Horticulture Innovation Australia

Final Report

Management of insecticide resistance in the green peach aphid

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cesar pty ltd

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Summary
The Problem
The green peach aphid (GPA) (*Myzus persicae*) is a widespread species and major horticultural pest within Australia. GPA attacks a broad range of plants, including capsicum, eggplants, tomatoes, broccoli and lettuce. Insecticides are the main tool presently used to control this pest, however, GPA can rapidly acquire insecticide resistance, which leads to control failures. Within Australia, GPA populations with resistance are increasingly common, posing issues both in the short and long term. This project was undertaken to better equip the Australian vegetable industry with knowledge of the current state of resistance levels in GPA populations across Australia. With this knowledge better insecticide resistance management (IRM) strategies may be devised.

Key Findings and Outcomes
This project revealed widespread resistance in GPA to three major insecticide groups that are commonly used to control aphids in Australia (synthetic pyrethroids, carbamates and organophosphates). The levels and distribution of resistance detected suggest resistance alleles are able to spread quite rapidly across large geographic distances. Additionally, low levels of resistance to neonicotinoids were detected in a small number of GPA populations from Queensland, South Australia and Western Australia. This is the first time neonicotinoid resistance has been detected in Australia. These novel findings have major implications for GPA management practices. Our industry survey report identified neonicotinoids as a high-use chemical group for GPA control in some regions of Australia, exposing an immediate need for new chemistries and resistance management strategies to help control this pest.

We identified the presence of several resistant super-clones (biotypes) that dominate GPA populations across horticultural regions, improving our understanding of the clonal (genetic) make-up of GPA populations regionally and nationally. It appears that GPA is able to move freely between crops, between production areas and even across states.

As well as determining the current levels of resistance in GPA, this project developed and optimised robust testing methodologies for newer chemistries available for GPA control (sulfoxaflor, pymetrozine, spirotetramat, cyantraniliprole). We then generated insecticide baseline sensitivity data to these 'newer' chemistries registered against GPA, allowing industry to monitor and respond quickly if there are any future changes in sensitivity of GPA to these products.

As part of this project we conducted shadehouse and field trials that document the effectiveness of new chemistries compared with current industry standards, and produced data on several chemical products from new chemical groups that are effective in controlling GPA. Increasing the number of insecticide groups that are registered to control GPA in vegetable crops is essential to the ongoing management of resistance in this pest. Rotation of chemicals from different chemical groups is the cornerstone of any insecticide resistance management plan, and having a larger number of products to choose from should decrease the potential for resistance developing to any one product if they are used appropriately.

The findings of this project, along with feedback from growers, advisors and agrichemical companies, have been incorporated into a regional resistance management strategy for GPA. Due to the wide range of vegetable crops grown across different regions nationally, along with a wide disparity in GPA

management, the resistance management strategy was focused on only one region: the Bundaberg vegetable growing region in Queensland. While the management strategy has been optimised to help growers and advisors specifically in this area, with chemical and cultural management options based on local cropping practices, pest control, and environmental conditions, there are many elements of the strategy that are applicable nation-wide.

This project contributes to a modern, effective, and sustainable approach to aphid management that will help to enhance local productivity and improve domestic market opportunities. A key component of this work is the integration of field resistance surveillance, aphid movement studies, and the development of testing methodologies and industry strategies, which will enable long-term management and monitoring guidelines for GPA to be continued well into the future.

Future Recommendations

1. There is a need to improve stewardship of insecticide use to control GPA in horticultural crops. This will minimise resistance issues and prolong the life of the agrichemicals that are currently effective in Australia. The project findings, particularly the increasing incidence neonicotinoid resistance in GPA, need to be broadly communicated to Australian vegetable growers.

2. Surveillance efforts should continue across Australia to monitor ongoing insecticide resistance in GPA populations within vegetable production regions. This will provide the greatest chance of detecting resistant individuals to new chemistries when they are at a low frequency; resistance management programs will have a greater chance of success than if a large portion of individuals are already resistant before intervention. Cross-industry investment with the grains industry would leverage significant efficiencies and cost savings.

3. The RMS developed for Bundaberg field vegetable crops should be adapted to suit other regions. This should be accompanied by a communication plan. The utilisation of a range of communication tools (including workshops, field days, print, video, and web products) is widely accepted as being critical in the uptake of RMS documents by growers.

4. There is a need for IPM programs for GPA in Australian vegetable crops, including the introduction of 'softer' insecticides that have new MoAs, and thus fit within a resistance management framework. Laboratory and field trials are required to look specifically at biological and cultural control practices, and how these could be integrated into current pest (and crop) management approaches.

5. Investment in the development of a scientifically robust guide outlining the impact of registered insecticides on key beneficial species of vegetable crops. This guide, along with supporting information will ensure growers have a tool to assist with IPM decision-making and maximise the positive impact of beneficial insects and mites. Greater confidence in the use of IPM practices in the Australian vegetable industry, and thus a reduced reliance on broad-spectrum insecticides, will position the vegetable industry as a market leader in sustainable crop production practice for the benefit of Australian consumers and the environment.

6. Research to better understand aphid-virus interactions and virus-specific management strategies to provide growers with management tools based on the best-available science, including automated traps and prediction models that indicate key aphid flight timings, and seasonal virus risk information.

Keywords
Green peach aphid; insecticide resistance; control; aphids; resistance management strategy

Introduction

The green peach aphid (GPA), *Myzus persicae*, is a serious pest throughout the world, and attacks a broad range of horticultural and broadacre crops in over 40 plant families (Blackman and Eastop, 2000; 2007). GPA has been identified as a pest in all Australian vegetable growing regions and a wide range of crops including capsicum, tomato, cucurbits, eggplant, beans, and brassicas, are affected (McDougall 2007). Weeds are also significant reservoirs for GPA infesting crops. GPA preferentially inhabit the undersides of lower leaves of host plants. Direct crop damage occurs through feeding resulting in leaf chlorosis, reduced plant growth and vigour (van Emden et al. 1969; Anstead et al. 2007; Blackman and Eastop, 2000; 2007). Indirect damage occurs by virus transmission (e.g. potato leafroll virus and mosaic viruses). GPA has been identified as the most important aphid vector for viruses in Australian brassica, lettuce, tomato, and potato crops (McDougall 2007). Aphids also excrete honeydew, which encourages sooty mould production resulting in reduced quality and marketability of the produce (van Emden et al. 1969; Anstead et al. 2007; Blackman and Eastop, 2000; 2007; McDougall 2007).

Insecticides, including synthetic pyrethroids, organophosphates, carbamates and neonicotinoids, have been the predominant control method for GPA in Australia. Extensive pesticide use has contributed to selection pressure, and resistance to a range of insecticides has been reported from Europe, Asia, USA, South America and Australia (Foster et al. 2000; Anstead et al. 2005; Bass et al. 2011, Umina et al. 2014). Anstead et al. (2005) reported that GPA has developed resistance to more classes of insecticide than any other insect species, with resistance to over 70 synthetic compounds reported (Silva et al. 2012). In 1993, Herron et al. (1993) reported resistance levels of up to 40, 20 and 4 times field application rates in Australian GPA for S-methyl, pirimicarb and methamidophos, respectively. Umina et al. (2014) confirmed widespread resistance in alpha-cypermethrin and dimethoate, as well as documenting high levels of resistance to pirimicarb across eastern Australia. Prior to undertaking this project, it was unclear how widespread insecticide resistance in GPA was within horticulture nationally.

At least four insecticide resistance mechanisms have previously been identified in GPA: (i) Amplification of the esterases, E4 and FE4, that sequester and degrade insecticide esters before they reach their target sites in the nervous system and confers resistance to organophosphates (Devonshire et al. 1998; Foster et al. 2002; 2007) and some carbamates and pyrethroids (Devonshire et al. 1982, Foster et al. 2007); (ii) Target site or knockdown resistance (kdr) conferring resistance to pyrethroids (Devonshire et al. 1998; Foster et al. 2002; 2007). Edwards et al. (2008) found kdr present in 25 – 100% of aphids sampled in an Australian survey, with the frequency increasing in vegetable growing regions; (iii) Modified acetylcholinesterase (MACE) resistance to carbamates; (iv) Enhanced detoxification by cytochrome P450 conferring resistance to neonicotinoids (Silva et al. 2012), which to date has not been identified in Australia.

The high frequency of resistance to synthetic pyrethroids, carbamates and organophosphates reported by Umina et al. (2014) suggests that several insecticide products may become completely ineffective against GPA in the future if high usage continues. Since 2009 growers in the Bowen, Gumlu and Ayr production regions of Queensland have reported spray failures and difficulty controlling GPA in capsicum, tomato and eggplant crops. In 2011, the Bowen and Gumlu growers association estimated over $20 million worth of market losses occurred due to honeydew and sooty mould fruit contaminations associated with uncontrolled aphids locally. Local grower and reseller records suggest that over $2.1 million was spent in 2011 on insecticide applications specifically targeting aphids. In some areas, growers repeatedly apply insecticides at regular intervals in an attempt to manage GPA infestations. Quite alarmingly it has been reported that these sprays are often applied twice a week. Difficulties controlling GPA populations has led to a marked increase in the cost of production and reduced vegetable supplies into domestic and export markets. This management practice places immense selection pressure on GPA to evolve insecticide resistance and has broad implications, threatening production across Australia. It also places other horticultural crops (e.g. brassicas, potatoes and lettuce) at risk. Recent research funded by the Grains Research and Development Corporation has demonstrated insecticide resistance in GPA has intensified and spread considerably in the last 5 years. Current management practices are clearly not sustainable.

Methodology

Understanding the current levels of insecticide resistance in GPA

This project completed a strategic national resistance surveillance program to determine the incidence of insecticide resistance in GPA, and deliver base-line data for a range of insecticide groups. We collected and cultured GPA populations from 25 different locations across Queensland, Victoria, Tasmania, South Australia and Western Australia. We targeted regions and growers with a history GPA pest reports, intensive cropping, high insecticide use and reported chemical control failures. At each location, GPS coordinates and plant host were recorded. Aphids were mostly collected from vegetable crops, although we also sampled from host weeds in some cases. Because of the presence of parasitoid hymenoptera in the field, it was necessary to ensure their removal before culturing aphids. To do this, individual aphids were placed onto a sprouting radish (*Raphanu sativus* L. *National*) cotyledon that was positioned with the underside exposed, in a small petri dish containing 1% agar. At least twenty petri dishes were established for each population. After 7 days, the petri dishes were checked for evidence of parasitism. Non-parasitised aphids were transferred to, and subsequently, cultured on *R. sativus* at the two-true leaf stage. Radish plants were grown in plastic tubs in potting mix, and each tub had a gauze window for ventilation. Tubs were kept at 19-20^{o}C and a 16 h light, 8 h dark photoperiod. Aphids were transferred to fresh tubs approximately every 7 to 10 days.

In order to assess the resistance status of GPA populations across Australia, we used fast, cheap, and reliable genetic assays to test for resistance to the most commonly used chemicals for GPA control in horticultural crops. These chemicals come from three different Insecticide Resistance Action Committee (IRAC) chemical mode of action classification groups (4 sub-groups): 1A carbamates (e.g. pirimicarb), 1B organophosphates (e.g. chlorpyrifos, dimethoate), 3A pyrethroids (e.g. α-cypermethrin, lambda-cyhalothrin), and 4A neonicotinoids (e.g. imidacloprid).

We optimised DNA extraction techniques and modified previously established diagnostic tests for the following resistance mechanisms: (i) modified acetylcholinesterase (MACE), which is known to confer resistance to carbamates; (ii) knockdown resistance (kdr and super-kdr), which are known to confer resistance to synthetic pyrethroids; (iii) E4/FE4 esterase genes, which are known to confer resistance to organophosphates; (iv) the R81T mutation in the nicotinic acetocholine receptor which is known to confer target site resistance to neonicotinoids, and (iv) increased CYP6CY3 (P450) copy number for low level metabolic resistance to neonicotinoids.

The reliability of using genetic assays to detect resistance to carbamates, organophosphates and synthetic pyrethroids has previously been verified by phenotypic bioassays in Australian GPA populations (Umina et al. 2014). Resistance ratios of up to 4500-fold for pirimicarb (a carbamate), and >1000-fold for alpha-cypermethrin (a synthetic pyrethroid) were observed in GPA populations that contained the MACE and super-kdr mutations, and resistance ratios of around 20-fold were observed for dimethoate (an organophosphate) in GPA populations that had increased expression of the E4 esterase gene (Umina et al. 2014).

For MACE, kdr, super-kdr, E4/FE4, and R81T, we developed TaqMAN® single nucleotide polymorphism

(SNP) assays (Life Technologies), to distinguish the susceptible and resistant alleles (see Table 1 for primers and reporter probes for each mutation assay). The TaqMAN® SNP PCR assays were undertaken on a Roche LightCycler 480 system in a 384-well format. 10 µl reactions containing 5 µl of 2 × Qiagen multiplex PCR Master Mix (Qiagen), 0.25 µl 40 TaqMAN® Gene Expression Assay, 2.75 µl ddH_2O and 2 µl of genomic DNA were prepared in triplicate. Included in each 384-well assay plate were control reactions containing DNA from aphids confirmed resistant and susceptible to the assayed SNP and controls with no DNA template. The amplification conditions were: 15 min at 95 °C, followed by 15 s at 95 °C and 1 min at 60 °C for 40 cycles. During each PCR cycle, the probes bind to their complimentary PCR products (providing one or both alleles are present) and DNA polymerase then cleaves the reporter dye separating it from the quencher. This cleavage occurs every cycle, resulting in an increase in fluorescence proportional to the amount of DNA present. The 'resistant' probes were labelled with VIC reporter dye, whilst the 'susceptible' probes were labeled with FAM reporter dye. The endpoint genotyping module of the LightCycler® 480 software package was used to call SNP alleles. The performance of the assay and amplification of each SNP was confirmed from the control reactions.

Table 1. TaqMAN® primers and MGB single nucleotide polymorphism (SNP) reporter probes

Assay Name	Forward Primer Seq.	Reverse Primer Seq.	Reporter 1 Seq. (VIC –susceptible)	Reporter 2 Seq. (FAM –resistant)
MACE_S431F	GCGCTTTTCTTGACGATTATCCT	ACCACCACGTTTTCCTCCTTT	AGGGTTACTATTCAATATTT	AGAGGGTTACTATTTTATATTT
neonic_R81T	TAGTTCTAACTTATTGCCTGCAGCTAT	GCGGTCAGGAAGTCTAATACGTTA	CTCACAAGTCTCAACC	CTCACAAGTGTCAACC
E4FE4	ACCAAGTAGCAGCATTGAAATGGAT	GGTGATCGTGACGCTGTTG	AAAACATCGTTGCATTC	ACATCGTGGCATTC
kdr_L1014F	CCATTCTTCTTGGCTACTGTTGTC	CCGAGTAGTACATATTTATCATTCAT	ACCACGAGGTTACC	ATACCACGAAGTTACC
skdr_M918T	CGTGGCCCACACTGAATCT	TTATGCACAAGACAAACGTTAGGTTA	CGACCCATTATGGATAT	CGACCCGTTATGGATAT
skdr_M918L	GTGGCCCACACTGAATCTTTTAAT	ACAAACGTTAGGTTACCCAAAGCA	ATGGTTCGACCCATTAT	ATGGTTCGACCCAATAT

In each assay, a substantial increase in VIC fluorescence alone indicates a homozygote for the resistant mutation, a substantial increase in FAM fluorescence alone indicates a homozygote for the susceptible allele, and a substantial increase in both signals indicates a heterozygote. To determine the full genotype, the end point fluorescence values for the two dyes are automatically corrected for background levels and plotted against each other in bi-directional scatter-plots. The clustering of samples allows for easy and accurate genotype scoring. Also, because the TaqMAN® is run as a quantitative real-time assay, it is possible to estimate the relative frequency of the FE4 and E4 genes using the end-point fluorescence measured at the two wavelengths specific for the two reporter dyes, in order to determine the level of metabolic resistance to organophosphates.

We used quantitative PCR (qPCR) to determine CYP6CY3 gene copy number by examining the gene expression profile. We used the approach of Bass et al. (2013) for this assay with targeted primers amplifying a fragment of the CYP6CY3 gene 90–150 bp in size. A SYBR green based qPCR assay was used and results normalized using three single copy genes.

Developing and optimizing phenotypic assays for GPA

Widespread and repeated use of chemicals within the same mode of action classification group poses a risk to the longevity of these products by aiding the emergence of insecticide-resistant aphid populations. To increase the ability of the horticultural industry to respond to potential control failures, we developed phenotypic assays for a range of chemicals used to control GPA in Australian crops. These chemicals come from four different Insecticide Resistance Action Committee (IRAC) chemical mode of action classification groups (5 sub-groups): 4A neonicotinoids (e.g. imidacloprid), 4C sulfoximines (e.g. sulfoxaflor), 9B pyridine azomethine derivatives (e.g. pymetrozine), 23 tetronic and tetramic acid derivatives (e.g. spriotetramat), and 28 diamides (cyantraniliprole). Baseline data from these phenotypic assays are crucial for establishing reliable discriminating doses for use in the evaluation of future resistance in Australian aphid populations and exploring potential shifts in population resistance as a result of insecticide exposure.

We tested formulations of the following insecticides: imidacloprid 200 g/L (Nuprid 200SC, NuFarm, Laverton North, VIC), sulfoxaflor 240 g/L (Transform™, Dow AgroSciences Australia, Frenchs Forest, NSW), pymetrozine 500g/kg (Chess®, Syngenta Crop Protection, Macquarie Park, NSW), spirotetramat 240 g/L (Movento® 240SC, Bayer CropScience, Hawthorn East, VIC), cyantraniliprole 100 g/L (Benevia®, Dupont™, Macquarie Park, NSW). Depending on the chemical, a stock solution of the recommended field rate application for each chemical was prepared and serially diluted to represent concentrations ranging from 0.00001 to 100 times the field rate application. We used formulated insecticides rather than technical grade active ingredients for the phenotypic bioassays, as this is common practice with topical bioassays and field-collected insects.

To develop the phenotypic bioassays for each of the chemicals listed above, firstly rate-range leaf-dip bioassays were run on a lab susceptible population of GPA. The leaf-dip bioassay method, modified for aphids from Moore et al. (1994), involved submerging *R. sativus* cotyledons or *Brassica rapa* subsp. *chinensis* leaf discs in insecticide solutions or water (control) and then placing them abaxial side up on 1% agar in small petri dishes. Aphids were transferred to the leaves, and the petri dishes were inverted to simulate natural aphid feeding on the underside of leaves. The petri dishes were stored at 18-20 ^{o}C with a 16 h light, 8 h dark photoperiod, after which time aphid mortality was scored. If the rate-range leaf-dip bioassay was successful, then the bioassay was repeated on the field-collected GPA populations we cultured for the duration of the project. However, if the rate-range leaf dip bioassay results were unsatisfactory, further assay optimization occurred. For each chemical, we spent some time optimizing the leaf host (*R. sativus* or *B. rapa*), the time of leaf submergence (1 s or 10 s), whether an adjuvant was added to the insecticide solutions, the scoring procedure (24 h, 48 h, 72 h and/or 96 h), the agar type, container type, temperature, and photoperiod in order to produce phenotypic assay procedures that were robust and produced repeatable results.

Leaf-dip bioassay for pymetrozine, spirotetramat and cyantraniliprole

Pesticide solutions were prepared in tap water and used immediately after preparation to minimise chemical decomposition. Concentrations of spirotetramat (Movento®) ranging from 0.0001 to 10 times the recommended field rate were tested, along with a water control. As spirotetramat (Movento®) is always used in conjunction with an adjuvant when sprayed on crops, we added the adjuvant Agridex™ to the prepared concentrations at the field rate of 0.02% v/v. Concentrations of pymetrozine (Chess®) ranging from 0.003 to 30 times the recommended field rate were tested, along with a water control. Concentrations of cyantraniliprole (Benevia®) ranging from 0.0001 to 100 ppm were tested, along with a water control. As cyantraniliprole (Benevia®) is always used in conjunction with an adjuvant when sprayed on crops, we added the adjuvant Agral™ to the prepared concentrations at the field rate of 0.02% v/v. Bok Choi (*Brassica rapa* cv. *Chinensis*) leaf discs were dipped for ten seconds in each solution, plated onto 1% agar in 35 mm petri dishes, and left to air dry at room temperature. Control leaf discs were treated in the same way, except that leaf discs were dipped in water rather than pesticide. Eight 3rd or 4th instar GPA nymphs were transferred to each petri dish with the aid of a soft brush, and five replicate petri dishes prepared per concentration. The petri dishes were inverted, and incubated at 20°C ± 1°C with a light regime of 16 L: 8 D.

Topical bioassay for imidacloprid and sulfoxaflor

For imidacloprid and sulfoxaflor, the initial leaf-dip bioassays did not produce repeatable, satisfactory results, so we optimized a topical application bioassay method originally developed by Puinean et al. (2010). Pesticide solutions were prepared in acetone and used immediately after preparation to minimise chemical decomposition. Concentrations of imidacloprid ranging from 0.01 ng to 10 ng per aphid were tested, along with a control of acetone. Concentrations of sulfoxaflor ranging from 0.00001 ng to 10 ng per aphid and acetone control were tested. Bok Choi (*Brassica rapa* cv. *Chinensis*) leaf discs were plated onto 1% agar in 35 mm petri dishes. Eight 3rd or 4th instar GPA nymphs were transferred to each petri dish with the aid of a soft brush, and five replicate petri dishes prepared per concentration. Using a micro-syringe, a 0.25 μL droplet of pesticide solution was placed behind the head of each aphid. Control aphids received droplets of acetone in place of pesticide. The petri dishes were inverted, and incubated at 20 °C ± 1 °C with a light regime of 16 L: 8 D.

Statistical Analysis

Depending on assay, mortality was evaluated at 48, 72 and/or 96 hours after exposure. Aphids were scored as being alive (moving freely), incapacitated (inhibited movement), or dead (no movement over a five second period). Incapacitated aphids were later pooled with dead individuals for analysis as these individuals invariably die and do not contribute to the next generation (Umina and Hoffman 1999). Aphid mortality data from the five replicate petri dishes per concentration was pooled for each population and subjected to probit regression analysis, using modified R script from Johnson et al. (2013). Lines were fitted to dose-mortality data on a log-probit scale for each pesticide using 'glm' in the R statistical package (R Development Core Team 2016). From these lines the lethal dose 50% (LD_{50}) values and accompanying 95% confidence intervals were calculated using Fieller's method, with correction for heterogeneity where appropriate (Finney 1971). Results from each aphid population were then compared with results from the susceptible control population within each assay to calculate differences in resistance, or resistance ratio. Analyses were conducted using R version 3.3.1.

Field and genetic studies to understand broad-scale movement and spread of resistance

Within Australia, GPA often form mixed populations of individuals that reproduce asexually (obligate parthenogenesis) and individuals that have occasional sex (cyclical parthenogenesis). Populations typically consist of multiple clonal types and resistance may be linked to particular genetic clones that are widespread throughout Australia. GPA are also highly mobile, moving from paddock to paddock, and region to region. This means that resistant clones can spread quite easily over large distances. The risk of spread is higher than many other aphid species due to the association of GPA with a broad host range, including plants in the vegetable, gardening, fruit, and grains industries. Understanding the movement patterns and origin of resistance is needed to devise effective resistance management guidelines for growers.

In 2013, a number of field populations of GPA were collected (over multiple sampling days) from adjacent vegetable and canola crops around Bairnsdale, Victoria. In 2014, GPA populations across a greater number of vegetable and canola crops were collected over a larger spatial-scale covering the Yorke Peninsula, Mid North, Mount Lofty Ranges, Murraylands and Upper South East regions of South Australia. All aphids were identified and GPA from each locality stored in vials containing 100% ethanol.

To understand the clonal make-up of GPA populations across different crops and regions, we optimized ten microsatellite DNA loci (M35, M37, M40, M49, M55, M63, M86, myz2, myz9 and myz25), as published in Sloane et al. (2001). We also developed a procedure that allows us to run high-throughput screening (whereby these DNA markers are pooled into 3 groups, labelled with unique fluorophores and co-amplified by PCR). Using the DNA microsatellite markers, we genotyped all aphids collected at Bairnsdale in 2013 and in South Australia in 2014 to investigate the clonal make-up of GPA populations and assess any differences between aphids found on horticultural and broadacre crops.

