not controlled early in the seedling stage and can even kill the seedlings that have grown from seed. Source: http://www.ipm.ucdavis.edu/PMG/r441301411.html Adults can stunt plants in the early weeks of plant growth and if numbers remain high throughout the life of the planting, problems can occur by delaying the harvest and contaminating the crop. (NSW DPI 2004) Reductions in head size and incidence of leaf chorosis have been associated with Sweetpotato whitefly colonization in lettuce (Palumbo 1996).	✓ (accessed 30/7/08)	✗	✗
	Onions	✗	✗	✗	✗	✗
	Sweet corn	✗	✗	✗	✗	✗
	Sweet potato	✓✓✓	✓✓Can occasionally get large numbers	✓✓Sooty mould on leaves – Bundaberg growers have reported delays in crop maturity (up to a few weeks) where significant SLW numbers have been in the crop (Ian Kay pers.com.m.)	✗	✗
	Asian vegetables	✓✓	✓	?	?	?

Appendix B: Silverleaf whitefly – Current registrations and permits

Chemical registrations and permits for SLW permits in Australian vegetable crops (Last updated: November 2007)

Registered chemicals

There are two formulations (200 SC for foliar spray and 350 SC for soil application) of imidacloprid registered for use against silverleaf whitefly on some vegetables.

There are also a number of other chemicals registered on a range of vegetables for use against any of the many types of whiteflies. These chemicals may or may not be effective against silverleaf whitefly (*Bemisia tabaci* Biotype B).

The following chemicals have been registered for use against SLW since December 2006.

Active constituent	Trade names	Chemical group	States	WHP (days)	Crops
bifenthrin (100 g/L)	**Talstar**	pyrethroid (3A)	QNWNt	1	cucurbits and tomatoes
thiamethoxam (250 g/kg)	**Actara**	neonicotinoids (4A)	QNVWSTNtA	42	tomatoes (apply to the soil as a planting hole application at time of transplant)

Permits (November 2007)

Permits still current for SLW control in various vegetable crops and in some or all states and territories include permits:

8249 (D-C-TRON Plus oil); **8963** (Applaud); **9178** (Applaud); **9184** (imidacloprid); **9242** (Confidor Guard); **9243** (bifenthrin); **9244** (Chess); **9269** (Confidor 200 SC); **9569** (Synergy plus Talstar 100 EC) and **10205** (Admiral).

Further information about permits for SLW control is available from the APVMA website at http://www.apvma.gov.au/permits/permits.shtml (accessed 30/7/08)

APVMA Permits			**No. & expiry date**			
bifenthrin (100 g/L)	Talstar 100 EC & other 100 g/L bifenthrin products	pyrethroid (3A)	**Per 9243** 31/03/08	QWNt	7 3 2	broccoli, brussels sprouts, cabbage (head), cauliflower, lettuce (head) cucumber, gherkin, melon, pumpkin, squash, zucchini beans
buprofezin (440 g/L)	Applaud	chitin inhibitor (17A)	**Per 9178** 31/03/10	QWNt	3	cucumbers, eggplant, tomato, zucchini
buprofezin (440 g/L)	Applaud	chitin inhibitor (17A)	**Per 8963** 01/07/10	QNVWSTNtA	3	cucumbers (greenhouse)
imidacloprid (200 g/L)	Confidor 200, Provado 200	chloronicotinyl (4A)	**Per 7098** 31/12/06	QNVWSTNtA	7	all culinary herbs, chervil, galangal, rucola (rocket), mizuna, lemon verbena, tumeric
imidacloprid (200 g/L)	Confidor 200, seedling drench	chloronicotinyl (4A)	**Per 9269** 31/01/10	QN	NA	**seedling cell tray drench:** tomato & peppers (excluding seedlings for hydroponic production)