To further investigate the broad-scale movement of GPA across Australia, we determined the clonal make-up of over 100 GPA populations from our extensive library of field-collected samples. These samples were obtained between 2011-2015 and included the 25 populations collected from vegetable crops as part of this project. Each population was genotyped across the ten microsatellite loci described above.

To understand the associations between different GPA clones and crops types, host plants and regions, we compared binomial generalized linear models (GLM) with a logit-link function, using Akaike's information criterion for small samples (AIC_c) as an estimate of Kullback Leibler information loss (Burnham & Anderson 2002). The difference between the AIC_c value of each model and that of the top-ranked model, ΔAIC_c, and the relative model weights, $wAIC_c$, was calculated. Thus the strength of evidence ($wAIC_c$) for any particular model relative to the entire model set varies from 0 (no support) to 1 (complete support). All models and associated analyses were conducted using the R statistical package v. 3.3.1 (R Development Core Team 2016).

Improved on-farm aphid control using insecticides

To improve on-farm aphid control for GPA, we conducted an exploratory process with major agrichemical companies to identify possible opportunities for new insecticide molecules to be registered for GPA control in vegetable crops. After detailed discussions with fifteen companies over several months, we shortlisted 8 different chemicals with various modes of action (MoAs) to screen against GPA. The shortlisted products were based on numerous factors, including expected efficacy against aphid species, anticipated cost and the likelihood of each product reaching market.

We conducted a large microcosm 'semi-field' trial in October 2014 (see Appendix 1 for full details). Based on the results from this microcosm trial, and further discussions with agro-chemical companies, the most promising chemical products were selected for investigation in field trials on brassica crops. As one of the products from our microcosm trial, Benevia®, was subsequently registered against GPA in fruiting vegetable crops during the project, we included this insecticide as a new standard in the field trials in place of pirimicarb (which can no longer effectively control many GPA populations due to widespread resistance). Two field trials were undertaken in spring 2015 in northern and southern Queensland (Bowen and Lockyer Valley), and one field trial was performed in autumn 2016 in Victoria. See Appendix 2 for full details of the methodology used.

Insecticide resistance management guidelines for GPA

To understand and identify resistance drivers and current management strategies for GPA in horticulture, we conducted an industry benchmarking survey from May to June 2014. The survey had a two-stage approach. The 1st stage included an online survey through SurveyMonkey, and focused on general issues such (i) where GPA are an issue nationally, (ii) the crops types that GPA are most important, (iii) where resistance issues are causing most concern, (iv) how GPA are presently controlled (chemical and non-chemical), and (v) the motivation behind particular pest management practices. The 2nd stage included phone interviews following up on respondents from the 1st stage that identified GPA as an important vegetable pest, focussing in on specific management issues. Expert input into the survey design was provided from Social Scientist, Leah Ruppanner (The University of Melbourne). The survey questions were developed for two target audiences (growers/farm managers and agronomists/ consultants). We publicized the survey through a variety of avenues including: AUSVEG, IK Caldwell, Bowen & Gumlu Growers Association, Vegetable Growers Association of Victoria, GrowCom, Tasmanian Farmers & Graziers, NSWFarmers, AUSVEG SA, Vegetables WA, Elders, EE Muirs & Sons, Landmark, Victorian Farmers Federation, Fruit Growers Tasmania, Hortex, NTDPIF, NT Farmers, DAFWA, SARDI, Fruit West, Fruit Growers Victoria, NSW DPI, Vic DEPI, Bundaberg Fruit & Vegetables.

Findings from the benchmarking survey revealed a multitude of management practices employed to deal with GPA in different vegetable crops and regions, depending on whether GPA was viewed as a major or minor pest. The complexity of these issues indicated that developing a single resistance management strategy (RMS) for GPA in Australia is not feasible. Therefore, within the scope of this project, we developed a RMS in a defined geographic region: the Bundaberg horticultural region of Queensland. This case study RMS was designed so that it could be later extrapolated to other regional and crop-specific strategies across Australia.

The Bundaberg horticultural region of Queensland was selected for the case study RMS as this region has experienced significant resistance issues with GPA in the recent past and has a variety of crop types that are grown year-round. We identified key horticultural contacts in this region, including Eddy Dunn, a senior consultant with Hortus Technical Services, and Peter Hocking, executive officer of the Bundaberg Fruit and Vegetable Growers Association. We held two meetings in September 2015**.** Background information (including GPA biology, life history, resistance to chemistries worldwide and in Australia, and current chemicals registered against GPA in horticultural crops) was sent to experts for review ahead of the meetings. The first meeting involved a number of key horticultural growers and consultants/agronomists in Bundaberg to discuss: (i) the major crops grown in the region; (ii) the seasonality and cropping practices; and (iii) current GPA management practices and issues. Findings from this meeting were reviewed in a second meeting held in Toowoomba, involving Geoff Cornwell, product development manager at DuPont, and Melina Miles, QDAF senior entomologist and resistance expert.

As an adjunct to the 3rd Australian Agrichemical Resistance Meeting held in Melbourne on 12th-13th November 2015, we held another workshop with resistance experts. This included researchers and resistance specialists: Dr Nancy Schellhorn (CSIRO), Dr Greg Baker (SARDI), Dr Owain Edwards (CSIRO) and Prof Ary Hoffmann (The University of Melbourne). During this workshop, a preliminary resistance management strategy was developed. The strategy was further developed by our team, prior to an industry consultation stage. This involved Jodie Pedrana (HIA), Dr Lewis Wilson (CSIRO), Dr Jamie Hopkinson (QLD DAFF), Dan Papacek (Bugs for Bugs), consultants/agronomists from the Bundaberg region, as well as representatives from the agrichemical industry (including Dow AgroSciences, Bayer Crop Science, DuPont Crop Protection and ISK). Following this meeting, it was decided that the RMS would include a section covering the sensitivity of beneficial species to different pesticides registered for GPA control in vegetable crops. Using a combination of scientific literature, expert and local knowledge, we refined the list of important beneficial species for vegetable crops in the Bundaberg region to include: predatory beetles, predatory bugs, predatory mites, spiders, five species of parasitic wasps, lacewing adults, thrips and bees. Information on insecticide toxicity for these species was collated from both local and international publically-available sources, before being reviewed by experts.

The fully developed RMS was launched at the Bundaberg Fruit and Vegetable Growers group (BFVG) quarterly meeting on 16th August 2016. The BFVG represents over 400 members growing more than 30 different commodities in the greater Bundaberg region. The RMS has been published on the **cesar** (http://cesaraustralia.com/latest-news/all/RMS-GPA-Bundaberg-vegetables) and AUSVEG (http://ausveg.com.au/biosecurity/GPA-RMS-Bundaberg-vegetables.pdf) websites, and will subsequently be made available on the BFVG and HIA websites.

Results

Understanding the current levels of insecticide resistance in GPA

For the national resistance surveillance program, we collected and cultured 25 GPA populations from the field. Populations were collected from capsicum, chilli, snapdragons, eggplants, cabbage, broccoli, liliums, potatoes and cauliflower. We collected 9 populations from Queensland, 4 populations from Victoria, 4 populations from South Australia, 5 populations from Tasmania and 3 populations from Western Australia (Fig. 1).

Figure 1. Locations of 25 field-collected GPA populations from vegetable crops

Our allelic TaqMAN® qPCR assays revealed widespread resistance to the three chemical groups screened (synthetic pyrethroids, organophosphates and carbamates) (Table 2). The genetic assays indicate aphids from all field-collected populations are expected to have a high level of resistance to synthetic pyrethroids (including bifenthrin and alpha-cypermethrin), and pirimicarb (a carbamate insecticide). The use of pyrethroids and pirimicarb (even at high rates) will not provide control against these populations. Furthermore, the mechanism of resistance to pyrethroids is also likely to render these products ineffective as an anti-feed.

Interpreting resistance-testing results for organophosphates is more complex. The amplified carboxyl-esterase mechanism leads to organophosphate resistance in GPA. This mechanism is unusual because it is regulated by DNA methylation, and can be ‘switched on’ in response to pesticide exposure. As a result, aphid populations carrying the gene amplification can quickly adapt to survive organophosphates, even though they may have recently been effective. Following DNA tests, all field-collected populations tested were found to contain gene amplification resistance at the esterase gene. Aphids from these populations are expected to have a moderate level of resistance (5-20 fold) to organophosphates, including dimethoate, omethoate and chlorpyrifos. However, the field efficacy of organophosphates against these aphids remains uncertain. Our research has shown an adequate level of control may be achieved initially against some populations, however the continued use of organophosphate insecticides is risky and likely to increase the local levels of resistance, rendering them ineffective.

These results are similar to other resistance testing we have recently undertaken on GPA populations from canola and pulses; across Australia there are high levels of resistance to carbamates, synthetic pyrethroids and organophosphates, which is contributing to control difficulties and grower frustrations.

Table 2. Resistance mechanism genotyping results for 25 field-collected GPA populations

			DNA Resistance Results*		
Population	**Region**	**Host plant**	**Carbamates**	**Pyrethroids**	**Organophosphates**
QLD1	Bowen	Capsicum	100% R	100% R	100% R
QLD2	Bundaberg	Eggplants	100% R	100% R	100% R
QLD3	Gumlu	Capsicum	100% R	100% R	100% R
QLD4	Ayr	Capsicum	100% R	100% R	100% R
QLD5	Osborne	Chilli (hot)	100% R	100% R	100% R
QLD6	Ayr	Capsicum	100% R	100% R	100% R
QLD7	Gumlu	Chilli (sweet)	100% R	100% R	100% R
QLD8	Gumlu	Capsicum	100% R	100% R	100% R
QLD9	Bowen	Capsicum	100% R	100% R	100% R
SA1	Adelaide Hills	Broccoli	100% R	100% R	100% R
SA2	Virginia	Eggplant	100% R	100% R	100% R
SA3	Virginia	Capsicum	100% R	100% R	100% R
SA4	Virginia	Capsicum	100% R	100% R	100% R
TAS1	Coal River Valley	Seed Cabbage	100% R	100% R	100% R
TAS2	Gawler	Cauliflower	100% R	100% R	100% R
TAS3	Wesley Vale	Broccoli	100% R	100% R	100% R
TAS4	Wynyard	Liliums	100% R	100% R	100% R
TAS5	Wesley Vale	Broccoli	100% R	100% R	100% R
VIC1	Werribee	Cabbage	100% R	100% R	100% R
VIC2	Murchinson	Snapdragons	100% R	100% R	100% R
VIC3	Warragul	Capsicum	100% R	100% R	100% R
VIC4	Werribee	Cabbage	100% R	100% R	100% R
WA1	Pemberton	Potatoes	100% R	100% R	100% R
WA2	Lancelin	Broccoli	100% R	100% R	100% R
WA3	Nannup	Potatoes	100% R	100% R	100% R

** R = resistance*

For the first time in Australia, we have documented resistance to neonicotinoids in GPA from horticultural crops. Of the 20 aphid populations screened to imidacloprid using phenotypic assays, 3 populations were found to be resistant (Table 3). Resistance ratios for these populations ranged between 4.5-fold (SA4) and 24.7-fold (QLD4) (Table 4). Genetic screening of aphids from each population confirmed our pesticide bioassay results. Every individual from the control susceptible population was found to carry susceptible alleles for R81T, and exhibited no increased copy number of the CYP6CY3 gene. Conversely, every aphid from SA4, WA1 and QLD4 had increased copy numbers of the CYP6CY3 gene compared with susceptible aphids (Table 4). None of these aphids had resistance alleles at the target site R81T loci.

Table 3. Resistance responses for GPA populations against imidacloprid at 72 h. All assays included a known susceptible population for comparison.

Bioassay	Population	Host plant	LD_{50} value (ng per aphid)	95% confidence limits	
				Lower	Upper
A	Susceptible		0.0084	1.8×10^{-6}	0.03
	QLD4*	Capsicum	0.209	0.099	0.49
	WA1*	Potatoes	0.155	0.039	0.63
B	Susceptible		0.009	0.0043	0.014
	TAS1	Cabbage	0.018	0.0028	0.039
	QLD3	Capsicum	0.021	0.011	0.033
	TAS4	Liliums	0.025	0.0015	0.069
C	Susceptible		0.007	0.002	0.021
	SA4*	Capsicum	0.034	0.024	0.051
	TAS3	Broccoli	0.0014	0.00073	0.0022
	TAS5	Broccoli	0.011	0.009	0.015
D	Susceptible		0.01	0.003	0.053
	SA2	Eggplants	0.0040#	-	-
	WA2	Potatoes	0.028	0.003	3.5
	VIC4	Cabbage	0.021	0.0055	0.11
E	Susceptible		0.0052#	-	-
	QLD1	Capsicum	0.0138	0.011	0.016
F	Susceptible		0.0024	2.7×10^{-12}	0.0082
	QLD2	Eggplants	0.00259	1.7×10^{-5}	0.0091
	SA3	Capsicum	0.011	2.4×10^{-8}	0.04
	VIC3	Capsicum	0.0068	0.0023	0.01
G	Susceptible		0.0071	5.6×10^{-8}	0.026
	QLD5	Chilli	0.004	0.00062	0.0088
	SA1	Broccoli	0.016	0.0075	0.027
	VIC1	Cabbage	0.0046	1.4×10^{-5}	0.018
H	Susceptible		0.018	0.013	0.023
	VIC2	Snapdragons	0.0044#	-	-
	QLD6	Capsicum	0.0196	0.0014	0.051

** Indicates populations that have significantly different LD_{50} compared to the susceptible population.*

 # Confidence intervals could not be computed.

Table 4. Resistance ratios and CYP6CY3 copy number of the four GPA populations showing phenotypic resistance to imidacloprid

Population	Resistance Ratio	CYP6CY3 copy number
SA4	4.5	6.0
QLD4	24.7	6.7
WA1	18.3	2.8
Susceptible	-	1.1

These findings indicate higher concentrations of imidacloprid and other neonicotinoids will be required to achieve the same level of control of some GPA populations compared with others. It also highlights the vulnerability of this chemical group and has implications for GPA management practices going forward. Imidacloprid is widely used in all horticultural regions of Australia. The presence of low-level resistance to neonicotinoids demonstrates current management practices are not sustainable. If GPA management practices remain the same, there is a reasonable likelihood that imidacloprid and other neonicotinoids will become completely ineffective due to resistance development and spread.

Developing and optimizing phenotypic assays for GPA

We developed and optimized phenotypic bioassays for sulfoxaflor (Transform™), pymetrozine (Chess®), spirotetramat (Movento®) and cyantraniliprole (Benevia®). Importantly, no resistance was detected in any field collected GPA population to any of these chemicals. This has considerable implications for the ongoing management of aphids in Australian vegetable crops.

We identified a suitable dose range for each insecticide, and the optimum time to score mortality. For all products except pymetrozine, we then screened a large number of field-collected GPA populations. These bioassay methods and baseline data are crucial tools for the early detection of any potential problems with insecticide resistance in the future. They enable a quick and relatively straightforward approach to respond to field control failures by testing a discriminating dose range, and comparing these results to those generated in this project.

For sulfoxaflor, we screened 12 GPA populations collected from Queensland, South Australia, Victoria, Western Australia and Tasmania. Our results show no difference in mortality between any of these populations when compared with a known susceptible control population at equivalent rates (Table 5).

Table 5. Resistance responses for GPA populations against sulfoxaflor at 72 h. All assays included a known susceptible population for comparison.

Bioassay	Population	Host plant	LD_{50} value (ng per aphid)	95% confidence limits	
				Lower	Upper
A	Susceptible		0.0055#	-	-
	TAS3	Broccoli	0.0046	0.00090	0.022
	SA4	Capsicum	0.020#	-	-
	TAS5	Broccoli	0.016	0.0023	0.12
B	Susceptible		0.0015	2.8×10^{-6}	0.073
	VIC2	Snapdragons	0.0037	0.00060	0.020
	QLD7	Chilli	0.0075	1.6×10^{-5}	2.5
C	Susceptible		0.0034	0.0011	0.011
	QLD1	Capsicum	0.0025	0.00016	0.026
	WA2	Potatoes	0.0064	0.0019	0.021
	VIC4	Cabbage	0.0026	1.3×10^{-6}	0.22
	QLD4	Capsicum	0.00025	4.2×10^{-5}	0.00098
D	Susceptible		0.0020	0.0012	0.0035
	WA3	Broccoli	0.011	0.0021	0.064
	QLD6	Capsicum	0.0031	0.00036	0.020
E	Susceptible		0.0017	7.0×10^{-6}	0.063
	WA1	Potatoes	0.0072	0.00013	0.27

Confidence intervals could not be computed.

For spirotetramat, we screened 10 GPA populations collected from Queensland, South Australia, Victoria, Western Australia and Tasmania. Our results show no difference in mortality between any of these populations when compared with a known susceptible control population at equivalent rates (Table 6).

Table 6. Resistance responses for GPA populations against spirotetramat at 96 h. Every assay includes a known susceptible population for comparison. a.i. = active ingredient

Bioassay	Population	Host plant	LD_{50} value (g a.i./L)	95% confidence limits	
				Lower	Upper
A	Susceptible		0.00048	0.00023	0.00077
	VIC2	Snapdragons	0.00036	0.00013	0.00058
	WA2	Potatoes	0.00049#	-	-
B	Susceptible		0.0011	0.00074	0.0016
	SA2	Eggplant	0.00019	0.000062	0.00038
	SA1	Broccoli	0.0011	0.00035	0.0032
C	Susceptible		0.00018#	-	-
	TAS1	Cabbage	0.00097	0.00028	0.0029
	VIC3	Capsicum	0.000081#	-	-
	TAS5	Broccoli	0.00042	1.0×10^{-12}	0.0052
D	Susceptible		0.00027	5.9×10^{-7}	0.0015
	WA1	Potatoes	0.00074	0.00044	0.0011
	QLD6	Capsicum	0.00039	0.00013	0.00086
	WA3	Broccoli	0.00042	0.00021	0.00073

 # Confidence intervals could not be computed.

For cyantraniliprole, we screened 7 populations collected from Tasmania, Victoria and Western Australia. Our results show no difference in mortality between any of these populations when compared with a known susceptible control population at equivalent rates (Table 7).

Table 7. Resistance responses for GPA populations against cyantraniliprole at 96 h. Every assay includes a known susceptible population for comparison.

Bioassay	Population	Host plant	LD_{50} value (ppm)	95% confidence limits	
				Lower	Upper
A	Susceptible		0.0033	4.7×10^{-7}	0.093
	TAS3	Broccoli	0.0010	5.0×10^{-26}	3.3
	VIC2	Snapdragons	0.40	0.067	2.4
B	Susceptible		0.51#	-	-
	QLD6	Capsicum	0.14	0.00090	33
	QLD7	Chilli	1.9	0.070	1663
C	Susceptible		0.19	0.0031	1.2
	VIC4	Cabbage	0.26	0.086	0.80
	WA2	Potatoes	0.37	0.022	8.0
	WA3	Broccoli	0.49	0.062	4.1

 # Confidence intervals could not be computed.

Field and genetic studies to understand broad-scale movement and spread of resistance

To better understand the movement of GPA and spread of insecticide resistance, we examined the clonal make up of aphid populations from adjacent horticulture and broadacre grain crops collected in 2013 in Bairnsdale, VIC, and in 2014 across South Australia (Fig. 2). In both instances we found that genetic clones were shared between broadacre and horticultural crops. In Bairnsdale, aphids were collected from five broadacre populations and three horticulture populations. Seven different clones were found in both broadacre and horticultural crops, and four of those clones were shared between the two crop types. The four shared clones dominated the population make up in both broadacre and horticultural crops, making up 94% of the aphids tested (Table 8a). In South Australia, from ten broadacre populations and four horticulture populations, the horticulture crops had four clones, and broadacre crops had thirteen clones, however, again the majority of the populations from both crop types (79%) consisted of four shared clones (Table 8b). The most common of these clones, clone A and clone B, were also shared between the Bairnsdale collections and the South Australian collections, and clone K, a clone found only in broadacre crops, was also found in both Bairnsdale and South Australia. The two dominant clones (clone A and clone B) accounted for 78% of all individuals screened across all populations. Unique clones (clones that were found only in broadacre or only in horticultural crops) accounted for only 18% of the total GPA collected.

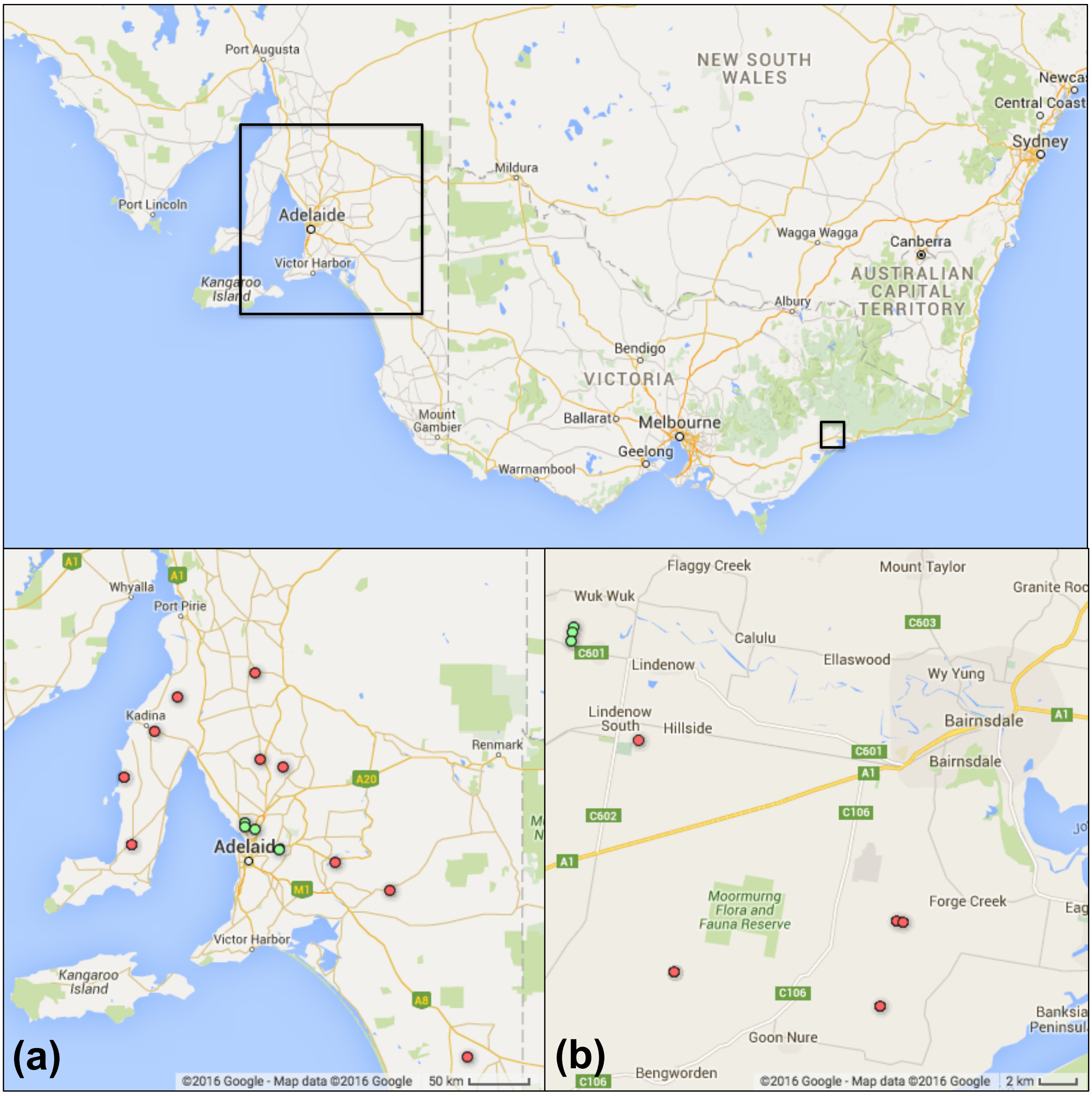

Figure 2. Location of GPA populations collected from horticultural (green) and broadacre (red) crops in: (a) South Australia; and (b) Bairnsdale, Victoria.

Table 8a. Clonal diversity of GPA populations collected from broadacre and horticultural crops in Bairnsdale, Victoria[#]

			Shared Clones				Unique Clones				
Population	**Host crop**	**# clones**	**A**	**B**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Broadacre1	Canola	2	60%	40%								
Broadacre2	Canola	5	17%	61%	11%	6%	6%					
Broadacre3	Canola	3	50%	35%				15%				
Broadacre4	Canola	3		90%	5%				5%			
Broadacre5	Canola	3	75%	20%		5%						
Horticulture1	Broccoli	6	41%	12%	6%	24%				6%	12%	
Horticulture2	Cauliflower	2		83%	17%							
Horticulture3	Broccoli	4	47%	42%		5%						5%

Table 8b. Clonal diversity of GPA populations collected from broadacre and horticultural crops in South Australia[#]

			Shared Clones			Unique Clones										
Population	**Host crop**	**# clones**	**A**	**B**	**L**	**C**	**K**	**M**	**N**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**
Broadacre1	Canola	3	65%	30%	5%											
Broadacre2	Canola	3	45%	50%				5%								
Broadacre3	Canola	6	16%	37%				5%	21%	5%	16%					
Broadacre4	Canola	4	28%	28%	39%			6%								
Broadacre5	Canola	2	89%	11%												
Broadacre6	Canola	4	30%	60%	5%							5%				
Broadacre7	Canola	7	30%	10%					5%	5%	40%		5%	5%		
Broadacre8	Canola	3	61%	33%			6%									
Broadacre9	Canola	3	75%	13%											13%	
Broadacre10	Canola	4		45%					40%	10						5%
Horticulture1	Eggplant	1		100												
Horticulture2	Broccoli	1	100													
Horticulture3	Capsicum	2	95%		5%											
Horticulture4	Capsicum	1				100%										

[#] *Letters represent different clones.*

These initial results suggested considerable movement of GPA between different crop types and between regions. We then looked nationally to investigate the broad-scale movement of aphids and spread of insecticide resistance alleles. Using 10 DNA microsatellite markers, we genotyped over 100 GPA populations from our extensive library of field populations collected for this and other concurrent research projects. This included 28 populations collected from horticulture crops across Australia. A total of 52 different clones were identified from 1618 GPA adult individuals screened. Surprisingly, we found three dominant clones that are widespread across Australia: clone A, clone B and clone C (Table 9). These clones make up ~80% (1288 individuals) of all GPA adults screened across all populations to date, and all three clones have a similar resistance profile, showing resistance to carbamates, synthetic pyrethroids and organophosphates. This is similar to the situation in Europe, where two dominant clones of GPA have spread across the continent (O. Edwards, pers comm.). In Australian GPA populations, clone A was the most widespread, found in 43 populations (858 adults) across all states, then clone B, found in 23 populations (268 individuals) and present in all states except Western Australia, and finally clone C, found in 12 populations (162 individuals), but only from Victoria, Queensland and South Australia.

Table 9. The number of populations in each state where each GPA 'super-clone' was detected

State	Clone A	Clone B	Clone C	TOTAL
Victoria	8	7	2	17
Tasmania	5	2	0	7
New South Wales	6	4	0	10
Queensland	2	1	8	11
Western Australia	9	0	0	9
South Australia	13	9	2	24

Of the remaining 49 clones identified, 6 were found in multiple populations, whilst the rest were unique to a single population. Fig. 3 highlights the genetic relationships between the 52 clones identified across Australia. Importantly, 29 clones identified had genotypes at the SNP markers that indicated they have resistance to carbamates, synthetic pyrethroids and different levels of resistance to organophosphates. Another five clones are likely to be resistant to synthetic pyrethroids (but not carbamates or organophosphates), while the remaining 18 clones (representing <7% of individuals screened) are likely to be susceptible to all three chemical groups. Interestingly, none of the clones had the R81T resistance alleles, indicating that this target site mutation that provides a high level of resistance to neonicotinoids in Europe, is unlikely to be present in Australian populations.

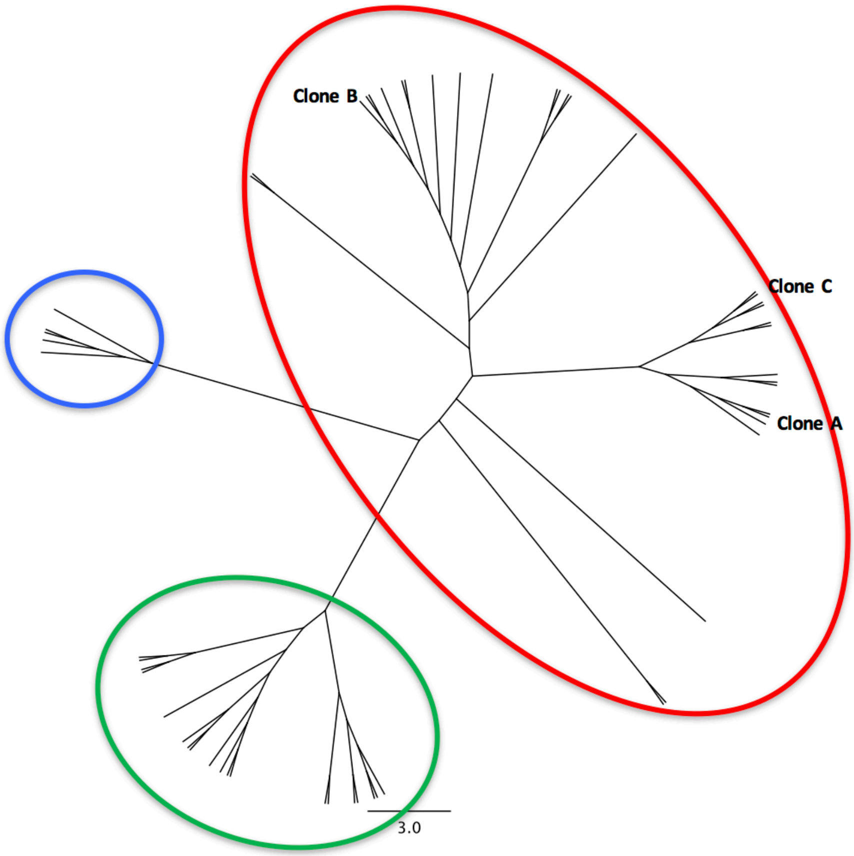

Figure 3. Unrooted dendogram of all GPA clones identified in Australia indicating genetic relationships. Tips of branches indicate a unique clone. Super clones are indicated (Clone A, B and C). Red circle indicates clones that have resistance to carbamates, synthetic pyrethroids and varying levels of resistance to organophosphates; blue circle highlights clones that have resistance to synthetic pyrethroids only; green circle indicates clones that are susceptible to carbamates, synthetic pyrethroids and organophosphates.

Statistical analyses looking at the relationships between the dominant clones (A, B and C) with region, host plants species, host plant family and crop type revealed several broad trends. Clone C appears more likely to be found on Solenaceaous host plants (e.g. capsicum, eggplant), and clone B is more likely to be associated with broadacre crops than horticultural crops (Tables 10 and 11). Clone A was largely associated with the south-western regions of Australia, and was more likely to be found on Brassicaceous hosts, while there were no obvious regional patterns identified for either clone B or clone C (Table 12). Once again, this work demonstrates the high dispersal capacity of GPA, both between different cropping systems and across wide regions of Australia.

Table 10. Model rankings, models weights and deviance explained for clone C. Explanatory variables include state, host plant family, host plant species, and crop type (broadacre or horticulture).

Model	ΔAIC_c	$wAIC_c$	% deviance
Family	0.00	0.67	39.94
Family + Crop	1.92	0.26	40.11
State + Family	5.37	0.05	45.36
Null	34.59	<0.0001	0

Table 11. Model rankings, models weights and deviance explained for clone B. Explanatory variables include state, host plant family, host plant species, and crop type (broadacre or horticulture).

Model	ΔAIC_c	$wAIC_c$	% deviance
Crop	0	0.51	2.15
Null	2.24	0.17	0.00
Family + Crop	3.48	0.09	2.48
State + Crop	3.57	0.09	5.62
State	3.96	0.07	4.35
Family	5.66	0.03	0.34
State + Family + Crop	5.70	0.03	6.74

Table 12. Model rankings, models weights and deviance explained for clone A. Explanatory variables include state, host plant family, host plant species, and crop type (broadacre or horticulture).

Model	ΔAIC_c	$wAIC_c$	% deviance
State + Family	0	0.12	8.81
Species	0.35	0.10	9.50
Species + Crop	0.35	0.10	9.50
Family + Species	0.35	0.10	9.50
Family + Species + Crop	0.35	0.10	9.50
State + Species	0.98	0.07	13.46
State + Species + Crop	0.98	0.07	13.46
State + Family + Species	0.98	0.07	13.46
State + Family + Species + Crop	0.98	0.07	13.46
State	1.08	0.07	6.81
State + Crop	1.25	0.06	7.54
State + Family + Crop	1.83	0.05	8.95
Null	9.02	0.00	0.00

Resistance levels in different colour morphs

Multiple field-collected and lab cultured populations of GPA in this project contained different coloured aphids, including light and dark green, pink, and dark red morphs. This colour variation has previously been noted overseas, and is due to the type of carotenoids (colour pigments) within the aphid. During our field experiments, we found no evidence for different levels of insecticide resistance between colour morphs.

A single clonal type of GPA can be made up of both green and red morphs; and these different morphs from a single clonal population respond in exactly the same way to insecticides. Furthermore, we found that the dose-response curves of both red and green morphs of insecticide susceptible GPA were identical across several laboratory bioassays we undertook. This demonstrates that factors other than body colour are the source of insecticide resistance in this species.

There is some belief held by growers and advisors that greater insecticide-resistance is present in red morph populations, with reports of the red morph of GPA surviving various insecticide sprays in vegetable in crops in Queensland. This idea is not supported by overseas research or our findings in this project. There are a few possible reasons why red GPA appear to survive spray applications: 1) a resistant population of GPA (that happens to contain red morphs) is present in the sprayed crop, and 2) the red morph is much more obvious (both larger and more distinct) than the green morph on plant leaves.

Improved on-farm aphid control using insecticides

Access to new insecticides with differing modes of action (MoA) is integral to the success of resistance management and the long-term control of GPA. After an extensive consultative phase, we conducted a microcosm 'semi-field' trial with 8 insecticides with the potential to be registered for GPA control in vegetable crops. Results from the microcosm trial found several new products that provided similar efficacy as standard 'conventional' registered products - Transform™ and Pirimor®. In particular, three chemicals were highly efficacious against GPA: Product 1, Product 6 and Product 7 (Fig. 4). These products significantly reduced GPA numbers compared with the control tubs at all sampling dates. Full details of the methodology and results are shown in Appendix 1. Final microcosm trial reports were submitted to agrichemical companies and directly to HIA.

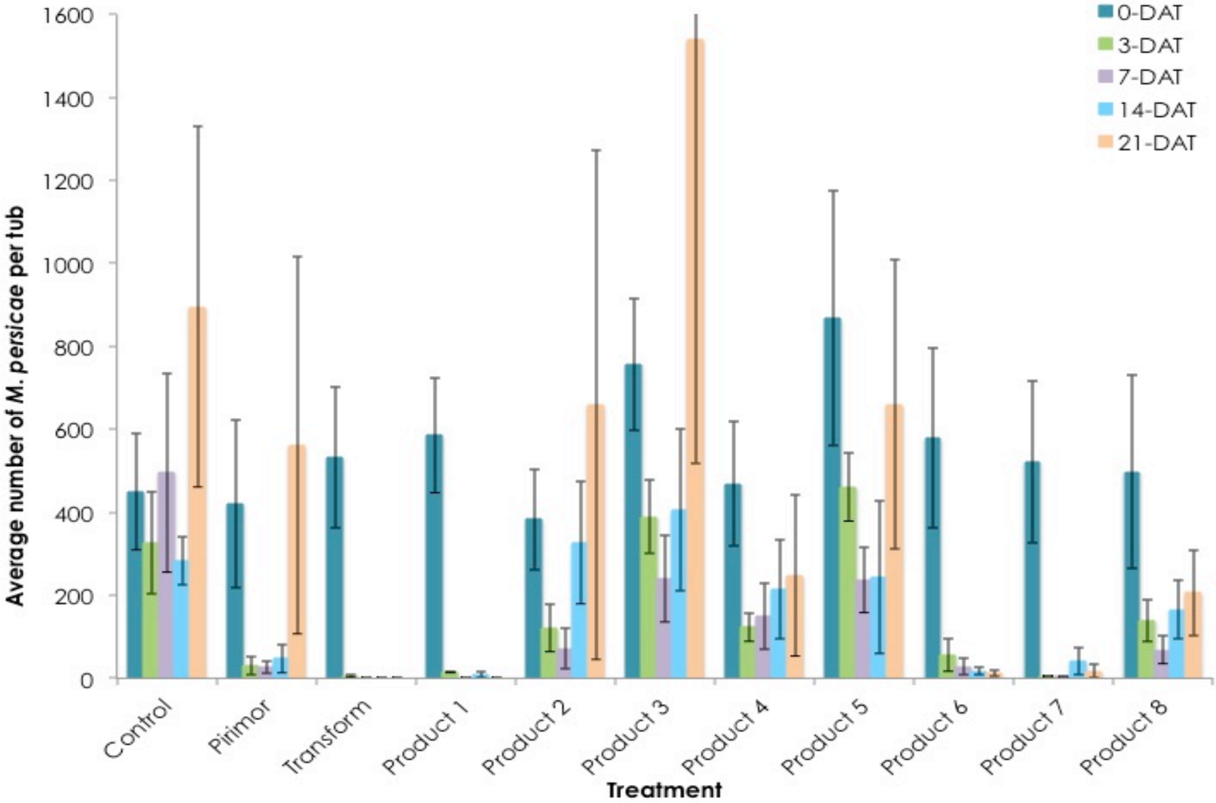

Figure 4. Average number of GPA per tub at each sampling date in microcosm spray trial.
Error bars represent standard error of the mean

The efficacy of Product 1 and Product 4 were further assessed in field trials on brassica vegetable crops. Two field trials were conducted in spring 2015 in northern and southern Queensland (Bowen and Lockyer Valley), and one field trial was undertaken in autumn 2016 in Victoria. In the two Queensland trials, field plots received an initial spray application, and a second application around 14 days later. Pest numbers were assessed prior to spraying and then at 3, 7, 14 and 21 days after each treatment. Plant damage, crop vigour and phytotoxicity were also assessed. In the Victorian trial, field plots received a single spray application. Pest numbers, plant damage, crop vigour and phytotoxicity were assessed prior to spraying and then at 3, 7, 17, 21 and 28 days after sprays were applied. Full details of the trial methodology are shown in Appendix 2.

Results from the two Queensland field trials indicate that one of the new products is highly efficacious against GPA (Product 1, Fig. 5 & 6). This product provided a similar level of control as the standard registered products – Transform™ and Beneiva®. Significant reductions in GPA numbers were seen 3-14 days following the application of Product 1 in the Bowen trial. Despite low aphid numbers in the Lockyer Valley trial, significant reductions were also seen 7 days following the application of Product 1. Product 4 also showed some efficacy against GPA at low numbers in the Lockyer Valley trial (Fig.6).

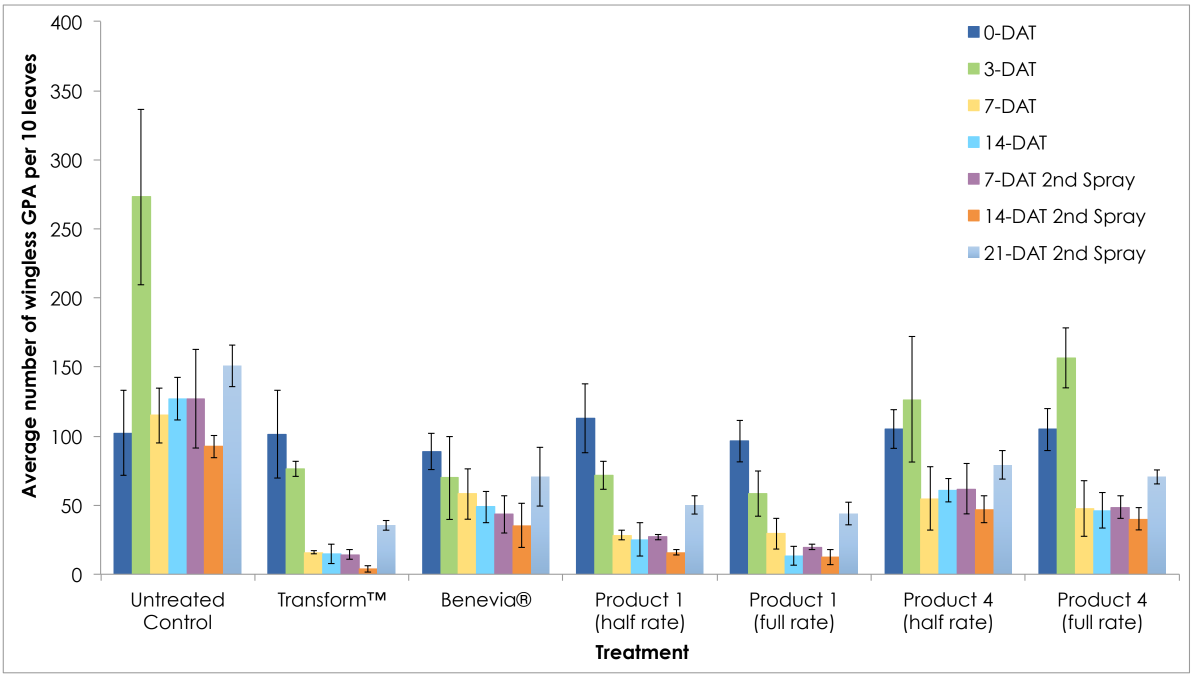

Figure 5. Average number of wingless GPA per 10 leaves in the Bowen field trial. Error bars represent standard error of the means.

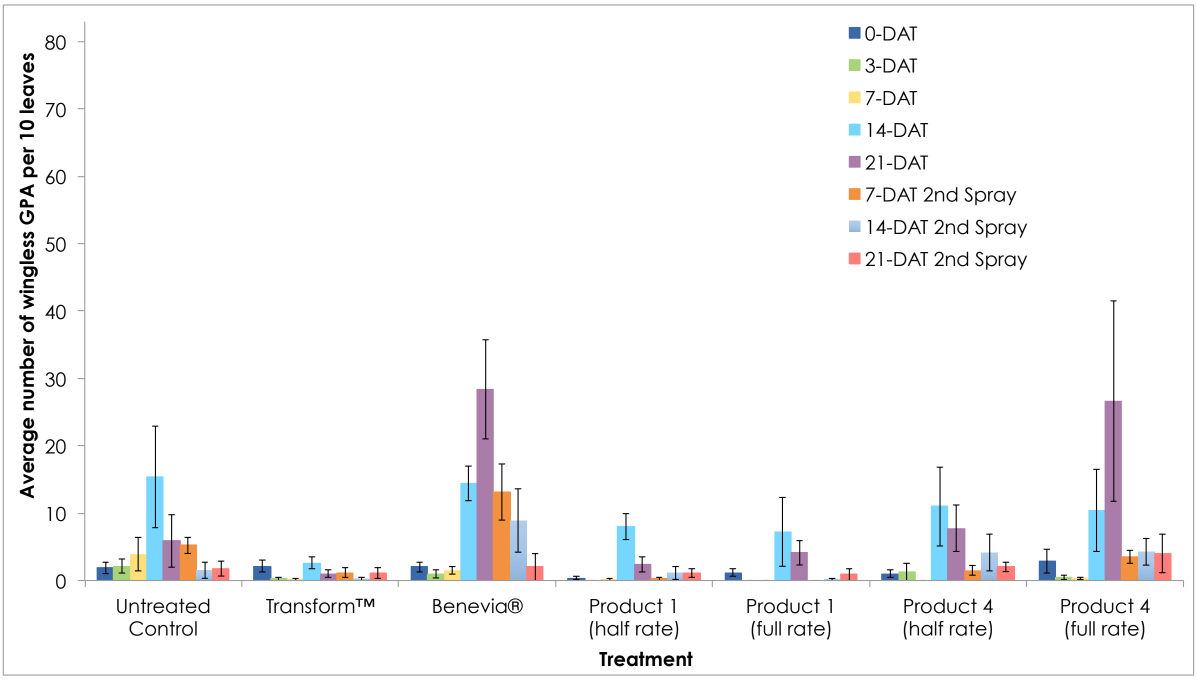

Figure 6. Average number of wingless GPA per 10 leaves in the Lockyer Valley field trial. Error bars represent standard error of the means.

Results from the Victorian field trial support the findings of the two Queensland field trials; Product 1 was highly efficacious against GPA (Fig. 7). Product 1 performed almost as well as the standard registered products – Transform™ and Benevia®, and significant reductions in GPA numbers were seen 3-17 days following application. Final reports and data packages from all trials were submitted to the relevant agrichemical companies to support the future registration of these products.

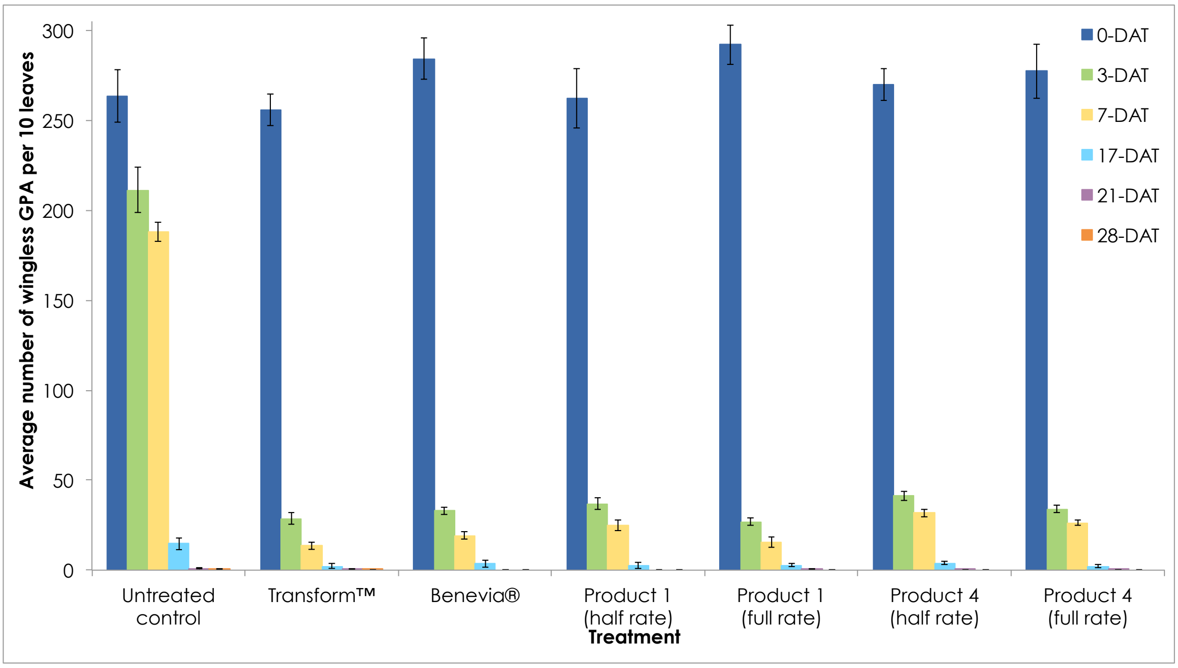

Figure 7. Average number of wingless GPA per 10 leaves in the Victorian field trial. Error bars represent standard error of the means.

Insecticide resistance management guidelines for GPA

To understand resistance drivers and current management strategies for GPA in horticulture, we conducted an industry benchmarking survey in 2014. We received 82 fully completed surveys. The majority of respondents were advisors (agronomists and consultants that work across more than one property), mostly from Victoria and Queensland. Analysis and interpretation of survey results were finalised in early 2015, and the final survey report was submitted to HIA (see Appendix 3).