imidacloprid (200 g/L)	Confidor 200, seedling drench	chloronicotinyl (4A)	**Per 9184** 30/09/08	QNWNt	NA	**seedling foliar drench:** broccoli, cauliflower, cabbage (head)
(200 g/L) (350 g/L)	Confidor 200, Confidor Guard (soil applied)					broccoli, common bean (*Phaseolus vulgaris*), cabbage (head), cauliflower, lettuce, okra
APVMA Permits			**No. & expiry date**			
imidacloprid (350 g/L)	Confidor Guard (soil applied)	chloronicotinyl (4A)	**Per 9242** 31/03/08	Q	NA	potato
petroleum oil (839 g/L)	DC-Tron Plus Spray Oil	insecticide/ spreader	**Per 8249** 31/03/10	QWNt	1	capsicum, cucurbits, eggplant, okra, tomato
piperonyl butoxide (800 g/L) plus bifenthrin (100 g/L)	Synergy plus Talstar	synergist pyrethroid (3A)	**Per 9569** 31/12/07	Q	7 3 2 1	broccoli, cabbage (head), lettuce (head) cucurbits (cucumbers, melons, pumpkins, squash, zucchini green beans tomatoes
Insecticidal soaps (285 g/L potassium salts of fatty acids as their only acitve constituent)	Natrasoap insecticidal soap spray and other registered products.		**Per 10184** 28/02/13	All States	None given	Glasshouse and hydroponically-grown capsicum, lettuce and cucumbers.
pymetrozine (500 g/L)	Chess	Feeding inhibitor (9A)	**Per 9244** 31/03/08	QNWNt	7 5 3	head lettuce broccoli cucurbits, eggplant, tomato
pyriproxyfen (100 g/L)	Admiral Insect Growth Regulator	juvenile hormone mimic (7C)	**Per 10205** 30/06/08	QWNt	1	cucurbits, eggplant, tomato

States: Q=Queensland; N=New South Wales; V=Victoria; S=South Australia; W=Western Australia; T=Tasmania; Nt=Northern Territory; A=Australian Capital Territory. NA = not applicable

Note: All users should read, or have read to them, the details and conditions of the permit and/or product label before using the product.

This update was compiled and edited by Jerry Lovatt, DPI&F. The Silverleaf Whitefly IPM project is a collaborative project between the Department of Primary Industries and Fisheries and NSW Department of Primary Industries.

Visit the SLW project web site: http://www2.dpi.qld.gov.au/horticultureresearch/18362.html (accessed 30/7/08)

Appendix C: Silverleaf whitefly SLW insecticides without regulatory approval in Australian vegetable crops.

Table 4: Insecticides known to be active against SLW but without regulatory approval in Australia for SLW control in vegetables (Search conducted early 2008)

Active constituent	Chemical group	Application method / Mode of action	Australian status - vegetables	Other Australian crops	Activity against”	Comments
Acetamiprid Company: Certis (Supreme®) Company: Dupont (Intruder®)	Neonicotinoids; Group 4A	Agonist of the nicotinic acetylcholine receptor, affecting the synapses in the insect central nervous system. Systemic insecticide with translaminar activity and with contact and stomach action. Foliar spray	Registered for use against green peach aphid in potatoes.	For the control of cotton aphid in cotton and green peach aphid in potatoes (Supreme®). Mirids and cotton aphid in cotton (Intruder®).	aphids, whiteflies	
Dinotefuran Company: Valent (Venom®) (discovered by Mitsui Chemicals	Neo-nicotinoid 4A (in the same nitroguanidine sub-class as clothianidin, which has not been considered for SLW control))	Systemic or locally systemic, depending on application method, long residual Granular or foliar applications, Granular applications can be made as a planting hole or seed furrow application. Dinotefuran acts through contact and ingestion and results in the cessation of feeding within several hours of contact and death shortly after. Dinotefuran does not inhibit cholinesterase or interfere with sodium channels. Therefore, its mode of action is different from those of organophosphate, carbamate, and pyrethroid compounds. It appears that Dinotefuran acts as an agonist of insect nicotinic acetylcholine receptors, but it is postulated that Dinotefuran affects the nicotinic	Not registered – none sought	Not registered – none sought	It is reported by the discovering company that dinotefuran was highly active on a certain silverleaf whitefly strain which developed resistance against imidacloprid http://www.mitsuichemhealthcare.com/dinotefuran.htm (accessed 30/7/08)	No references found indicating widespread commercial release/use. Broad-spectrum insecticide. Cross resistance not-expected between dinotefuran and other neonicotinoid pesticides. This should help with pest resistance management: from http://www.udel.edu/pesticide/briefsmay02.htm (accessed 30/7/08) In US, registered for food uses in/on leafy vegetables as Venom® (except Brassica) and for use in professional turf management, professional ornamental production, and in the residential indoor, pet, lawn and garden markets. Conditional US registration given in 2004 http://www.epa.gov/opprd001/factsheets/dunotefuran.pdf (accessed 30/7/08)