Survey respondents reported GPA as a major and minor pest in many crops, and these varied with region. Where GPA is a minor or negligible pest, e.g. in fruit and tree crops, growers will typically not use insecticides to control GPA, rather relying on biological control agents such as beneficial insects. Where GPA is a major pest, in crops such as capsicum/chillis, Asian vegetables and potatoes, control methods used by growers tend towards high levels of insecticide spraying, often more than twice in a growing season. In some crops, insecticide application levels were reported to be as high as 10 sprays in one season. The majority of respondents report carrying out regular monitoring for GPA – at least once a week for most crops. The most common control method used was to only apply insecticide(s) once GPA populations had reached a threshold level in the crop. There were differences between regions with regards to the main chemical used for GPA control. Queensland growers were reported to have the highest application of sulfoxaflor in the country, whereas Victorian and New South Wales growers mainly use neonicotinoids, and South Australian and Western Australian growers rely heavily on carbamates. Most respondents indicated they rotate between chemical groups when applying more than once spray per growing season. The main reason respondents gave for rotating chemical groups was concerns about insecticide resistance. Respondents reported the highest level of control failures for GPA in Victoria, but control failures were reported from all states. When a control failure was experienced, all but one grower believed the failure was due to insecticide resistance. This contrasted the advisors; only 50% believed the spray failures they had experienced were due to resistance in GPA.

Using this benchmarking information and results generated through this project, we developed a resistance management strategy (RMS) for GPA in a defined geographic region: the Bundaberg horticultural region of Queensland. Six key regional consultants/agronomists attended the Bundaberg RMS development meeting, held on 23rd September 2015. We delivered a presentation on the current resistance status of GPA in Australia, and led a discussion on Bundaberg-specific crop practices and management issues. We also visited several farms in the region to discuss GPA management practices with growers.

Key findings from this meeting included:

- Most aphid management in cucurbit crops is focused on aphid-transmitted virus prevention
- Spraying practices are intensive and occur year-round
- Several cultural practices are used, such as planting adjacent crops up-wind to prevent aphid population migration
- Transform™ is often seen as a 'silver bullet' solution for GPA management, and is the most commonly used insecticide for GPA control

Following the Bundaberg meeting, we met with Geoff Cornwell (DuPont Crop Protection) and Dr Melina Miles (QDAF) in Toowoomba on the 24th September 2015. After reviewing the background information and management practices from Bundaberg, a preliminary area-wide spray window strategy was proposed. Further review by key Bundaberg contacts, Eddy Dunn and Peter Hocking, indicated that an area-wide spray window restricting chemical use to very specific times (week-to-week) across the entire Bundaberg region would have very little potential for grower uptake. The preliminary RMS was reworked and proposed as a 4-window strategy, with specific chemical groups restricted to either the autumn and spring windows or the summer and winter windows. The new strategy allows for a 3-month rest for chemistries in between windows. See Appendices 4 and 5 for the resistance management strategy, including background information and scientific rationale.

As an adjunct to the 3rd Australian Agrichemical Resistance Meeting held in Melbourne on 12th-13th November 2015, we held another workshop with resistance experts. During this workshop, expert opinion confirmed that the window methodology would reduce the risk of further resistance developing in GPA populations in this region. The strategy was expanded to include cultural practices aimed directly at aphid/plant virus management, and a section of the RMS devoted to the sensitivity of beneficial insects to the various chemistries proposed for GPA management.

Using a combination of scientific literature, expert and local knowledge, we refined the list of important beneficial species for vegetable crops in the Bundaberg region to include: predatory beetles, predatory bugs, predatory mites, spiders, lacewings, thrips, bees and five species of parasitic wasps (Figure 8). Information on the impact of insecticides on beneficial species was then collated from a variety of sources including the Cotton Pest Management Guide (2015), the Biobest side-effects manual (2015), and The Good Bug Book (2002). The impact rating gives the % reduction in beneficial species following chemical application: VL (very low), less than 10%; L (low), 10–20%; M (moderate), 20–40%; H (high), 40–60%; VH (very high), > 60%. '–' indicates no data available for specific local species. The completed table was sent to beneficial toxicity experts Dr Lewis Wilson (CSIRO), Dr Jamie Hopkinson (QDAF) and Dan Papacek (Bugs for Bugs) for review. Certain toxicity ratings were revised based on their advice (e.g. see footnote 7, Fig. 8).

Finally, we sent the completed RMS to relevant agrichemical companies for comment. The RMS was reviewed by Geoff Cornwell (DuPont Crop Protection), Shane Trainer (Bayer Crop Science), Gerry Shepard (ISK) and Rob Annetts (Dow AgroSciences), and further refined following this feedback. Several chemical company representatives mentioned company data on the toxicity of chemicals to beneficial insects and mites. This was not included in our RMS. It is recommended that all available information on the toxicity to beneficials is considered in any future efforts to compile insecticide sensitivity data.

The RMS was launched to Bundaberg growers and advisors on 16th August 2016 at the Bundaberg Agronomic Group Meeting, hosted by Bree Grima, director of the Bundaberg Fruit and Vegetable Growers group (BFVG). This meeting was attended by 20-30 advisors, who provide advice to the majority of horticultural growers in the wider Bundaberg region.

Figure 8. Impact of insecticides on beneficial insects and mites of relevance to vegetable crops.

Insecticide	Predatory beetles[1]				Predatory bugs					Predatory mites	Spiders	Parasitic Wasps						Lacewing adults	Thrips[6]	Toxicity to bees[9]
	Total[2]	Red & Blue beetle	Minute 2-spotted lady beetle	Other lady beetles	Total[3]	Damsel bugs	Big-eyed bugs	Other Predatory bugs	Apple Dimpling			Total	*Eretmocerus*[7]	*Encarsia formosa*	*Trichogramma*	*Aphytis*	*Aphidius*			
Paraffinic oil	VL	L	L	VL	VL	VL	VL	VL	VL	-	L	VL	-	-	VL	-	VL	VL	VL	VL
Petroleum oil	-	-	-	L	-	-	-	-	-	M	-	-	-	H	-	M	-	-	-	-
Cyantraniliprole	M	M	VL	L	M	M	M	H	L	-	M	VL	L	-	VL	-	VL	VH	H	-
Spirotetramat	M	L	H	H	VL	VL	VL	VL	M	-	M	M	L	-	M	-	M	VH	M	-
Pirimicarb	H	VL	VL	L	M	L	M	VL	VL	L	VL	VL	M	H	H	L	VL	L	L	VL
Flonicamid	L	VL	VL	VL	H	H	VH	H	H	-	M	M	L	-	H	-	M	L	H	-
Diafenthiuron	M	H	VL	M	L	M	VL	L	H	-	L	L	H	-	L	-	L	L	L	M
Pymetrozine	M	M	M	M	M	L	L	VL	H	L	L	L	L	M	L	L	L	M	VL	VL
Sulfoxaflor	H	L	M	H	L	VL	L	M	VH	-	L	M	-	-	H	-	M	H	H	-
Chlorantraniliprole/ Thiamethoxam	-	-	-	-	-	-	-	-	-	-	-	-	M	-	-	-	-	-	-	-
imidacloprid (irrigating)	H[4]	-	-	-	VH	-	-	-	-	-	-	-	L	-	L	-	-	L	-	-
Acetamiprid	H	M	VH	H	H	M	H	M	VH	-	VL	L	H	-	H	-	L	L	VH	M[10]
Imidacloprid (spraying)	H	L	VH	H	H	M	H	L	VH	M	L	L	VH	VH	H	H	L	M	H	M
Thiamethoxam	H	H	H	H	H	M	M	H	H	-	VL	M	M	-	H	-	M	M	H	H
Organophosphates[5]	H	M	H	H	H	M	H	H	VH	H	M	H	VH	VH	VH	H	H	M	H	H
Tau-fluvalinate	VH	-	-	-	VH	-	-	-	-	-	-	-	VH	-	VH	-	-	M	-	-
Piperonyl Butoxide / Pyrethrins	VH	-	-	-	VH	-	-	-	VH	-	VH	VH	VH	-	VH	-	VH	H	VH	H
Bifenthrin/ Chlorpyrifos	VH	-	-	-	VH	-	-	-	VH	-	VH	VH	VH	-	VH	-	VH	VH	VH	H
Permethrin	VH	-	-	H	VH	-	-	-	VH	H	VH	VH	VH	VH	VH	H	VH	VH	VH	H

1. Toxicity ratings for predatory beetles and Hymenoptera are for adults only.
2. Total predatory beetles – ladybeetles, red and blue beetles, other predatory beetles.
3. Total predatory bugs – big-eyed bugs, minute pirate bugs, brown smudge bugs, glossy shield bug, predatory shield bug, damsel bug, assassin bug, apple dimpling bug.
4. This rating is for the larval stage of predatory beetles because irrigating affects soil organisms.
5. Organophosphates: diazinon, chlorpyrifos, dimethoate, maldison, methamidophos, omethoate, phorate.
6. Toxicity ratings for Hymenoptera are for adults only.

7. Rankings for Eretmocerus based on data from Jamie Hopkinson in semi-laboratory replicated experiments (QDAF) and on ranking for E. mundus (P. De Barro, CSIRO, unpublished) and for E. eremicus (Koppert Biological Systems, The Netherlands (http://side-effects.koppert.nl/#).
8. Effects on thrips are for populations found on leaves. This is relevant to seedling crops, where thrips damage leaves, and to mid-late season when thrips adults and larvae help control mites by feeding on them as well as on leaf tissue.
9. Data Source: British Crop Protection Council. 2003. The Pesticide Manual: A World Compendium (Thirteenth Edition). Where LD50 data is not available impacts are based on comments and descriptions. Where LD50 data is available impacts are based on the following scale: very low = LD50 (48h) > 100 ug/bee, low = LD50 (48h) <100 ug/bee, moderate = LD50 (48h) < 10 ug/bee, high = LD50 (48h) < 1 ug/bee, very high = LD50 (48h) < 0.1 ug/bee.
10. Wet residue of these products is toxic to bees, however, applying the products in the early evening when bees are not foraging will allow spray to dry, reducing risk to bees the following day.

Extension and Communication

We have extended our work and communicated findings to industry throughout the project, as detailed below.

AUSVEG Weekly Update (Date TBC). Insecticide resistance in Green Peach Aphids: Red or Green? You're asking the wrong question.

Bundaberg Fruit and Vegetable Grower Group Meeting - Bundaberg, Queensland. "Resistance management strategy for green peach aphids in Bundaberg vegetable crops". 16/08/2016.

AUSVEG Weekly Update (26/07/2016). New resistance management strategy for Green peach aphid. 26/07/2016

AUSVEG Biosecurity website. Resistance management strategy for the green peach aphid in Bundaberg field vegetable crops. 22/07/2016

Minor Use Education Symposium, held in conjunction to the 2016 National Horticulture Convention – Gold Coast, Queensland. "Management of insecticide resistance in the green peach aphid." 25/06/2016

cesar pty ltd website. Resistance management strategy for the green peach aphid in Bundaberg field vegetable crops. 21/06/2016

ABC Rural Radio. Discussing insecticide resistance issues in green peach aphids. 12/05/2016

AUSVEG Magazine: Potatoes Australia (April/May 2016). Green peach aphid: a deceptive name for a potato pest. 15/04/2016

cesar pty ltd website. Insecticide resistance in Green Peach Aphids: Red or Green? You're asking the wrong question. 07/03/2016

AUSVEG Magazine: Vegetables Australia (April-March 2016). Researchers contribute innovative solutions to the fight against Green peach aphid. 18/02/2016

ABC Rural Radio. Discussing insecticide resistance issues in green peach aphids and redlegged earth mites. 14/11/2015.

3rd Australian agrichemical resistance meeting – Melbourne, Victoria. "The contrasting stories of resistance evolution and spread in green peach aphids and redlegged earth mites". 12/11/2015.

Radio 3WM. Discussing green peach aphid resistance and availability of resistance testing service. 05/06/2015.

51st Australian Entomological Society annual conference - Cairns, Queensland. "Management of insecticide resistance: using leading-edge technologies in on-farm management". 30/09/2015.

Hortus Technical Services Consultant Meeting - Bundaberg, Queensland. "Green peach aphids and insecticide resistance management". 23/09/2015.

Melon News (Volume 1, 2015) "Managing insecticide resistance in the green peach aphid" (pg. 9). March 2015

VegeNotes (Issue 43) "Management of insecticide resistance in the green peach aphid". August 2014

Outputs

This project has produced recommendations about insecticide resistance management and improved control methods for GPA. A key component of the work is the integration of field surveillance and aphid movement studies, which enables long-term management and monitoring guidelines to be implemented including:

- Benchmarking the management practices of growers across different crop types and geographic regions to help identify resistance drivers and assist in the development of resistance management strategies for GPA.
- A clear understanding of the level and distribution of insecticide resistance to multiple chemical groups in GPA populations across Australia.
- Development of robust testing methodologies and generating insecticide baseline sensitivity data for a range of chemical products.
- An improved understanding of the movement of resistant GPA clones regionally, and nationally.
- A series of efficacy trials assessing the potential of multiple chemistries against GPA.
- Providing data sets to agrichemical companies to support the registration of insecticides against GPA in vegetable crops.
- Development of a regionally-specific resistance management strategy that can be adapted to suit other regions.
- Collation of best-available information on the toxicity of insecticides (those registered to control GPA in vegetable crops) to beneficial insects and mites.
- An improved understanding of the different colour morphs of GPA clones, particularly the finding of no difference in the levels of insecticide resistance between different red and green morphs.

Outcomes

Greater understanding of the nature, distribution and importance of insecticide resistance in GPA nationally

Genetic testing and clonal typing has revealed the existence of three super-clones that dominate GPA populations in horticulture across Australia. These clonal types have a profile of resistance to carbamates, pyrethroids and organophosphates, indicating resistance to these three chemical groups is found nationally. The use of pyrethroids and pirimicarb (even at high rates) will not provide control against these populations of aphids. Furthermore, the mechanism of resistance to pyrethroids is also likely to render these products ineffective as an anti-feed. Aphids from these populations are expected to have a moderate level of resistance to organophosphates, however the field efficacy of organophosphates against these aphids remains uncertain. Some control may be achieved initially, however the continued use of organophosphate insecticides is risky and may not be effective (particularly if the population has previously been exposed to insecticides in a given season).

Through both genetic testing and pesticide bioassays, we have also identified the first evidence of imidacloprid resistance in GPA in Australia. Four populations tested (from Queensland, Western Australia and South Australia) were found to have low-level resistance to imidacloprid. This is the first time neonicotinoid resistance has been detected in Australia. These novel findings have major implications for GPA management practices. Our industry survey report identified imidacloprid as a high-use chemical for GPA in some regions of Australia, identifying an immediate need for new chemistries and resistance management strategies to help control this pest.

A reduction in the use of broad-spectrum insecticides (e.g. synthetic pyrethroids, organophosphates and neonicotinoids) will reduce the potential for spray failures, decrease the selection for further resistance to these chemistries, and enhance IPM practices that utilise beneficial insects and mites. Importantly, no resistance has been found to Transform™, Movento® or Benevia in GPA populations tested across Australia. This project has developed valuable base-line sensitivity data to these newer chemistries, information that will be vital in future monitoring of GPA responses to these insecticides.

Vegetable growers will better understand GPA movement and have tools to more effectively manage aphid populations

In addition to the three super-clones that make up the majority of all GPA populations, we found a large number of clones present in vegetable (and broadacre) growing regions. Our work indicates widespread movement of different GPA clones between crops, between production regions and even across states. This highlights the importance of nationally aligned resistance management practices for GPA across regions and industries. This project undertook several microcosm and field trials exploring potential new chemistries for use against GPA in vegetables. Registration of chemicals with new modes of action (MoA) will increase the number of chemical tools growers have available to control GPA, reducing the reliance on any one product, and therefore reducing the potential of resistance evolving. We identified several promising chemicals and generated valuable data sets to assist agrichemical companies in the registration of insecticides against GPA in vegetable crops.

Improved sustainability and consumer safety by reducing broad-spectrum insecticide use in vegetable production

Our industry benchmarking survey of current control practices for GPA revealed that many different management practices are employed to deal with aphids in vegetable crops within Australia. There are differences between geographic regions and crop types with regards to the main chemicals used for GPA control, and the number of insecticide sprays applied per season. The survey indicated widespread use of neonicotinoids and carbamates to control GPA. This project has identified resistance to both these chemistries, indicating the importance for ongoing resistance monitoring, and effective communication of resistance findings to growers, to allow them to make effective and sustainable management choices. The survey also indicated that most respondents rotate between chemical groups when applying more than once spray per growing season due to concerns about insecticide resistance, showing that growers and advisors are aware of resistance issues, and already taking steps to mitigate current and future resistance in this pest.

The complexity of regional differences in GPA management across Australia reveals that developing a single national resistance management strategy (RMS) for GPA in Australia is not feasible. Region- and crop-specific strategies have the best chance of targeting and changing unsustainable insecticide use practices, and as part of this project, and in consultation with growers, advisors and resistance experts, we developed an RMS for GPA in a defined geographic region: the Bundaberg horticultural region of Queensland. This case study RMS can be later extrapolated to other horticultural regions in Australia. A major focus of the RMS is on the rotation of insecticide groups when targeting GPA in order to reduce the selection pressure for resistance evolution. The strategy also includes cultural practices aimed directly at aphid/plant virus management, and best-available information on the sensitivity of beneficial insects to the various chemistries registered against GPA in vegetable crops. In the medium-term, the adoption of this RMS will improve pest management and insecticide stewardship. This will reduce selection pressure for resistance and increase the lifespan of those agrichemicals that are currently effective against GPA.

Evaluation and Discussion

This project was undertaken to explore and understand the current issues around resistance and control of GPA in vegetable crops using the best available scientific techniques. Given the history of control problems for GPA in northern Queensland, we initially focused field collections of GPA on the Bowen/Gumlu vegetable production region, sampling from nine different properties in the region. We also collected GPA from major vegetable growing regions in Victoria, Western Australia, South Australia and Tasmania. The national benchmarking survey we conducted on the current understanding and control strategies used to deal with GPA in vegetable crops revealed many differences in the management of GPA, with insecticide usage highest in Queensland and Western Australia, particularly in crops where GPA is considered a major pest. The findings of this benchmarking survey illustrate the complexity of GPA management within the horticultural system. In some regions, crops are reportedly sprayed up to 10 times in a single growing season, a practice that will greatly increase the probability of resistance evolving in pest species.

The project revealed that there is a nation-wide distribution of three clones of GPA that have a high level of resistance to synthetic pyrethroids and carbamates, and a moderate to high level of resistance to organophosphates. These three clones make up the majority of GPA populations in all horticultural and broadacre regions, indicating the widespread movement of different GPA clones between crops, between production regions and even across states. As these resistant clones have the potential to move extensively across landscapes, resistance issues in this pest species need to be addressed nationally and across industries. These results have been communicated widely to industry, raising the awareness of growers and advisors to the issues of managing highly resistant GPA within crops. As well as documenting and distributing these findings, we also investigated the relationship between GPA body colour and insecticide resistance. There is a long-standing belief among some growers, advisors and representatives from agrichemical companies that red colour morphs of GPA are more resistant to insecticide than green morphs. Our findings revealed that there is no relationship between GPA body colour and resistance, and that red and green colour morphs of GPA respond in exactly the same way to insecticides. These findings have been published online, in industry publications and presented to grower groups in order to dispel this conjecture about the GPA red-morph.

Low levels of resistance to neonicotinoids were detected in several GPA populations from Queensland, South Australia and Western Australia. This is the first time neonicotinoid resistance has been detected in Australian GPA populations, and this novel finding will be published as a peer-reviewed scientific journal. Using cutting-edge genetic technology and optimized bioassay techniques, we confirmed that the mechanism of resistance found in Australia is the same as that found in the majority of GPA populations worldwide. Given the extremely high use of neonicotinoids in the vegetable industry (up to 80% of vegetable nursery seedlings are drenched with neonicotinoids before planting), it will be essential for growers to practice resistance management when controlling GPA, and also understand the number of products that they use that are part of the IRAC neonicotinoid chemical group. We communicated these findings to industry, and have included information on IRAC chemical groups in the Resistance Management Strategy to aid in furthering understanding of true chemical MoA group rotation strategies to mitigate further resistance evolving.

As well as determining the current levels of resistance in GPA, this project developed and optimized robust testing methodologies for newer chemistries available for GPA control (sulfoxaflor, pymetrozine, spirotetramat, cyantraniliprole). As GPA are currently resistant to 4 IRAC MoA chemical groups, the use of these newer chemistries will undoubtedly increase in the future, and this baseline sensitivity data will allow industry to monitor and respond quickly if there are any future changes in sensitivity of GPA to these products. As part of this project we also conducted microcosm and field trials that document the effectiveness of new chemistries compared with current industry standards, and produced data on several chemical products from new chemical groups that are effective at controlling GPA. Increasing the number of IRAC MoA groups that are registered to control GPA in vegetable crops is essential to the management of resistance in this pest. Rotation of chemicals from different MoA groups is the cornerstone of any insecticide resistance management plan, and having a larger number of products to choose from should decrease the potential for resistance developing to any one product if they are used appropriately.

The findings of this project, along with feedback from growers, advisors and agrichemical companies, have been incorporated into a regional resistance management strategy for GPA. Due to the wide range of vegetable crops grown across different regions nationally, along with a wide disparity in GPA management, the resistance management strategy was focused on only one region: the Bundaberg vegetable growing region in Queensland. While the management strategy has been optimized to help growers and advisors in this area specifically with chemical and cultural management options based on local cropping practices, pest control, and environmental conditions, there are many elements of the strategy that are applicable nation-wide. In particular, the rotation of chemicals from different IRAC mode of action groups, spraying insecticides to control GPA only when economic thresholds are reached, and restricting the use of chemicals where there is already resistance, are all management strategies that will decrease the potential of further resistance developing in this pest across Australia. As well as communicating these resistance management options to growers and advisors through industry publications, and national and local presentations, as part of this project we have also promoted IPM principles as part of any GPA management strategy. In particular, with help from resistance experts, beneficial insect specialists and agrichemical companies, we have developed a preliminary table showing the toxicity to beneficial insects of current chemicals registered for GPA control in vegetable crops. This table is a valuable tool to assist growers with IPM decision-making and allow them to maximise the positive impact of beneficial insects and mites.

Recommendations

1. There is a need to improve stewardship of insecticide use to control GPA in horticultural crops. This will minimise resistance issues and prolong the life of the agrichemicals that are currently effective in Australia. The project findings, particularly the increasing incidence neonicotinoid resistance in GPA, need to be broadly communicated to Australian vegetable growers.

2. Surveillance efforts should continue across Australia to monitor ongoing insecticide resistance in GPA populations within vegetable production regions. This will provide the greatest chance of detecting resistant individuals to new chemistries when they are at a low frequency; resistance management programs will have a greater chance of success than if a large portion of individuals are already resistant before intervention. Cross-industry investment with the grains industry would leverage significant efficiencies and cost savings.

3. The RMS developed for Bundaberg field vegetable crops should be adapted to suit other regions. This should be accompanied by a communication plan. The utilisation of a range of communication tools (including workshops, field days, print, video, and web products) is widely accepted as being critical in the uptake of RMS documents by growers.

4. There is a need for IPM programs for GPA in Australian vegetable crops, including the introduction of 'softer' insecticides that have new MoAs, and thus fit within a resistance management framework. Laboratory and field trials are required to look specifically at biological and cultural control practices, and how these could be integrated into current pest (and crop) management approaches.

5. Investment in the development of a scientifically robust guide outlining the impact of registered insecticides on key beneficial species of vegetable crops. This guide, along with supporting information will ensure growers have a tool to assist with IPM decision-making and maximise the positive impact of beneficial insects and mites. Greater confidence in the use of IPM practices in the Australian vegetable industry, and thus a reduced reliance on broad-spectrum insecticides, will position the vegetable industry as a market leader in sustainable crop production practice for the benefit of Australian consumers and the environment.

6. Research to better understand aphid-virus interactions and virus-specific management strategies to provide growers with management tools based on the best-available science, including automated traps and prediction models that indicate key aphid flight timings, and seasonal virus risk information.

Scientific Refereed Publications

de Little, S. C., Edwards, O., van Rooyen, A., and Umina P. A. (Submitted) Discovery of metabolic resistance to neonicotinoids in green peach aphids (*Myzus persicae*) in Australia. *Pest Management Science*

de Little, S. C. and Umina P. A. (In Prep) Toxicity baseline studies of three recently registered insecticides for *Myzus persicae* in Australia. *Journal of Economic Entomology*

Intellectual Property/Commercialisation

Commercially valuable IP developed from this project includes data relating to the potential for new chemistries against GPA. This data will be used to assist agrichemical companies in moving towards registration of new insecticide products. During the microcosm trial and field trials in 2015 and 2016, we worked with 8 new chemical products from five companies. The names, active compound and MoA of these products are protected under confidentiality/intellectual property agreements with each company. All other project data arising from this project is publically available.

References

Anstead, J.A., Williamson, M.S. and Denholm, I. (2005). Evidence for multiple origins of identical insecticide resistance mutation in the aphid *Myzus persicae*. Insect Biochemistry and Molecular Biology 35: 249-256.

Anstead, J.A., Mallet, J. and Denholm, I. (2007). Temporal and spatial incidence of alleles conferring knockdown resistance to pyrethroids in the peach-potato aphid, *Myzus persicae* (Hemiptera: Aphididae), and their association with other insecticide resistance mechanisms. Bulletin of Entomological Research 97: 243-252.

Bass, C., Puinean, A. Andrews, M., Cutler, P., Daniels, M., Elias, J., Paul, V., Crossthwaite, A., Denholm, I., Field, L., Foster, S., Lind, R., Williamson, M. and Slater, R. (2011). Mutation of a nicotinic acetylcholine receptor β subunit is associated with resistance to neonicotinoid insecticides in the aphid *Myzus persicae*. Neuroscience 12: 51-62.

Bass, C., Zimmer, C.T., Riveron, J.M., Wilding, C.S., Wondji, C.S., Kaussmann, M., Field, L.M., Williamson, M.S. and Nauen, R. (2013) Gene amplification and microsatellite polymorphism underlie a recent insect host shift. Proc. Natl. Acad. Sci. U. S. A., 110: 19460–19465

Blackman, R.L. and Eastop, V.F. (2000) Aphids on the world's crops, an identification and information guide. Chcichester, UK. John Wiley & Sons Ltd.

Blackman, R.L. and Eastop, V.F. (2007) Taxonomic Issues. In. van Emden, H.F. and Harrington, R. Aphids as crop pests. Ch 1. CABI, UK.

Burnham, K.P. and Anderson, D.R. (2002) Model selection and multimodel inference: a practical information-theoretic approach. 2nd edition. New York, NY: Springer.

Devonshire, A.L., Field, L.M., Foster, S.P., Moores, G.D., Williamson, M.S. and Blackman, R.L. (1998). The evolution of insecticide resistance in the peach-potato aphid, *Myzus persicae*. Philosophical Transactions of the Royal Society of London 353: 1677-1681.

Devonshire, A. and Moores, G. (1982). A carboxylesterase with broad substrate specificity causes organophosphorus, carbamate and pyrethroid resistance in peach-potato aphid (*Myzus persicae*). Pesticide Biochemistry and Physiology 18: 235 – 246.

Edwards, O., Franzmann, B., Thackray, D. and Micic, S. (2008). Insecticide resistance and implications for future aphid management in Australian grains and pastures: a review. Australian Journal of Experimental Agriculture 48: 1523-1530.

Finney, D. (1971). Probit analysis. Cambridge, Cambridge University Press.

Foster, S.P., Denholm, I. and Devonshire, A.L. (2000) The ups and downs of insecticide resistance in peach-potato aphids (*Myzus persicae*) in the UK. Crop Prot. 19:873-879.

Foster, S.P., Denholm, I. and Devonshire, A.L. (2002) Field-simulator studies of insecticide resistance to dimethylcarbamates and pyrethroids conferred by metabolic- and target site-based mechanisms in peach-potato aphids, *Myzus persicae* (Hemiptera: Aphididae). Pest Management Science, 58: 811-816

Foster, S.P., Devine, G. and Devonshire, A.L. (2007) Insecticide Resistance. In. van Emden, H.F. and Harrington, R. Aphids as crop pests. Ch 10. CABI, UK.

Herron, G.A., Gibson, T.S. and Horwood, M.A. (1993). Insecticide resistance in *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) in southeastern Australia. Journal of the Australian Entomological Society 32: 23-27.

Johnson, R.M., Dahlgren, L., Siegfried, B.D. and Ellis, M.D. (2013). Acaricide, fungicide and drug interactions in honey bees (*Apis mellifera*). Plos One 8(1).

McDougall S. 2007. Field Vegetable IPM Stocktake. Final Report of Project VG05043 to Horticulture Australia Ltd.

Moores, G.D., Devine, G.J. and Devonshire, A.L. (1994) Insecticide-insensitive acetylcholinesterase can enhance esterase-based resistance in *Myzus persicae* and *Myzus nicotianae*. Pestic. Biochem. Physiol., 49: 114-120.

Puinean, A. M., Foster, S. P., Oliphant, L., Denholm, I., Field, L. M., Millar, N. S., Williamson, M. S. and Bass, C. (2010). Amplification of a cytochrome P450 gene is associated with resistance to neonicotinoid insecticides in the aphid *Myzus persicae*. Plos Genetics, 6, p. e1000999

R Development Core Team (2016). R: A Language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing.

Silva, A., Jander, G., Samaniego, H., Ramsay, J. and Figueroa, C. (2012). Insecticide resistance mechanisms in the green peach aphid *Myzus persicae* (Hemiptera: Aphididae): A transcriptomic survey. PLoS ONE 7(6) e36366. doi:10.1371/journal.pone.0036366

Sloane, M. A., Sunnucks, P., Wilson, A. C. C. and Hales, D. F. (2001). Microsatellite isolation, linkage group identification and determination of recombination frequency in the peach-potato aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae). Genetic Res Cambridge, 77: 251–260.

Umina, P. and Hoffmann, A. (1999) Tolerance of cryptic species of blue oat mites (*Penthaleus spp.*) and the redlegged earth mite (*Halotydeus destructor*) to pesticides. Australian Journal of Experimental Agriculture, 39(5): 621 – 628

Umina P., Edwards O., Carson, P., van Rooyen, A. and Anderson A. (2014). High levels of resistance to carbamate andpyrethroid chemicals widespread in Australian *Myzus persicae* (Hemiptera: Aphididae) populations. Journal of Economic Entomology, 107(4):1626 - 1638

van Emden, H.F., Eastop, V.F., Hughes, R.D. and Way, M.J. (1969). The ecology of *Myzus persicae*. Annual Review of Entomology 14: 197-270.

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Appendix I

Microcosm trial examining the efficacy of new insecticides against green peach aphid

Public Report

Dr Paul Umina
cesar pty ltd

Project Number: VG12109

Author: Dr Siobhan de Little & Dr Paul Umina

VG12109

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Contents

Executive Summary

The green peach aphid (*Myzus persicae*) is a major pest of numerous vegetable crops through direct feeding damage and by vectoring many important plant viruses. Insecticides provide the main basis for controlling *M. persicae*, yet increasing resistance to several chemical classes in this pest has led to a demand for alternatives. In this study, the efficacy of eight new chemicals was tested against *M. persicae* under semi-field conditions and compared with Pirimor® 500WG and Transform™ 240SC. Pest numbers were assessed prior to spraying, and then at 3-, 7-, 14-, and 21-days after treatment (DAT). Plant vigour and phytotoxicity were also assessed at 0-, 3-, 7-, 14- and 21-DAT.

This study has revealed three new potential chemicals that appear highly efficacious against *M. persicae*: Product 1, Product 6 and Product 7. These products significantly reduced *M. persicae* numbers compared with the control tubs at all sampling dates, and showed similar levels of control as the conventional product, Transform™ 240SC. Field trials investigating the efficacy of different rates of these products should be considered. Product 4 and Product 8 may be worth pursuing at higher rates and/or different formulations, although a final decision will not be made until discussions are held with all agri-chemical companies and Horticulture Innovation Australia.

Introduction

The green peach aphid (*Myzus persicae*) is an important pest of a variety of vegetable crops. Control of this pest relies heavily on the application of broad-spectrum pesticides. However, resistance in *M. persicae* to multiple chemical classes, including pyrethroids, organophosphates and carbamates, is widespread across Australia and appears to be increasing. The aim of this study was to examine the efficacy of eight new chemicals against *M. persicae* under semi-field conditions and to compare these products with two commonly used insecticides and an untreated control.

Methods

The efficacy of eight chemical products was examined and compared with pirimicarb (Pirimor® 500WG) and sulfoxaflor (Transform™ 240SC) using microcosm tubs under shade-house conditions. This method has been used previously to determine numerous aspects of invertebrate biology, including responses to pesticides (e.g. Umina & Hoffmann 2003).

In October 2014, broccoli seedlings (*Brassica oleracea var. italica*) were transplanted into clear plastic tubs (approximately 35 cm long, 24 cm wide and 26 cm deep) using a combination of sandy loam soil and Miracle Gro potting mix (3:1). Following transplant, each tub was watered, enclosed with a clear plastic lid that had a large gauze window for ventilation (and to prevent the movement of aphids), and randomly placed in a shade-house. Each tub contained 6-8 plants at a BBCH growth stage between 2.3 – 2.6 when planted. Plants were given 18 days to establish, then *Myzus persicae* were directly added to each tub. Approximately 20 aphid individuals from a brassicaceous host (*Raphanus sativus* – Cherry Belle Radish) were transferred into tubs using a fine-haired paintbrush. Afterwards, a leaf from the culture plant containing 20-50 further aphids was placed amongst the foliage in each tub to boost numbers and provide a back-up should one transfer method fail.

Eighteen days after aphid introductions, when a nominal threshold for aphid density was reached, tubs were sprayed with one of ten treatments (see Table 1). Five replicate plastic tubs were assigned to each chemical treatment and five for the untreated control (55 tubs in total). Treatments were applied using an Inter® 16L knapsack with a hand-held lance and Goizper® flat fan nozzle (02 – Fine). Pressure was maintained at 300 kPa and a total volume of 13 mL was applied per tub.

Tubs were scored for pest numbers prior to pesticide treatments and 3, 7, 14 and 21 days after the application of treatments (DAT) by directly counting the number of aphids alive on six leaves chosen at random within each tub. A whole tub count was also performed for each treatment at 3-, 7-, 14- and 21-DAT. The tub for the whole-tub count per treatment was selected randomly each time. Plant vigour was recorded in each tub at 0-, 3-, 7-, 14- and 21- DAT. Phytotoxicity was also scored within each tub at 3-, 7-, 14- and 21-DAT. Vigour and phytotoxicity scores were based on the average density and growth of broccoli using a 0 – 10 scale in comparison to the best tub. No phytotoxicity was recorded for any treatment, and plant vigour was scored at 10 for all treatments on all sampling dates. Neither of these assessments are discussed further.

Differences between treatments at each sampling date were determined using one-way ANOVAs with post-hoc Tukey HSD tests. Data analysed for aphid number was log- transformed. Aphid numbers per tub were determined by plotting the relationship between the whole tub count for each treatment on each sampling date against the average number of aphids per leaf count (see Fig. 1). This relationship (R-squared = 0.90275) was then used to determine the number of aphids per tub for replicates where this count was not undertaken. All analyses were conducted in R (version 3.1.0).

Table 1. List of treatments applied in this trial. Treatments are coded and no further information given regarding the active ingredient or concentration to maintain client privacy.

Treatment	Active ingredients(s)	Field rate (product/ha)
Control	-	-
Pirimor® 500WG	pirimicarb (500 g/kg)	1000 g/ha
Transform™ 240SC	sulfoxaflor (240 g/L)	300 mL/ha
Product 1	confidential	confidential
Product 2	confidential	confidential
Product 3	confidential	confidential
Product 4	confidential	confidential
Product 5	confidential	confidential
Product 6	confidential	confidential
Product 7	confidential	confidential
Product 8	confidential	confidential

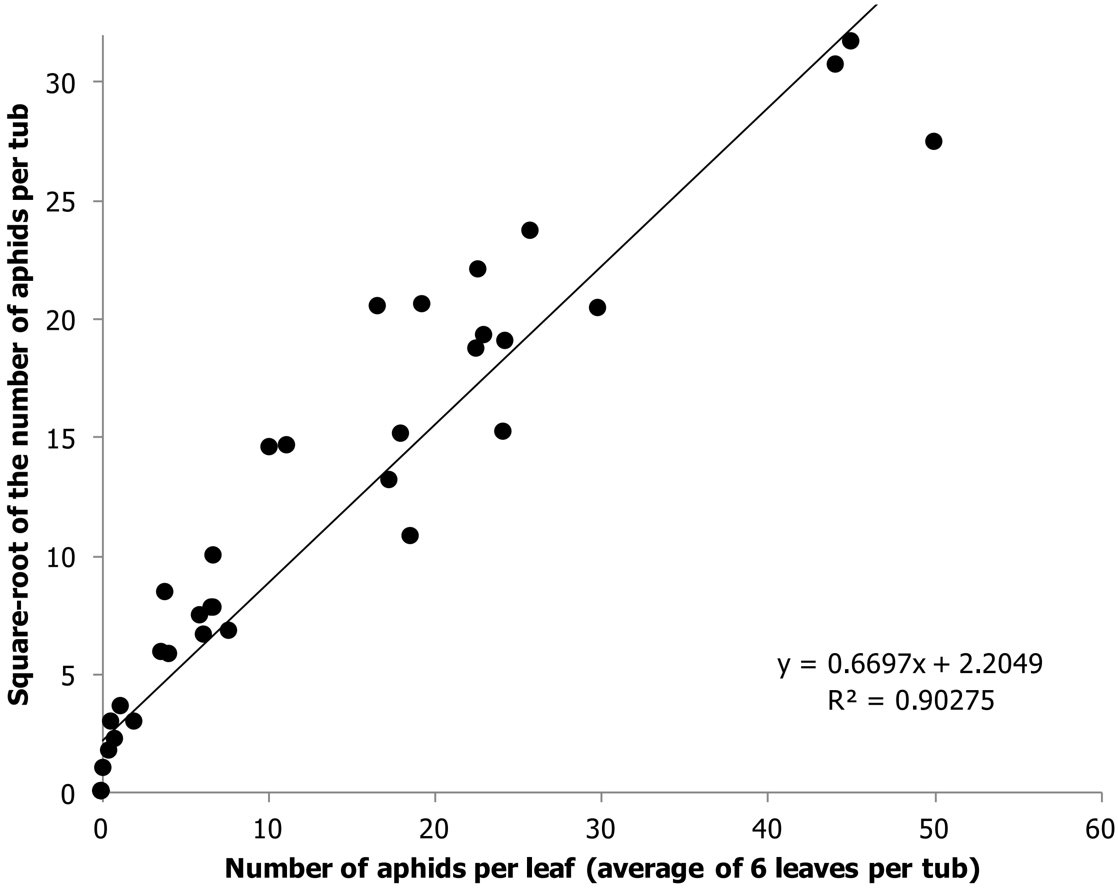

Figure 1. Average number of *M. persicae* alive on a single lower leaf per tub versus the number of M. persicae alive in an entire tub (square-root transformed).

Results

One-way ANOVAs with Tukey HSD post-hoc comparisons showed significant treatment effects at individual sampling dates (Table 2). Several chemical treatments, on all sampling dates, reduced M. persicae numbers compared to the control tubs. A 26 - 99% reduction in aphid numbers from 0-DAT to 3-DAT was evident for each chemical treatment (Fig. 2). Control of aphids by 7-DAT had increased to 51 – 100%. By 14-DAT, Product 1, Product 6 and Product 7 provided 100%, 92% and 94% control of M. persicae, respectively. Product 2, Product 4 and Product 8 provided some control against M. persicae, particularly at the early sampling dates (i.e. 3- and 7-DAT). As expected, Transform provided a high level of efficacy against M. persicae, while Pirimor was reasonably effective.

Table 2. Average number of *M. persicae* per tub per sampling date and results from one-way ANOVAs, comparing all treatment groups. Different letters indicate significantly different means at each sampling date (at the *P* < 0.05 level, multiple comparison with Tukey HSD adjustment).

Treatment	0-DAT	3-DAT		7-DAT		14-DAT		21-DAT	
Control	450	326	b	496	b	283	c	895	c
Pirimor® 500WG	420	29	ae	27	acfg	81	abc	561	abc
Transform™ 240SC	531	5	ae	0	a	0	a	0	a
Product 1	585	15	aeg	0	a	0	a	0	a
Product 2	383	121	bgh	72	bdef	180	abc	659	abc
Product 3	757	389	b	239	b	519	c	1539	bc
Product 4	469	123	bc	149	bc	135	abc	248	abc
Product 5	868	460	b	237	b	364	bc	659	bc
Product 6	579	57	acdh	28	acd	14	ab	13	ab
Product 7	522	5	e	2	ae	10	a	16	ab
Product 8	498	139	bd	68	bdg	166	abc	206	abc
P-value	-	<0.001		<0.001		<0.001		<0.001	
F-statistic	-	20.3		13.4		6.329		4.968	
df	-	10, 44		10, 44		10, 44		10, 44	

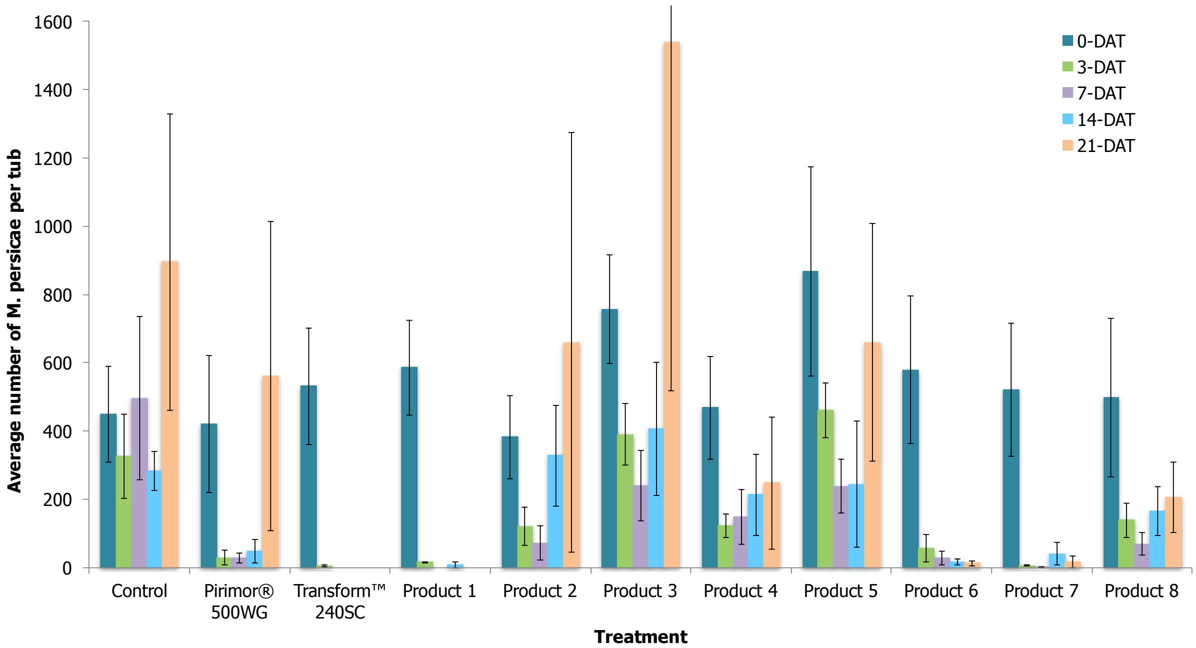

Figure 2. Average number of *M. persicae* per tub at each sampling date. Error bars represent standard error of the mean.

Conclusions

This study has revealed three new potential insecticides that appear highly efficacious against *M. persicae*: Product 1, Product 6 and Product 7. These products significantly reduced *M. persicae* numbers compared with the control tubs at all sampling dates, and showed similar levels of control as the conventional product, Transform™ 240SC. Aphid mortality was 97%, 99% and 90%, respectively for Product 1, Product 7 and Product 6 by 3-DAT and increased to 100%, 100% and 95% control by 7-DAT. The level of control by Transform at 3-DAT was 99%.

A moderate level of control was observed with Pirimor® 500WG at 3-, 7- and 14-DAT, however aphid numbers increased by 28-DAT. This result may reflect a population containing a proportion of individuals with resistance to carbamates. Resistance to pirimicarb has been shown to be varied within Australian populations of *M. persicae*, varying from 11-fold to >1800-fold (Umina et al. 2014).

Product 2, Product 4 and Product 8 provided some control against M. persicae at 3- and 7- DAT, however similar to the results with Pirimor, aphid numbers increased substantially from 14- DAT onwards. Product 3 and Product 5 showed poor efficacy against M. persicae at the rates tested in this trial.

Based on these findings, field trials investigating the efficacy of Product 1, Product 6 and Product 7 will be considered. This would allow us to further determine the potential for these products against *M. persicae* in vegetable crops and provide data to assist in product registration. Product 4 and Product 8 may be worth pursuing at higher rates and/or different formulations, although a final decision will not be made until discussions are held with all agri-chemical companies and Horticulture Innovations Australia.

References

Umina PA and Hoffmann AA (2003). Diapause and implications for control of *Penthaleus* species and *Halotydeus destructor* (Acari: Penthaleidae) in southeastern Australia.
Experimental and Applied Acarology 31: 209-223.

Umina PA, Edwards O, Carson, P *et al.* (2014). High levels of resistance to carbamate and pyrethroid chemicals widespread in Australian *Myzus persicae* (Hemiptera: Aphididae) populations.
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Appendix II

Field trials examining the efficacy of new insecticides against green peach aphid

Public Report

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VG12109

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Executive Summary

Green peach aphids (*Myzus persicae*) attack a variety of crops through direct feeding damage and transmitting plant viruses. Pesticides provide the main basis for controlling *M. persicae*, yet increasing resistance to several chemical classes in this pest has led to a demand for alternatives. In this study, the efficacy of several insecticides was tested on *M. persicae* under field conditions on broccoli in Queensland and Victoria, and compared with Transform™, Benevia® and an untreated control. In the two Queensland trials, plots received an initial spray application, and a second application around 14 days later. In the Victorian trial, plots received only one spray. Pest numbers were assessed prior to spraying and then at 3, 7, 14 and 21 days after each treatment. Plant damage, crop vigour and phytotoxicity were also assessed.

This study suggests that Product 1 is efficacious against *M. persicae* in broccoli crops. In the Victorian trial, this product, sprayed at full rate, was comparable in efficacy to Transform™. Product 4 also showed some efficacy against *M. persicae* at low numbers in the Lockyer valley trial, and at higher *M. persicae* numbers in the Victorian trial. Further field trials are recommended for Product 1 to confirm the effects demonstrated in this study and provide data to assist in product registration. Product 4 may be worth pursuing at higher field rates, which would allow further investigation of the potential for this product against *M. persicae* in vegetable crops.

Introduction
The green peach aphid (*Myzus persicae*) is an important pest of a variety of horticultural crops. Control of this pest relies heavily on the application of broad-spectrum pesticides. However, resistance in *M. persicae* to multiple chemical classes, including pyrethroids, organophosphates and carbamates, is widespread across Australia and resistance to imidacloprid is emerging in some areas. The aim of this study was to further evaluate the efficacy of two new chemicals previously determined efficacious by a microcosm trial, and to compare these with commonly used insecticides (i.e. Transform™ and Benevia®) applied under field conditions.

Methods
Two chemical products that had previously shown efficacy against *M. persicae* in a microcosm trial were selected for further investigation and compared with sulfoxaflor (Transform™), cytraniliprole (Benevia®) and an untreated control in two field trials in northern and southern Queensland (Bowen and Lockyer Valley), and one field trial in Montgomery, Victoria. These trials were conducted on broccoli and performed by Prospect Agriculture Pty. Ltd (Bowen) and Peracto Pty Ltd (Lockyer Valley and Montgomery).

In August 2015, sites in northern and southern Queensland (Bowen and Lockyer valley) were selected and broccoli seedlings were transplanted. In December 2015, a site was selected in Montgomery, Victoria and broccoli seedlings were transplanted (Table 1).

A randomised complete block design with four replicate blocks was planted out at each site (Fig. 1). Spray timing was determined once the aphid population was established (application 1), and again after 14 days if efficacy level was below 80% (application 2). Plots were sprayed with one of seven treatments (Table 2). Treatments were applied using spray equipment as governed by availability and mimicking commercial application (Table 1).