		acetylcholine binding in a mode that differs from other neonicotinoid insecticides.				Regulatory approval in New York State has been troubled due to concerns about impact on non-target organisms and groundwater resources. http://pmep.cce.cornell.edu/profiles/insect-mite/ddt-famphur/dinotefuran/dinotef_venom_den_0108.pdf (accessed Oct 07)
Spirotetramat Bayer (Movento®)	Tetronic acid-derivative	Can be applied as furrow treatment, but most likely will be used as a foliar treatment. Impressive systemic action and translocation throughout the plant, long residual. MOA: Lipid biosynthesis inhibitor – affects reproduction and adults and especially juveniles of target pests.	Company is actively pursuing registration in Australia in a range of vegetable crops for SLW and thrips control. SLW registration expected soon in brassicas at least.	No indication that registration is being sought in cotton.	Whiteflies, aphids, thrips	Now registered in the US for a range of crops. Believed to be relatively specific, i.e. reduced impact on beneficial arthropods.
Spirodiclofen Bayer	Tetronic acid-derivative	Foliar miticide. Long residual (up to 21 days) Movento, inhibitor (LBI). Used in tree crops Not systemic - Active by contact against all developmental stages of mites, including eggs, nymphs and female adults. MOA similar to spirotetramat, i.e. lipid biosynthesis inhibitor.	Not registered	Not registered	Mites, whiteflies	Widely used in US tree crops for mite control.
Spiromesifen Bayer	Tetronic acid-derivative	Insecticide/Miticide for foliar application in annual crops. MOA: inhibitor of lipid synthesis; most effective on juvenile stages of mites and on nymphs and pupae of whiteflies and psyllids Not systemic, high level of residual control.	Not registered	Not registered	mites, psyllids, whiteflies	Oberon® (spiromesifen) widely used in US cotton and melons for whitefly control, as well as a many other crops for SLW/mite control.