Plots were scored for *M. persicae* numbers prior to the first spray and at 3, 7, and 14 days after the first application of treatments (DAT1), and 7, 14 and 21 days after the second application of treatments (DAT2). In the Montgomery trial, only one spray application was made, so *M. persicae* numbers were also scored at 21 and 28 days after the initial application. Plots were scored by directly counting the number of aphids alive on 10 leaves chosen at random from each plot. Feeding damage to plants was assessed at 14-DAT1, 14-DAT2, and 21-DAT2 in the Bowen trial, and at 17-DAT, 21-DAT and 28-DAT in the Montgomery trial. This was based on a visual assessment using a 0–10 scale, where 0 indicates no visible damage, 5 indicates 50% of the leaves damaged and 10 indicates all plants dead or dying. Feeding damage was observed only in the Bowen trial, and on DAT-17 in the Montomery trial (where one of the untreated control plots had 10% plant damage). The feeding damage scores for the Lockyer valley and Montgomery trials are therefore not included in the results and not discussed further.

To determine if there were any negative side effects of the treaments on the host crop, plant vigour and phytotoxicity were scored. In the two Queensland trials, plant vigour was recorded at 7-DAT1 and 7-DAT2 relative to the untreated plots (untreated = 100%), and phytotoxicity was scored on 14-DAT1 and 14-DAT2 relative to the untreated plots (untreated = 0%). In the Mongomery trial, plant vigour was recorded at 17-, 21- and 28-DAT, and phytotoxicity was scored on 7-, 17-, 21- and 28-DAT. No phytotoxic effects were seen on any of the sampling dates, and plant vigour was scored as equal to or better than the untreated plots on all sampling dates. These scores are discussed further for any trials.

Table 1. Trial site details and spray information.

Location	Bowen, Queensland	Lockyer Valley, Queensland	Montgomery, Victoria
GPS co-ordinates	-20.00315, 148.11450	-27.541034, 152.332321	-38.03535, 147.05387
Soil type/ texture	Grey chromosol, Sandy loam	Sandy clay loam	Clay loam
Crop	Broccoli	Broccoli	Broccoli
Variety	Kuba	Aurora	Annapurna
Transplant date	4/08/2015	24/08/2015	15/12/2015
Plot size	1 bed (1.5 m) x 8 m	3 m x 6 m	2 m x 8 m
Plant spacing	40 cm	30 cm	30 cm
Row spacing	1.5 m	1.5 m	70 cm
Plant density	44,670 per hectare	44,444 per hectare	-
Irrigation type	Sub-surface drip tape under plastic mulch	Overhead sprinkler	Solid-set
Fertiliser	Base fertiliser of CK88 at 600 kg/ha	-	-
Insecticide applications (maintenance)	Success Neo at 0.3 L/ha 21/08/15 Coragen at 0.1 L/ha 28/08/15 Coragen at 0.1 L/ha 04/09/15	Confidor at 0.3 L/ha 24/08/15 Proclaim at 0.3 kg/ha on 03/10/15	Dimethoate 400 at 75 mL/100 L on 22/02/16
Spray method	Walk-on foliar application of treatments using motorised knapsack sprayer with hand held boom, 4 nozzles.	CO_2 Pressurised backpack sprayer with hand held boom, 6 nozzles.	Walk-on foliar application of treatments using CO_2 pressurised backpack sprayer with 2 m hand held boom, 4 nozzles.
Spray volume	500 L/ha	400 L/ha	500 L/ha
Spray pressure	400 kPa	300 kPa	400 kPa
Nozzle type	Turbo TeeJet TT110-02 flat fan with 37.5 cm nozzle spacing	AVI twin 110 025 with 50 cm spacing	AVI Twin 110-03 double flat fan
Walking speed	1 meter/second	0.75 meter/second	1 meter/second
Spraying conditions Application 1	22.6°C, 50% RH, 4 km/h wind SE	26.0°C, 58% RH, 1 km/h wind SE	23°C, 70% RH, 1-2 km/h wind E
Spraying conditions Application 2	21.2°C, 48% RH, 5 km/h wind SE	30.1°C, 53% RH, 1.7 km/h wind SE	-
Crop stage Application 1	BBCH 19	BBCH 49	BBCH 43
Crop stage Application 2	BBCH 45	BBCH 63	-

(a)

7	3	6	4	2	1	5	**Block 4**
2	7	4	1	5	6	3	**Block 3**
4	1	5	3	7	2	6	**Block 2**
5	2	7	6	4	3	1	**Block 1**

(b)

6	7	3	1	5	4	2	**Block 4**
3	1	4	7	6	2	5	**Block 3**
1	5	6	2	7	3	4	**Block 2**
7	2	5	3	4	6	1	**Block 1**

(c)

1	7	3	2	4	6	5	2	7	6
6	4	1	5	7	3	1	4	3	5
2	5	6	3	1	4	2	7		

Figure 1. Schematic illustration of the site designs used in the (a) Bowen and (b) Lockyer Valley and (c) Montgomery field trials, whereby numbers represent different treatments and colours represent different blocks.

Table 2. List of treatments applied in this trial. Treatments are coded and no further information given regarding the active ingredient or concentration to maintain client privacy.

Treatment	**Active ingredients(s)**	**Field rate (product/ha)**
Control	-	-
Transform™ 240 SC	sulfoxaflor (240 g/L)	300 mL/ha
Benevia® 100 SC	cyantraniliprole (100 g/L)	750 mL/ha
Full Rate Product 1	confidential	confidential
Half Rate Product 1	confidential	confidential
Full Rate Product 4	confidential	confidential
Half Rate Product 4	confidential	confidential

All data was checked for normality using a one-sample Kolmogorov-Smirnov test (normal distribution of studentised residuals) following Sokal & Rohlf (1995). Differences between treatments for aphid numbers and crop damage at different sampling dates were then determined using one-way MANCOVAs and LSD post hoc tests (significance level 0.05). None of the three trials had raw aphid count data that was normally distributed, and therefore all count data was log-transformed. For the Bowen trial, all log-transformed count data was normal apart from the 14-DAT1 score. For the Lockyer valley trial, log-transformed scores 0-DAT, and 21-DAT1 were normal (according to the Kolmogorov-Smirnov normality test), and for the Montgomery trial only the log-transformed 17-DAT score was normal, however the other log-transformed scores were not normally distributed, and this violates one of the key assumptions of the MANCOVA model. Therefore, results for these scores from these two trials should be interpreted with caution. All analyses were conducted using the software SPSS Statistics (version 22).

Results

Aphid numbers

Table 3. Mean number of wingless *M. persicae* per 10 leaves in the Bowen field trial. Different letters indicate a significant difference between treatments at each sampling date once *M. persicae* numbers had been adjusted for pre-treatment levels (at the *P* < 0.05 level, LSD post hoc test).

Treatment	0-DAT	3-DAT1		7-DAT1		14-DAT1		7-DAT2		14-DAT2		21-DAT2	
Untreated control	102.3	273	b	115	a	127.3	b	127	a	92.5	a	150.8	a
Transform™	101.5	76	ab	15.8	b	14.8	a	14.3	b	3.8	b	35.5	b
Benevia®	89	69	a	58	ab	48.8	ab	43.5	ab	35.3	ab	70.5	ab
Half Rate Product 1	112.8	71.5	a	28.3	ab	25	ab	27	ab	15.8	ab	50	ab
Full Rate Product 1	96.3	58	a	29.3	ab	13.5	a	19.8	ab	12.5	ab	43.8	ab
Half Rate Product 4	105	126.5	ab	54.8	ab	60.8	ab	61.8	ab	46.8	a	79	ab
Full Rate Product 4	104.8	156.5	ab	47.8	ab	46.3	ab	48.5	ab	40	a	70.5	ab
P-value	-	0.04		0.009		0.003		0.027		0.017		0.05	
F statistic	-	4.66		3.93		4.84		3.06		3.45		2.60	
df	-	6, 20		6,20		6,20		6, 20		6, 20		6, 20	

Table 4. Mean number of wingless *M. persicae* per 10 leaves in the Lockyer Valley field trial. Different letters indicate a significant difference between treatments at each sampling date once M. persicae numbers had been adjusted for pre-treatment levels (at the *P* < 0.05 level, LSD post hoc test).

Treatment	0-DAT	3-DAT1	7-DAT1		14-DAT1	21-DAT1		7-DAT2		14-DAT2	21-DAT2
Untreated control	1.9	2.1	3.9	a	15.4	5.9	ab	5.3	bc	1.5	1.8
Transform™	2.1	0.3	0.1	b	2.6	1	b	1.1	abcd	0.3	1.1
Benevia®	2	1	1.5	a	14.4	28.4	a	13.1	b	8.9	2
Half Rate Product 1	0.4	0	0.1	a	8.0	2.4	ab	0.3	ad	1.1	1.1
Full Rate Product 1	1.1	0	0	b	7.3	4.1	ab	0	a	0.1	0.9
Half Rate Product 4	1	1.3	0	b	11	7.8	ab	1.5	ac	4.1	2
Full Rate Product 4	2.9	0.5	0.3	a	10.4	26.6	ab	3.5	bd	4.3	4
P-value	-	0.314	0.004		0.329	0.016		<0.001		0.665	0.671
F statistic	-	1.27	4.65		1.24	3.49		7.78		0.684	0.675
df	-	6, 20	6, 20		6, 20	6, 20		6, 20		6, 20	6, 20

Table 5. Mean number of wingless *M. persicae* per 10 leaves in the Montgomery field trial. Different letters indicate a significant difference between treatments at each sampling date once *M. persicae* numbers had been adjusted for pre-treatment levels (at the *P* < 0.05 level, LSD post hoc test).

Treatment	0-DAT	3-DAT		7-DAT		17-DAT		21-DAT	28-DAT
Untreated control	264	211	a	188	a	15	a	1	1
Transform™	256	29	c	14	e	2	b	1	0
Benevia®	284	33	bc	19	cd	4	b	0	0
Half Rate Product 1	262	37	b	25	bc	3	b	0	0
Full Rate Product 1	292	27	c	16	de	3	b	1	0
Half Rate Product 4	270	41	b	32	b	4	b	0	0
Full Rate Product 4	277	34	bc	26	bc	2	b	0	0
P-value	-	<0.001		<0.001		0.03		0.39	0.69
F statistic	-	80.93		68.09		2.94		1.11	0.65
df	-	6, 20		6, 20		6, 20		6. 20	6. 20

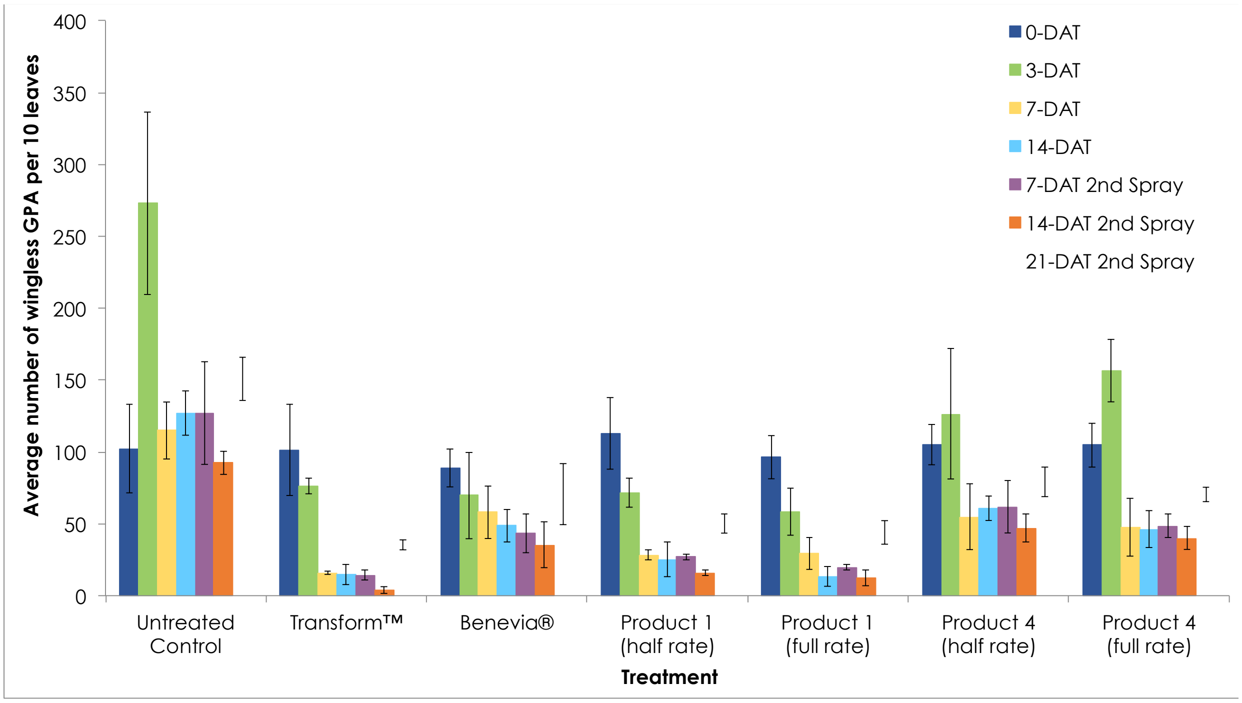

Figure 2. Average number of wingless *M. persicae* per 10 leaves in the Bowen field trial. Error bars represent standard error of the means.

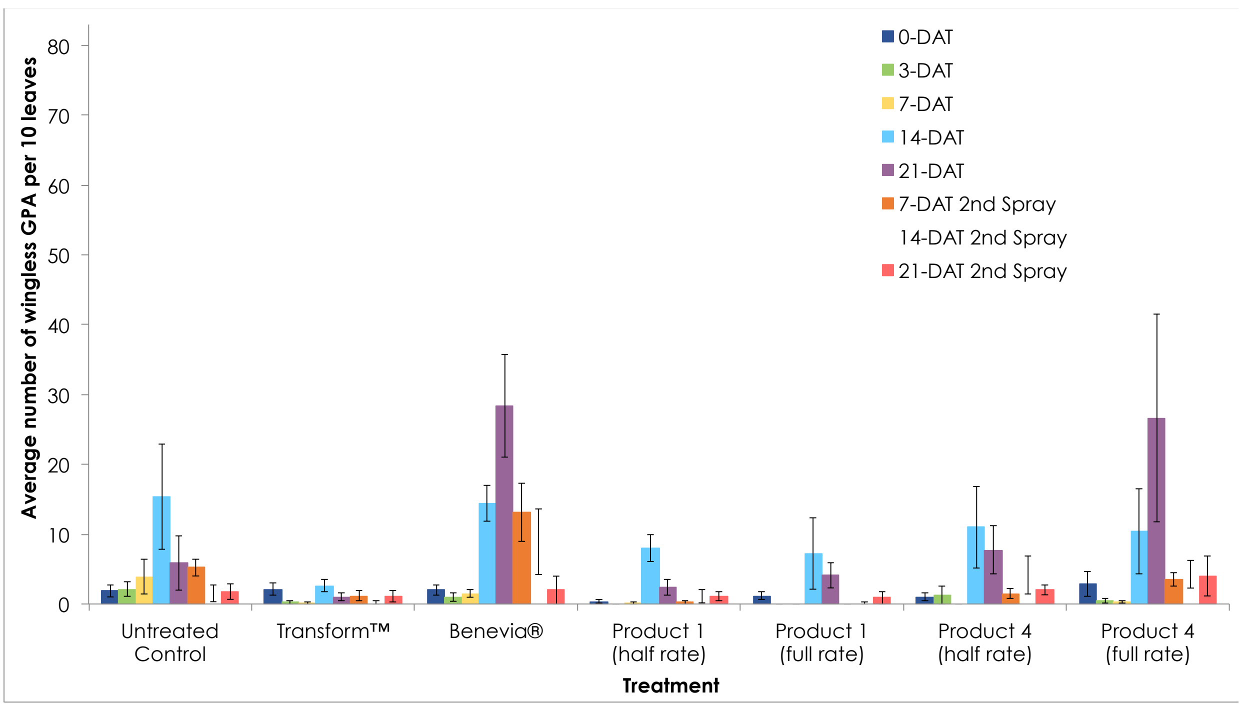

Figure 3. Average number of wingless *M. persicae* per 10 leaves in the Lockyer Valley field trial. Error bars represent standard error of the means.

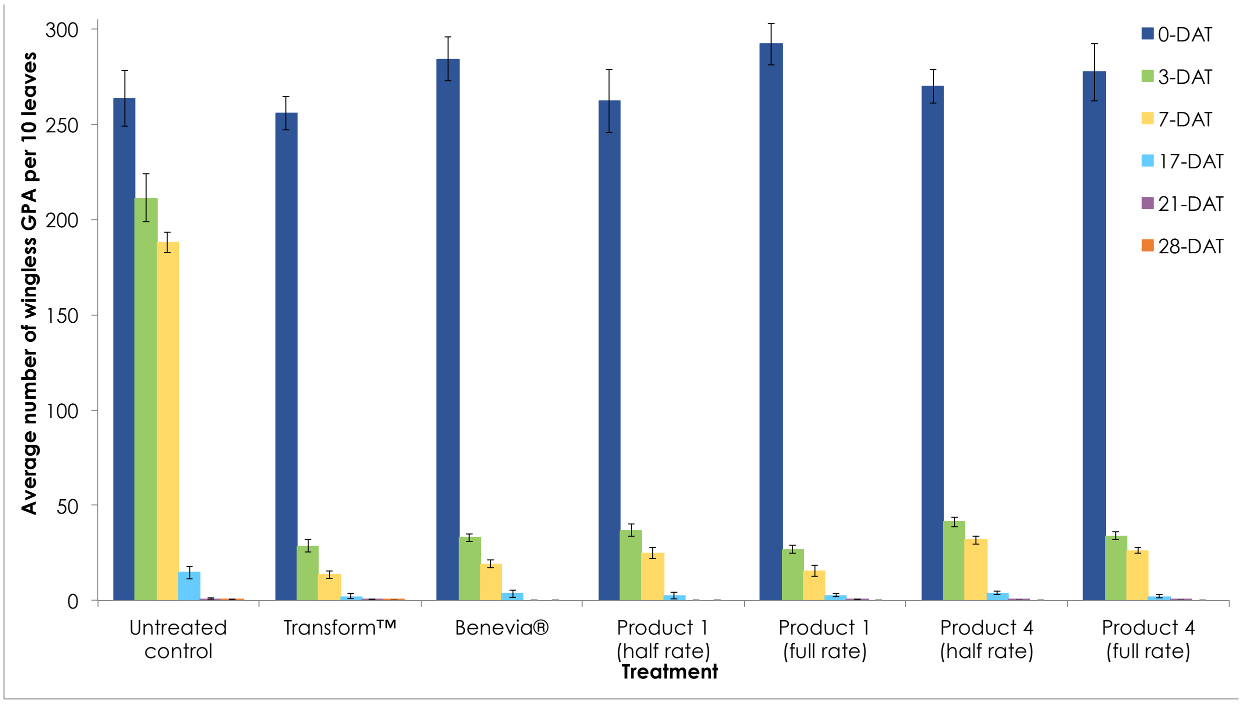

Figure 4. Average number of wingless *M. persicae* per 10 leaves in the Montogmery field trial. Error bars represent standard error of the means.

Feeding damage

Table 6. Average feeding damage score caused by *M. persicae* in the Bowen field trial. Different letters indicate significantly different means at each sampling date (at the *P* < 0.05 level, LSD post hoc test).

Treatment	**14-DAT1**		**14-DAT2**		**21-DAT2**	
Untreated control	1.3	a	1.8	a	3	a
Transform	0	d	0	d	0.1	d
Benevia	0.4	cb	0.3	cb	1.5	cb
Half Rate Product 1	0	d	0	d	0.4	d
Full Rate Product 1	0	d	0	d	0.3	d
Half Rate Product 4	0.5	b	0.4	b	1.9	b
Full Rate Product 4	0.2	cd	0.1	cd	1.3	cd
P-value	<0.001		<0.001		<0.001	
F statistic	47.7		76.3		115.1	
df	6, 21		6, 21		6, 21	

Conclusions

Resistance in *M. persicae* to chemicals currently registered for aphid control has led to a demand for alternative chemistries by the horticultural industry. In this study two new chemicals unregistered for *M. persicae* control in Australia were trialed on broccoli (each at two different rates) to further evaluate their efficacy in the field after being deemed efficacious in previous field and microcosm trials.

Results for the two trials in Queensland are somewhat different as there were large differences in aphid pressures between trials. In the Bowen trial, aphid pressure was high and uniform across all plots at 0-DAT. Subsequent reductions in aphid number were demonstrated by Product 1 (half and full rates) and Benevia® at DAT-3, and by Transform™ at DAT-7 compared with the untreated control (Table 3, Figure 2). Aphid numbers started to increase by DAT-14, and reductions in aphid numbers following the second treatment application were observed only in the Transform™ treated plots compared to the untreated plots (Table 3, Figure 2).

The Lockyer valley had very few aphids present and the aphid pressure was somewhat different across plots at DAT-0 (Table 4). There were no significant differences in aphid numbers at DAT-3, however reductions in aphid number were demonstrated by the Bayer product (half rate), Product 1 (full rate), and Transform™ at DAT-7 compared with the untreated control (Table 4, Figure 3). Aphid numbers were higher than the starting numbers in all treatments by DAT-21, when the second treatment was applied. Subsequent reductions in aphid numbers following the second application were observed only in the Product 1 plots (half and full rates) compared to the untreated plots (Table 4, Figure 3).

In the Montgomery trial, a natural decline in aphids in all plots occurred over the course of the trial, with such a severe reduction by 21-DAT that no treatment differences in aphid numbers were seen after this time (Table 5). At 3-, 7- and 17-DAT numbers of aphids in untreated control plots were significantly higher than in any treatment (Table 5, Figure 4). However, due to the marked decline in aphids, most treatment differences were seen at 3- and 7-DAT. On these sampling dates, Transform™ and Product 1 at full rate were similar in efficacy at reducing aphid numbers. Product 4 at full rate had an efficacy similar to Product 1 at half rate.

Feeding damage by aphids was only assessed in the Bowen trial. There were differences between treatments at 14-DAT after both spray applications and 21-DAT after the second application (Table 6). The differences in scores were consistent over time, and plants in all treated plots suffered significantly less damage than the untreated control, with Transform™, Product 1 (half and full rates) having the least feeding damage of all plots.

This study suggests that Product 1 is efficacious against high *M. persicae* pressure in broccoli crops. Product 4 also showed some efficacy against *M. persicae* at low numbers in the Lockyer valley trial, and against higher numbers in the Mongemery trial. Based on these findings, further field trials are recommended for Product 1 to confirm the effects demonstrated in this study and provide data to assist in product registration. Product 4 may be worth pursuing at higher field rates.

References

Sokal RR and Rohlf FJ. 1995. Biometry: The principles and practice of statistics in biological research, 3rd edition. New York: W.H. Freeman. 887 p.

Appendix

Chronology of events

Bowen field trial.

Date	Days after treatment (DAT)	Event
11.09.15	0	Assessment 1 – Aphid count
11.09.15	0	Spraying – application 1
14.09.15	3	Assessment 2 – Aphid count
18.09.15	7	Assessment 3 – Aphid count, phytotox.
25.09.15	14	Assessment 4 – Aphid count, crop vigour, leaf damage.
25.09.15	14	Spraying – application 2
02.10.15	7	Assessment 5 – Aphid count, phytotox.
09.10.15	14	Assessment 6 – Aphid count, crop vigour, leaf damage.
16.10.15	21	Assessment 7 – Aphid count, crop vigour, leaf damage.

Lockyer Valley field trial.

Date	Days after treatment (DAT)	Event
06.11.15	0	Assessment 1 – Aphid count
06.11.15	0	Spraying – application 1
09.09.15	3	Assessment 2 – Aphid count, phytotox.
13.09.15	7	Assessment 3 – Aphid count.
20.09.15	14	Assessment 4 – Aphid count, crop vigour.
27.09.15	21	Assessment 5 – Aphid count.
27.09.15	21	Spraying – application 2
04.12.15	7	Assessment 6 – Aphid count, phytotox.
11.12.15	14	Assessment 7 – Aphid count, crop vigour.
18.12.15	21	Assessment 8 – Aphid count, crop vigour.

Montgomery field trial.

Date	Days after treatment (DAT)	Event
04.03.16	0	Assessment 1 – Aphid count, Spraying
07.03.16	3	Assessment 2 – Aphid count
11.03.16	7	Assessment 3 – Aphid count, phytotoxicity
21.03.16	17	Assessment 4 – Aphid count, feeding damage, crop vigour, phytotoxicity.
25.03.16	21	Assessment 5 – Aphid count, feeding damage, crop vigour, phytotoxicity.
01.04.16	28	Assessment 6 – Aphid count, feeding damage, crop vigour, phytotoxicity.

Appendix III

Current management practices for the green peach aphid

Industry Survey Report

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VG12109

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Contents

Executive Summary

The green peach aphid (GPA - *Myzus persicae*) is a major horticultural pest, attacking a broad range of crops. GPA has a high tendency to develop insecticide resistance, and this is becoming commonplace across numerous industries. Within Australia, there are documented cases of resistance to several insecticide classes, including synthetic pyrethroids, organophosphates and carbamates. Achieving adequate control of resistant green peach aphid populations is challenging for growers in many regions.

In 2014, a survey of horticultural growers and consultants across Australia was undertaken to better understand the insecticide spray practices (and underlying motivations) for GPA across crop types and different geographic regions. The online administered survey consisted of quantitative and qualitative questions.

104 horticultural advisors and growers responded to the online survey, of which 82 surveys were fully completed. The majority of respondents were advisors (agronomists and consultants that work across more than one property), mostly from Victoria and Queensland. Due to the relatively low response rates, some survey results should be treated with caution.

Survey respondents reported GPA as a major and minor pest in many crops, and these varied with region. Where GPA is a minor or negligible pest (e.g. in fruit and tree crops) growers will typically not use insecticides to control GPA, rather relying on biological control agents such as beneficial insects. Where GPA is a major pest (e.g. capsicum/chillies, Asian vegetables and potatoes), control methods tend towards high levels of insecticide spraying, often more than twice in a growing season; in some crops, insecticide application levels are as high as 10 sprays in a single growing season.

Regular monitoring is typically carried out for GPA – at least once a week for most crops. The most common control method is to only apply an insecticide once GPA populations have reached threshold levels within a crop. There were differences between regions with regards to the main chemicals used for GPA control. Queensland, Victorian and New South Wales growers tended to have the highest application of neo-nicotinoids, while South Australian and Western Australian growers still rely heavily on carbamates. Most respondents indicated they rotate between chemical groups when applying more than once spray per growing season. The number one reason respondents gave for rotating chemical groups was concerns about insecticide resistance.

Respondents reported the highest level of control failures for GPA in Victoria, but all states reported chemical control failures. When a control failure occurred, all but one grower believed the failure was due to insecticide resistance. This contrasted the advisors; approximately 50% believe spray failures they have experienced are caused by factors other than insecticide resistance.

The information gathered through this survey will be used to better understand resistance drivers and assist in the future development of resistance management strategies for GPA within Australia.

Introduction

The green peach aphid (GPA - *Myzus persicae*) is a major pest throughout the world, attacking a broad range of horticultural crops in over 40 plant families. GPA feed by sucking the sap from undersides of leaves and flower buds, although when populations are large they can cover the entire crop foliage. GPA predominantly reproduces asexually via parthenogenesis whereby females give birth to live young. Mature females can produce many generations during the growing season although the number of generations varies with host species. For example, on brassicas crops such as cauliflower and cabbage, GPA can produce 30-40 nymphs/month, while only 6-10 nymphs/month are typically produced on lettuce.

Young plants with high GPA populations may have reduced or stunted growth, and secretion of honeydew by aphids can cause secondary fungal growth (i.e. sooty moulds), which inhibits photosynthesis and can decrease plant growth. When deposited on the fruit, honeydew and sooty mould greatly reduces the marketability of produce. GPA also have the capacity to transmit over 100 plant viruses, and GPA is one of the most important aphid vectors for viruses in Australian brassica, lettuce, tomato and potato crops with the capacity to greatly affect produce yield and marketability.

GPA has recently emerged as a serious threat to capsicum, eggplant and tomato production, causing significant issues for growers by reducing marketable yields in affected crops by up to 60%. In some areas, growers are forced to apply insecticides at regular intervals in an attempt to manage GPA infestations. Quite alarmingly it has been reported that these sprays are often applied twice a week. This management practice places immense selection pressure on GPA to evolve insecticide resistance and multiple control failures have been reported to several chemical classes. This has broad implications, threatening vegetable production across Australia. It also places other horticultural crops (e.g. brassicas, potatoes and lettuce) at risk.

Although there are several insecticides registered against GPA in Australia, many populations have developed resistance to multiple classes of insecticide. Globally, GPA has developed resistance to more insecticides than nearly any other insect species. Previous work, including surveys of field populations of GPA across Australia, has shown widespread and high levels of resistance to a range of commonly used insecticides, including organophosphates (e.g. dimethoate), synthetic pyrethroids (e.g. alpha-cypermethrin) and carbamates (e.g. pirimicarb). Resistance in GPA appears to spread quickly across Australia, and thus farmers are likely to have fewer chemical control options in the future. Care must therefore be taken to use a range of chemicals in rotation to avoid, or limit, the evolution and spread of resistance. It is important to establish resistance management strategies that rotate insecticides, spray only when economically necessary and incorporate non-chemical control methods.

A survey was undertaken in 2014 to better understand the management practices of growers across crop types and different geographic regions. The results will help identify resistance drivers and assist in the future development of resistance management strategies for GPA within Australia.

Methods

A survey of horticultural growers and advisors (agronomists and consultants) across Australia was conducted from 28th March – 21st July 2014. The survey was administered through the online survey tool, SurveyMonkey (www.surveymonkey.com), and consisted of a series of quantitative and qualitative questions.

The main objective of this survey was to better understand the insecticide spray practices (and underlying motivations) for GPA across crop types and different geographic regions. In particular, questions were designed to understand:

- which different crops and regions GPA are considered a pest
- the current control methods used for GPA
- which chemical classes are commonly used to control GPA
- the current difficulties controlling GPA with insecticides
- what influences pest management decisions

Horticultural growers and advisors were invited to take part in the survey through direct emails targeting agribusinesses and through short articles in various industry newsletters and networks, such as AUSVEG, Vegetable Growers Association of Victoria, GrowCom, Tasmanian Farmers & Graziers, NSW Farmers, Vegetables WA, Victorian Farmers Federation, and Fruit Growers Tasmania. The survey was also publicized through various state agricultural departments. Participants were informed that they could end the survey at any time without giving reason or justification. In these cases, the data was deleted and not used in any way.

The survey consisted of 35 linked questions. Depending on the answers that participants gave to the first few questions, they were directed down different lines of enquiry (e.g. advisors answered one line of questions and growers answered a similar but different line of questions). This survey design resulted in different numbers of responses for different questions.

Survey Results

1. Demographics of survey respondents

We received 104 responses to our survey, and after removing incomplete surveys 86 complete responses remained. 64 were from agronomists and consultants, only 19 were from growers, and the remaining 3 were from researchers/entomologists (Table 1). We categorized respondents as either "advisors" – who worked across multiple properties, or "growers" – who worked with just one property. Advisors included retail agronomists, consultants, fee-for service agronomists, and researchers/entomologists. Growers included growers and farm managers/farm agronomists. Many of the questions asked of both advisors and growers are identical, so these responses have been combined in some of the following analyses.

Table 1. Number of respondents by occupation

Occupation	
Grower	19
Farm manager/ farm agronomist	4
Retail agronomist/consultant	38
Fee-for-service agronomist/consultant	22
Researcher/entomologist	3
TOTAL	**86**

66.7% of advisors and 78.2% of growers had 11+ years experience (Table 2). Proportionately more growers (56.5%) with >20 years experience answered than advisors (20.6%) with the same experience, however the total number of responses from each group was the same (13). The lowest response was from individuals with less than 5 years experience (only 12.8% of all responses).

Table 2. Number of respondents by experience level

Experience Level	Growers	Advisors
Less than 5 years	3	8
5 – 10 years	2	13
11 – 20 years	5	29
Greater than 20 years	13	13
TOTAL	**23**	**63**

The majority of respondents (45.3%) were from Victoria, and then Queensland (20.9%). There were also responses from Western Australia (11.6%), South Australia (11.6%), New South Wales (7.0%) and one response from the Northern Territory (Table 3). The respondent from the Northern Territory was a research entomologist, with 11-20 years experience, who works with 11-20 different growers. While a small proportion of the crops they advise on are cucurbits (10%) and tomatoes (3%), the majority of crops this advisor works with (87%) have little relevance to this report, and thus this survey response is not included in any further analysis.

Table 3. Number of respondents by state

State	Growers	Advisors
Victoria	12	27
New South Wales	-	6
Queensland	5	13
South Australia	-	10
Western Australia	4	6
Northern Territory	-	1
Not Specified	2	-
TOTAL	**23**	**63**

The majority of growers have properties between 10 and 80 Ha (52.2%). 21.7% of growers have properties smaller than 10 Ha, and 2 growers have 2000 Ha properties (Fig. 1). One grower in Victoria has 2000 Ha of potatoes, and one grower in Queensland has a 2000 Ha property made up of beans/peas (40%), capsicum/chilli (10%), broccoli (8%) and an unspecified crop (42%).

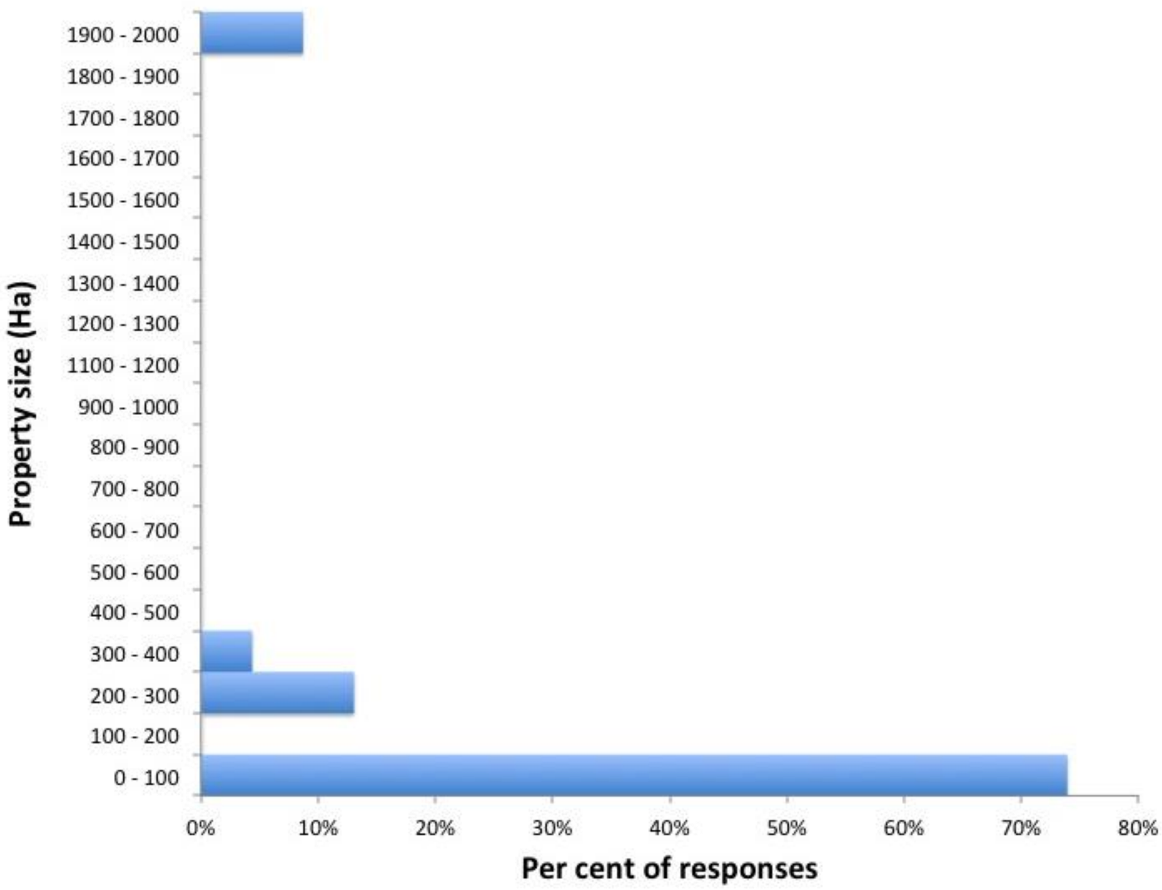

Figure 1. Property size of respondents (Ha)

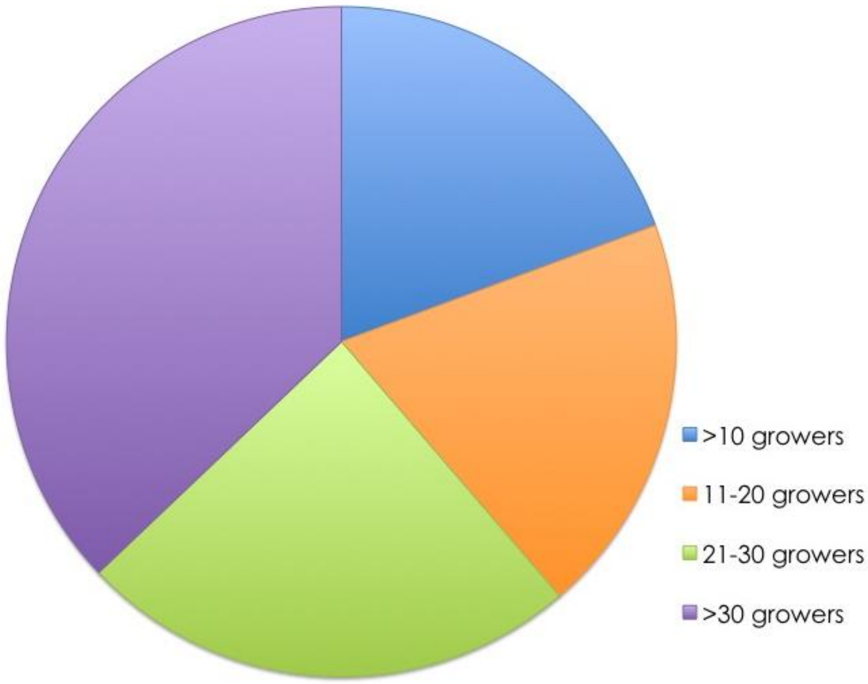

Figure 2. Number of growers managed by each Advisor

Overall, 37.1% of advisors managed over 30 growers each (Fig. 2). In Victoria, 39.3% of advisors managed over 30 growers each, and this was also the case in Western Australia (50%) and South Australia (50%). Six advisors from New South Wales responded to this question with two advisors each managing 11-20 growers, 21-30 growers and >30 growers. In Queensland, advisors tended to manage fewer numbers of growers, with 61.5% of advisors managing 20 or fewer growers.

2. Crops grown or advised on in 2013 by survey respondents

90% of respondents worked with more than one crop in 2013. The most common crops were cucurbits, tomatoes, lettuce, capsicum/chilli, broccoli and potatoes (Fig. 3). The least common crops were cotton, nut trees, pulse crops, oilseeds and cut flowers. A large number of respondents also worked with "other crops". These crops included: pome fruit, spinach, strawberries, corn, tropical fruit trees, celery, onion, carrots, vines, eggplant, cereals and pasture, fennel, chard, rocket, ornamental plants and coriander.

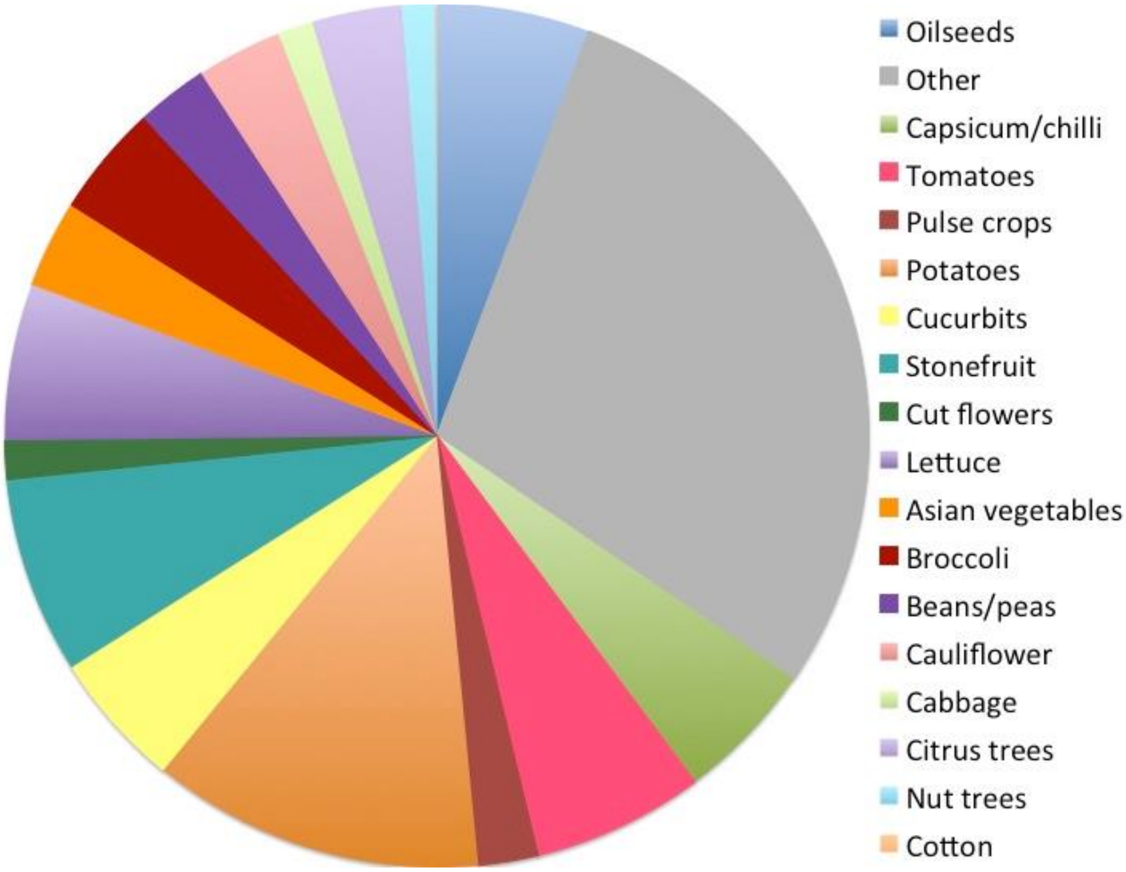

Figure 3. Crops grown in 2013 (All respondents)

For the remainder of the report, responses for cut flowers, pulse crops, oilseeds, cotton and "other" are not included in the analyses.

Respondents from all states grew or advised on a variety of fruit and vegetable crops in 2013. In Victoria, Western Australia and South Australia, the majority of crops grown or advised on by respondents in 2013 were potatoes, while the main crops in Queensland were capsicum/chillies and cucurbits, and in New South Wales the main crop grown or advised on in 2013 was capsicum/chillies (Fig. 4).

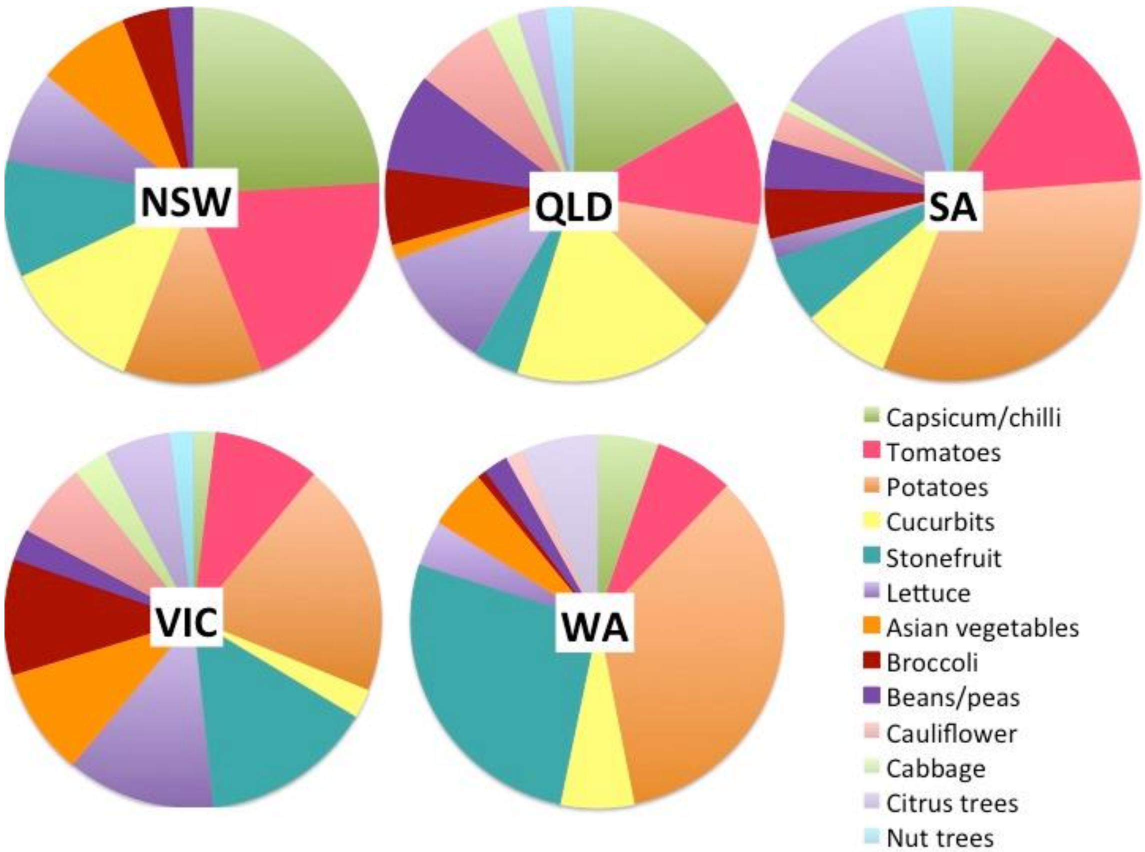

Figure 4. Main vegetable and fruit crops grown in each state (2013)

3. Pest status of GPA in vegetable and fruit crops

21% of respondents rated GPA as a major pest in capsicum/chilli crops whereas only 12.2 % of respondents rated GPA as a minor pest (Table 4). GPA were also more likely to be scored as a major pest in Asian vegetable crops, and more likely to be scored as a minor pest in potatoes, lettuces, beans/peas, tomatoes, broccoli, cabbages, cucurbits, stonefruit, citrus trees, and nut trees. Responses varied by region (Tables 5-9).