Novaluron Company: Makhteshim Chemicals: (Rimon)	Novel IGR / Benzoylphenyl urea	Inhibits chitin formation, resulting in abnormal endocuticular deposition and abortive molting. Ingestions and contact. translaminar. 10-30 days residual, depending on environment.			Whiteflies, thrips and leafminers In sweet potatoes: armyworms, loopers, other foliage feeding caterpillars, whiteflies (suppression only)	No cross resistance detected between novaluron and pyriproxyfen and two leading neonicotinoid compounds, thiamethoxam and acetamiprid (Ishaaya et al, 2002); No appreciable affect on natural enemies and phytoseiid mites. Mild effect on other natural enemies (Ishaaya et al 2001, 2002)
Insecticidal soaps		Foliar. Mode of action believed to be mechanical, not toxin-based.	SLW permit for glasshouse/hydroponic eggplants, lettuce and cucumbers only.	Various	aphids, leafhoppers, mites, thrips, whiteflies	
Cypress oil extract		Foliar	Still in early R&D phase		Known activity against SLW	Formulations are currently being tested by DPI&F against SLW.
Beauveria bassiana (Mycotrol®)	Biopesticide	Foliar. Contact biopesticide, slow acting lethal infection.	No fungal biopesticides registered	No fungal biopesticides registered	aphids, leafhoppers, whiteflies	
Azadirachtin/neem extracts (e.g. Neemix®)(		Foliar. Slow acting, also acts as feeding repellent	Not registered	Not registered	broad spectrum	Would be harsh on beneficial arthropods. Indications are that regulatory approval would be unlikely (J. Duff, *pers. comm.*)
Pyrethrin + rotenone (Pyrellin®)		Foliar spray; Contact and ingestion	Not registered (pyrethrin registered separately; rotenone not registered for SLW in vegetables)	Not registered (pyrethrin registered separately)	aphids, leafhoppers, leafminers, loopers, *Lygus* bug, mites, plant bugs, thrips, whiteflies	Organic option approved in US. Would not be highly effective against SLW due to pyrethrin/pyrethroid resistance. Efficacy of this organic option could be enhanced if researchers are able to develop an organic synergist functionally similar to piperonyl-butoxide, PBO.
Diafenthiuron Syngenta: Pegasus®	12B	Foliar treatment. Translaminar. Has vapour action and so works well in	Not registered	Controls two-spotted mite and cotton aphids	Miticide and aphicide; suppresses SLW.	Only registered in cotton overseas, not in other crops.

		dense crops and in large fields. Diafenthiuron is a pro-insecticide, which has first to be converted to its active form. The active compound then acts on a specific part of the energy-producing enzymes in the mitochondria. This results in immediate paralysis of the pest after intake or contact with the product.		and suppresses SLW in cotton.		Mite/aphid and SLW rates are the same (600 or 800mL/ha. Low rate is only recommended for aphids when using ground rigs) WHP = 14 days.)
Endosulfan	Organochlorine, 2A	Foliar. Contact. Nerve toxin. Cyclodiene compounds antagonize the action of the neurotransmitter gamma-aminobutyric acid (GABA), which induces the uptake of chloride ions by neurons. The blockage of this activity by cyclodiene insecticides results in only partial repolarization of the neuron and a state of uncontrolled excitation.	Still registered in many vegetable, vine and tree crops for various pests, but not for SLW. Various restrictions including downwind buffers etc.	Withdrawn from all grain crops except some pre-emergent applications, and still available in cotton with various restrictions including downwind buffers etc.	armyworms, cabbage looper, green peach aphids, leafhoppers, whiteflies	Less harsh towards natural enemies than many broad spectrum options used to control sucking pests other than SLW, e.g. dimethoate to control aphids. SLW is highly resistant to endosulfan.

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David	Carey	Vegetech	Crop consultant
Lachlan	Chillman	Manchil IPM services	Crop consultant
Peter	Cochrane		Producer
Geoff	Cornwall	(DuPont Australia)	
Deborah	Corrigan		Producer
Danny	Deleso		Producer
Laurie	DeRuvo		Producer
Eddy	Dunn	T-Systems Australia	Crop consultant
Denise	Harslett		Producer
Greg	Hauser		Producer
Grant	Heron		Entomologist
Iain	Kay	(DPI&F)	Entomologist
Col	Kiehne		Producer
Anthony	Mason		Producer
Sandra	McDougall	(NSW DPI)	Entomologist
Clinton	McGrath	(DPI&F)	
Geoff	Messer	(Dow Agrosciences)	
Xavier	Molloy		Producer
Robert	Naïve		Producer
Brendan	Nolan	(DPI&F)	Entomologist
Tim	O'Grady	(Bayer Australia)	
Denis	Persley	(DPI&F)	Virologist
Leigh	Pilkington	(NSW DPI)	Entomologist
Darren	Schreurs		Producer
Murray	Sharman	(DPI&F)	Virologist
Robin	Sproule		Producer
Siva	Subramanium	(DPI&F)	Entomologist
John	Thomas	(DPI&F)	Virologist
Vandy	Von		Producer