Table 4. Pest status of GPA in vegetable and fruit crops across Australia

	Grower Responses (n=16)			Advisor Responses (n=49)		
	Not a pest	**Minor pest**	**Major pest**	**Not a pest**	**Minor pest**	**Major pest**
Potatoes	50%	-	50%	5%	55%	40%
Lettuce	33%	67%	-	-	60%	40%
Beans/peas	50%	50%	-	24%	59%	18%
Tomatoes	-	100%	-	8%	65%	27%
Capsicum/chilli	-	25%	75%	-	36%	64%
Broccoli	-	67%	33%	-	68%	32%
Cauliflower	-	50%	50%	-	55%	45%
Cabbage	-	50%	50%	-	62%	38%
Cucurbits	-	100%	-	10%	63%	27%
Asian vegetables	-	-	100%	10%	40%	50%
Stonefruit	50%	50%	-	6%	67%	28%
Citrus trees	-	-	-	47%	47%	7%
Nut trees	-	-	-	63%	38%	-

Table 5. Pest status of GPA in Victorian vegetable and fruit crops

	VIC Grower Responses (n=6)			VIC Advisor Responses (n=19)		
	Not a pest	**Minor pest**	**Major pest**	**Not a pest**	**Minor pest**	**Major pest**
Potatoes	-	-	100%	17%	17%	67%
Lettuce	-	100%	-	-	50%	50%
Beans/peas	-	100%	-	50%	50%	-
Tomatoes	-	100%	-	-	57%	43%
Capsicum/chilli	-	50%	50%	-	80%	20%
Broccoli	-	50%	50%	-	40%	60%
Cauliflower	-	50%	50%	-	13%	88%
Cabbage	-	50%	50%	-	50%	50%
Cucurbits	-	100%	-	13%	75%	13%
Asian vegetables	-	-	100%	17%	33%	50%
Stonefruit	-	-	-	-	57%	43%
Citrus trees	-	-	-	67%	17%	17%
Nut trees	-	-	-	33%	67%	-

Table 6. Pest status of GPA in Queensland vegetable and fruit crops

	QLD Grower Responses (n=4)			QLD Advisor Responses (n=13)		
	Not a pest	Minor pest	Major pest	Not a pest	Minor pest	Major pest
Potatoes	-	-	-	-	100%	-
Lettuce	-	100%	-	-	71%	29%
Beans/peas	100%	-	-	20%	60%	20%
Tomatoes	-	-	-	-	88%	13%
Capsicum/chilli	-	-	100%	-	25%	75%
Broccoli	-	100%	-	-	75%	25%
Cauliflower	-	-	-	-	67%	33%
Cabbage	-	-	-	-	60%	40%
Cucurbits	-	100%	-	-	77%	23%
Asian vegetables	-	-	-	-	67%	33%
Stonefruit	-	-	-	-	100%	-
Citrus trees	-	-	-	100%	-	-
Nut trees	-	-	-	100%	-	-

Table 7. Pest status of GPA in Western Australian vegetable and fruit crops

	WA Grower Responses (n=4)			WA Advisor Responses (n=5)		
	Not a pest	Minor pest	Major pest	Not a pest	Minor pest	Major pest
Potatoes	-	-	100%	-	67%	33%
Lettuce	-	100%	-	-	100%	-
Beans/peas	-	-	-	-	33%	67%
Tomatoes	-	-	-	-	-	100%
Capsicum/chilli	-	-	-	-	-	100%
Broccoli	-	-	-	-	100%	-
Cauliflower	-	-	-	-	100%	0%
Asian vegetables	-	-	100%	-	-	-
Stonefruit	50%	50%	-	20%	60%	20%
Citrus trees	-	-	-	-	100%	-

Table 8. Pest status of GPA in South Australian vegetable and fruit crops

SA Advisor Responses (n=9)

	Not a pest	Minor pest	Major pest
Potatoes	-	50%	50%
Lettuce	-	100%	-
Beans/peas	-	100%	-
Tomatoes	40%	60%	-
Capsicum/chilli	-	50%	50%
Broccoli	-	80%	20%
Cauliflower	-	100%	-
Cabbage	-	100%	-
Cucurbits	50%	50%	-
Stonefruit	-	100%	-
Citrus trees	50%	50%	-
Nut trees	50%	50%	-

Table 9. Pest status of GPA in New South Wales vegetable and fruit crops

	NSW Advisor Responses (n=3)		
	Not a pest	Minor pest	Major pest
Potatoes	-	50%	50%
Lettuce	-	-	100%
Beans/peas	-	100%	-
Tomatoes	-	100%	-
Capsicum/chilli	-	-	100%
Cucurbits	-	50%	50%
Asian vegetables	-	-	100%
Stonefruit	-	-	100%

- Advisors were more likely to rate GPA as a minor or major pest in most crops as compared to growers (Table 4).
- Both growers and advisors report that GPA is more likely to be a major pest than a minor pest in capsicum/chilli crops (Table 4).
- GPA is considered a major pest in potatoes in Victoria, Western Australia, South Australia and New South Wales (Tables 5,7,8,9).
- In lettuce, GPA is a major pest in Victoria, Queensland and New South Wales, and a minor pest elsewhere (Tables 5,6,9).
- All growers in Victoria, Queensland and Western Australia, and advisors in New South Wales rate GPA as a major pest in Asian vegetable crops (Tables 5,6,7,9).
- GPA is a major pest of capsicum/chilli crops in Queensland, Western Australia and New South Wales, and a minor to major pest in Victoria and South Australia (Tables 5-9).
- GPA is not considered a major pest of citrus trees and nut trees (Table 4).

4. Monitoring of GPA in vegetable and fruit crops

Both growers and advisors answered similarly for this question, with the most likely monitoring time being once a week, followed by once a fortnight (Tables 10 & 11). No growers, and only a few advisors reported not monitoring for GPA at all. Most crops where GPA was recorded as either a minor or major pest are most likely to be monitored at least once a week. In citrus trees and nut trees (where GPA is a relatively minor pest) monitoring was more likely once a fortnight.

Table 10. Frequency of monitoring for GPA in fruit and vegetable crops by growers

	Grower responses (n=16)			
	At least once a week	**Once a fortnight**	**Once a month**	**Not at all**
Potatoes	60.00%	40.00%	-	-
Lettuce	66.67%	33.33%	-	-
Beans/peas	100.00%	-	-	-
Capsicum/chilli	100.00%	-	-	-
Broccoli	100.00%	-	-	-
Cauliflower	100.00%	-	-	-
Cabbage	100.00%	-	-	-
Cucurbits	100.00%	-	-	-
Asian vegetables	100.00%	-	-	-
Stonefruit	100.00%	-	-	-

Table 11. Frequency of monitoring for GPA in fruit and vegetable crops by advisors

	Advisor responses (n=49)			
	At least once a week	**Once a fortnight**	**Once a month**	**Not at all**
Potatoes	81.25%	12.50%	-	6.25%
Lettuce	94.12%	5.88%	-	-
Beans/peas	46.67%	33.33%	13.33%	6.67%
Tomatoes	78.26%	17.39%	-	4.35%
Capsicum/chilli	77.27%	18.18%	-	4.55%
Broccoli	88.89%	11.11%	-	-
Cauliflower	73.68%	26.32%	-	-
Cabbage	75.00%	25.00%	-	-
Cucurbits	84.00%	12.00%	-	4.00%
Asian vegetables	87.50%	-	-	12.50%
Stonefruit	56.25%	37.50%	6.25%	-
Citrus trees	25.00%	75.00%	-	-
Nut trees	16.67%	50.00%	-	33.33%

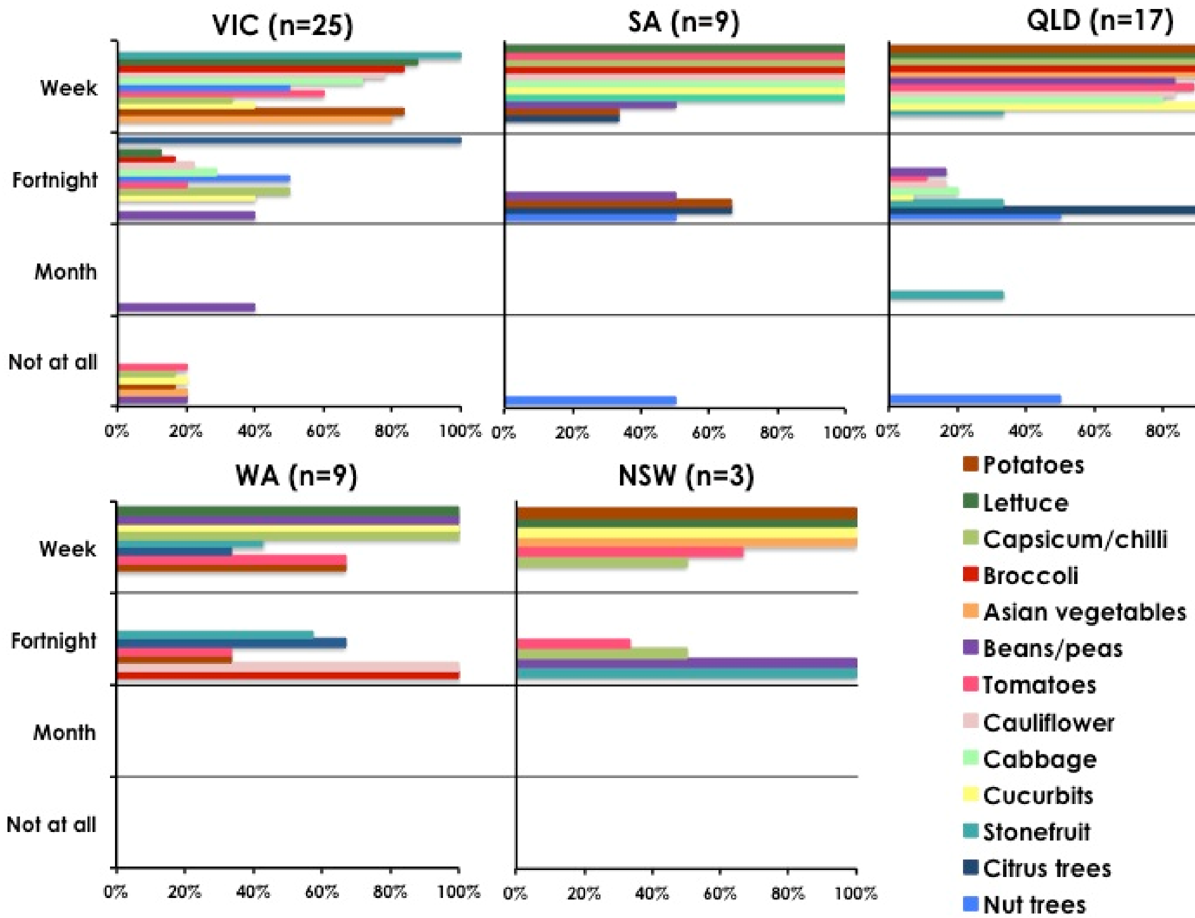

Figure 5. Frequency of monitoring for GPA in vegetable and fruit crops in each state (grower and advisor responses combined)

- Growers reported monitoring for GPA weekly in every crop, except for potatoes and lettuce (Table 10).
- Citrus trees are mostly monitored once a fortnight (Table 11).
- The only region where GPA was not monitored at all in vegetable crops was Victoria. Around 20% of respondents from Victoria reported not monitoring at all in potatoes, tomatoes, capsicum/chillies, cucurbits, and Asian vegetables (Fig. 5).
- Nut tree crops are not monitored at all for GPA in many cases (Fig. 5).
- Monthly monitoring for GPA was reported in some Victorian bean/pea crops and Queensland stonefruit crops (Fig. 5). In these situations, GPA is not regarded as a major pest (see Tables 5 & 6).

5. Control practices for GPA

Respondents were asked the most common control method they used for GPA. The options given were: 1) routine/calendar spraying, 2) applying insecticides when spraying other chemicals, 3) only using insecticides when GPA reach threshold levels, 4) relying on biological control agents, 5) removing host plants between seasons, or 6) doing nothing to control them. In addition, several other control methods were specified by survey respondents (e.g. using chemicals in furrow when planting potatoes, transplanting seedlings that have been treated with insecticides in nurseries, and applying seed treatments as preventative measures).

- There are a variety of control practices used to control GPA, and these vary with crop type.
- Both growers and advisors were most likely to spray only when GPA have reached threshold levels (Tables 12 & 13).
- In crops, where growers or advisors previously reported GPA as a major pest (e.g. potatoes and Asian vegetables), advisors are more likely to either recommend a routine/calendar spray or to apply insecticides when spraying other chemicals. Some growers are more likely to follow a routine/calendar approach to spraying, while others are likely to apply sprays when GPA have reached threshold levels (Tables 12 & 13).
- Removal of host plants is a common control method used in brassica crops (broccoli, cabbage and cauliflower) (Tables 12 & 13).
- Although there was some indication that growers and advisors rely on biological control agents in most fruit and vegetable crops, this control method was less likely to be used than insecticide application (Tables 12 & 13).
- Advisors indicated that they would do nothing to control GPA in nut trees (Table 13), and previously 62% of responses indicate GPA is not considered a pest in this crop.

Table 12. Control methods used for GPA in fruit and vegetable crops by growers

	Grower (n=16)					
	Routine spraying	**Add to other sprays**	**GPA threshold**	**Biological agents**	**Remove host plants**	**Nothing**
Potatoes	50.0%		50.0%			
Lettuce	33.3%		33.3%	16.7%	16.7%	
Beans/peas		100.0%				
Capsicum/chilli			50.0%	50.0%	0.0%	
Broccoli			33.3%	33.3%	33.3%	
Cauliflower			33.3%	33.3%	33.3%	
Cabbage			33.3%	33.3%	33.3%	
Cucurbits			50.0%	50.0%		
Asian vegetables	25.0%		50.0%	25.0%		
Stonefruit			50.0%			50.0%

Table 13. Control methods used for GPA in fruit and vegetable crops by advisors

	Advisor (n=48)					
	Routine spraying	**Add to other sprays**	**GPA threshold**	**Biological agents**	**Remove host plants**	**Nothing**
Potatoes	25.0%	36.1%	22.2%	5.6%	8.3%	2.8%
Lettuce	18.8%	28.1%	21.9%	15.6%	15.6%	
Beans/peas	23.5%	29.4%	47.1%			
Tomatoes	13.2%	26.3%	36.8%	13.2%	10.5%	
Capsicum/chilli	14.0%	20.9%	30.2%	18.6%	16.3%	
Broccoli	5.6%	13.9%	41.7%	22.2%	16.7%	
Cauliflower	8.8%	20.6%	35.3%	20.6%	14.7%	
Cabbage	13.0%	30.4%	30.4%	13.0%	13.0%	
Cucurbits	15.0%	25.0%	30.0%	17.5%	12.5%	
Asian vegetables	6.7%	46.7%	26.7%	6.7%	13.3%	
Stonefruit	17.9%	28.6%	39.3%	14.3%		
Citrus trees	27.3%	9.1%	45.5%	9.1%		9.1%
Nut trees			42.9%			57.1%

There are differences in control practices used for GPA across regions. The different crop types grown within each region are the main reason for these differences, and bias due to the low number of respondents from some states may also contribute to these differences. Due to low numbers of advisor respondents from these states, and from growers, we only present data from Victorian, Queensland and South Australian advisors below.

Table 14. Control methods used for GPA in fruit and vegetable crops by Victorian advisors

	VIC Advisor (n=19)					
	Routine spraying	**Add to other sprays**	**GPA threshold**	**Biological agents**	**Remove host plants**	**Nothing**
Potatoes	20.0%	30.0%	20.0%		20.0%	10.0%
Lettuce	18.2%	27.3%	27.3%	9.1%	18.2%	
Beans/peas		33.3%	66.7%			
Tomatoes		27.3%	54.5%	9.1%	9.1%	
Capsicum/chilli		33.3%	44.4%	11.1%	11.1%	
Broccoli		11.1%	44.4%	22.2%	22.2%	
Cauliflower	10.0%	30.0%	30.0%	10.0%	20.0%	
Cabbage	10.0%	30.0%	30.0%	10.0%	20.0%	
Cucurbits		27.3%	27.3%	27.3%	18.2%	
Asian vegetables		37.5%	25.0%	12.5%	25.0%	
Stonefruit	8.3%	41.7%	33.3%	16.7%		
Citrus trees			66.7%	33.3%		
Nut trees			100.0%			

Table 15. Control methods used for GPA in fruit and vegetable crops by Queensland advisors

	QLD Advisor (n=13)					
	Routine spraying	**Add to other sprays**	**GPA threshold**	**Biological agents**	**Remove host plants**	**Nothing**
Potatoes	33.3%	33.3%	22.2%	11.1%		
Lettuce	7.1%	21.4%	28.6%	21.4%	21.4%	
Beans/peas	33.3%	16.7%	50.0%			
Tomatoes	5.6%	22.2%	38.9%	16.7%	16.7%	
Capsicum/chilli	13.6%	18.2%	22.7%	22.7%	22.7%	
Broccoli	12.5%	12.5%	43.8%	18.8%	12.5%	
Cauliflower	14.3%	14.3%	35.7%	21.4%	14.3%	
Cabbage	18.2%	18.2%	36.4%	18.2%	9.1%	
Cucurbits	15.0%	20.0%	40.0%	20.0%	5.0%	
Asian vegetables	16.7%	50.0%	33.3%			
Stonefruit		20.0%	60.0%	20.0%		
Citrus trees						100.0%
Nut trees						100.0%

Table 16. Control methods used for GPA in fruit and vegetable crops by South Australian advisors

	SA Advisor (n=8)					
	Routine spraying	**Add to other sprays**	**GPA threshold**	**Biological agents**	**Remove host plants**	**Nothing**
Potatoes	16.7%	33.3%	33.3%		16.7%	
Lettuce	50.0%	50.0%				
Beans/peas		100.0%				
Tomatoes		33.3%	33.3%	33.3%		
Capsicum/chilli		16.7%	50.0%	33.3%		
Broccoli		25.0%	37.5%	25.0%	12.5%	
Cauliflower		33.3%	33.3%	33.3%		
Cabbage		100.0%				
Cucurbits		50.0%			50.0%	
Stonefruit			100.0%			
Citrus trees			100.0%			
Nut trees			50.0%			50.0%

- Victorian and Queensland advisors work across a variety of crops and recommend a wide variety of control methods for GPA. The most common method in both states recommended by advisors is to spray once GPA numbers have reached a threshold (Tables 14 & 15).
- There is a reliance on biological controls in Victoria, Queensland and South Australia, although a heavier reliance in Queensland than other states.
- Across the majority of crops, South Australian advisors often recommend insecticides are added when other chemical sprays are being applied, however for capsicum/chilli, broccoli and cauliflower crops, they were more likely to wait till GPA reached a threshold before recommending a spray (Table 16).

6. Number of sprays for GPA per cropping season

Respondents were asked to give the approximate number of times they would apply an insecticide to control GPA during a cropping season. Grower responses were in agreement with the advisor responses for this question, and are combined below.

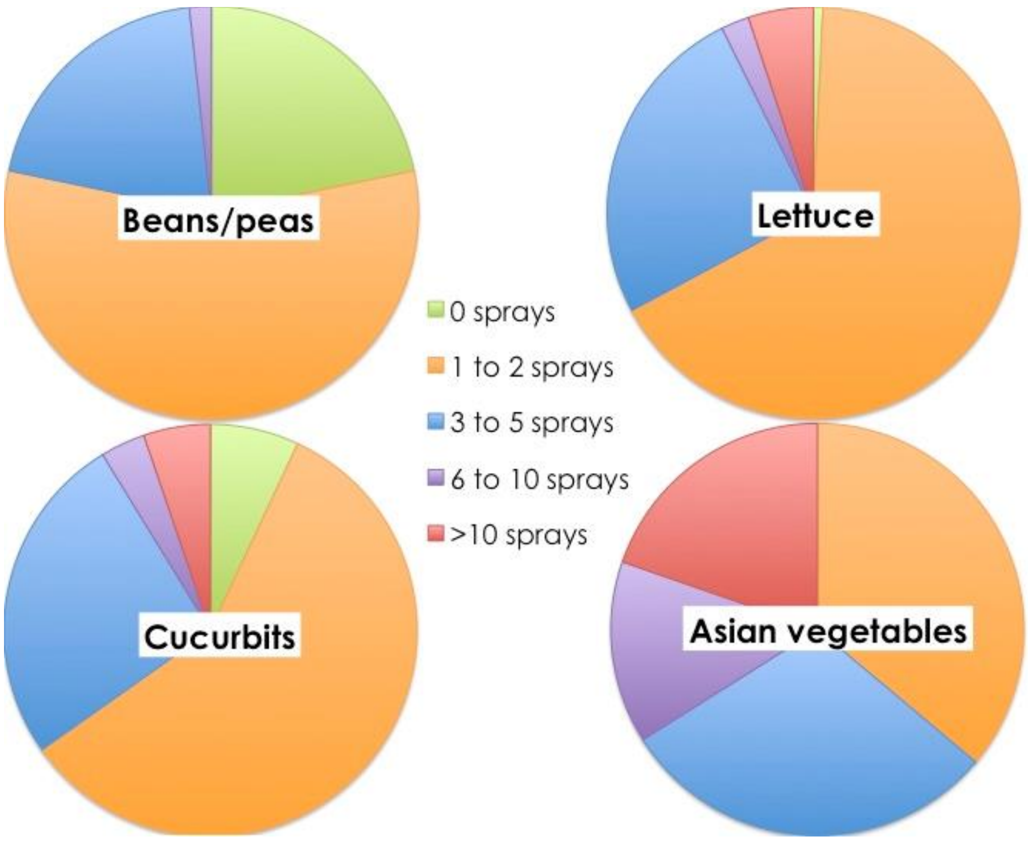

Figure 6. Number of sprays per season applied for various vegetable crops

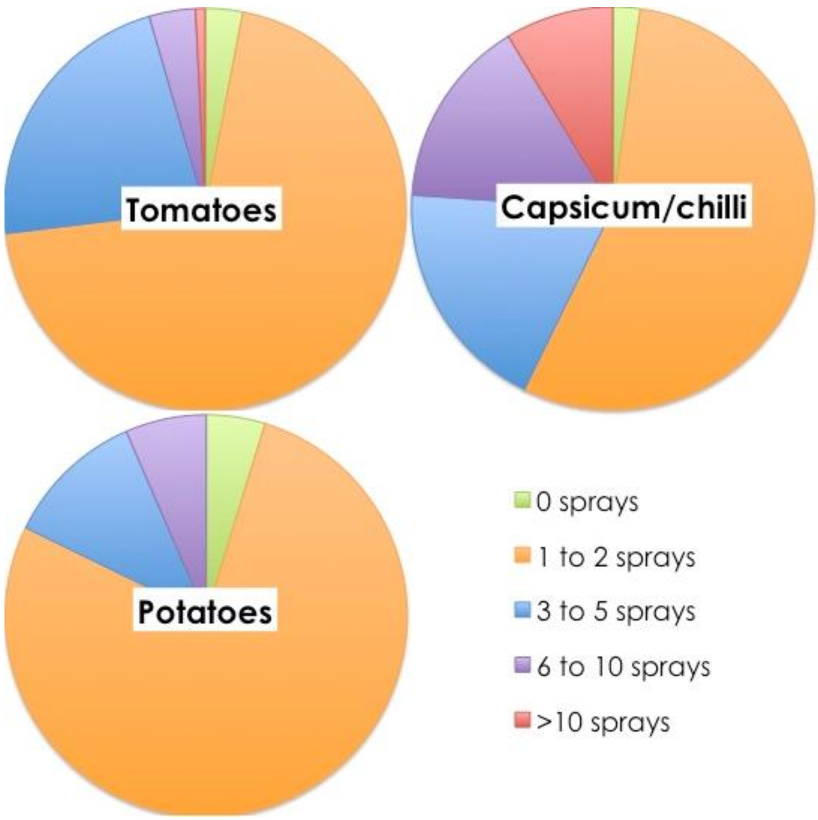

Figure 7. Number of sprays per season applied for Solenaceae

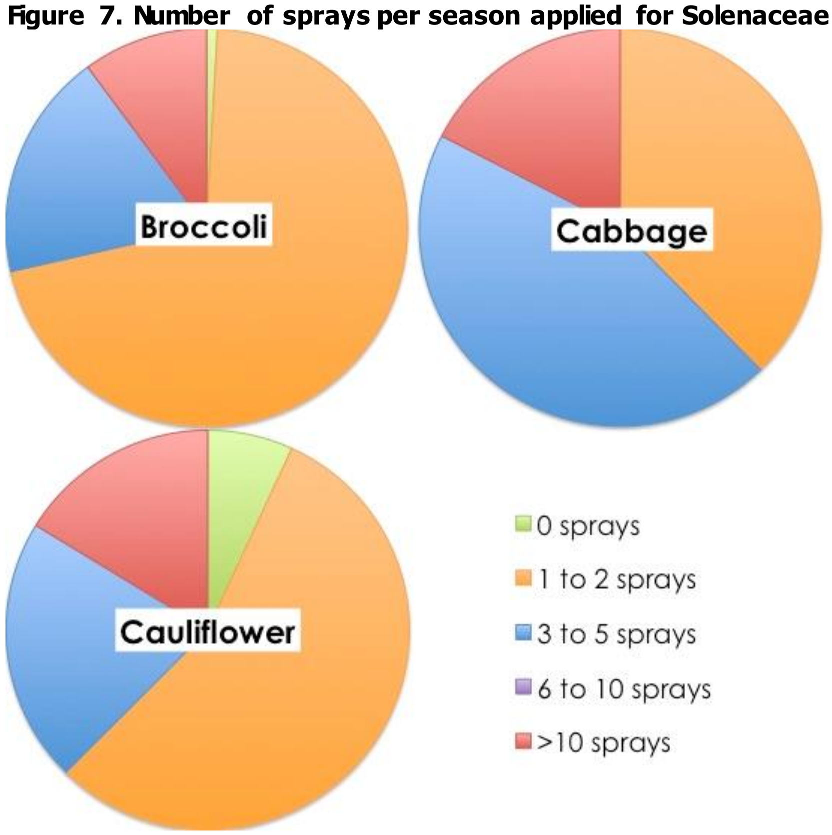

Figure 8. Number of sprays per season applied for Brassicas

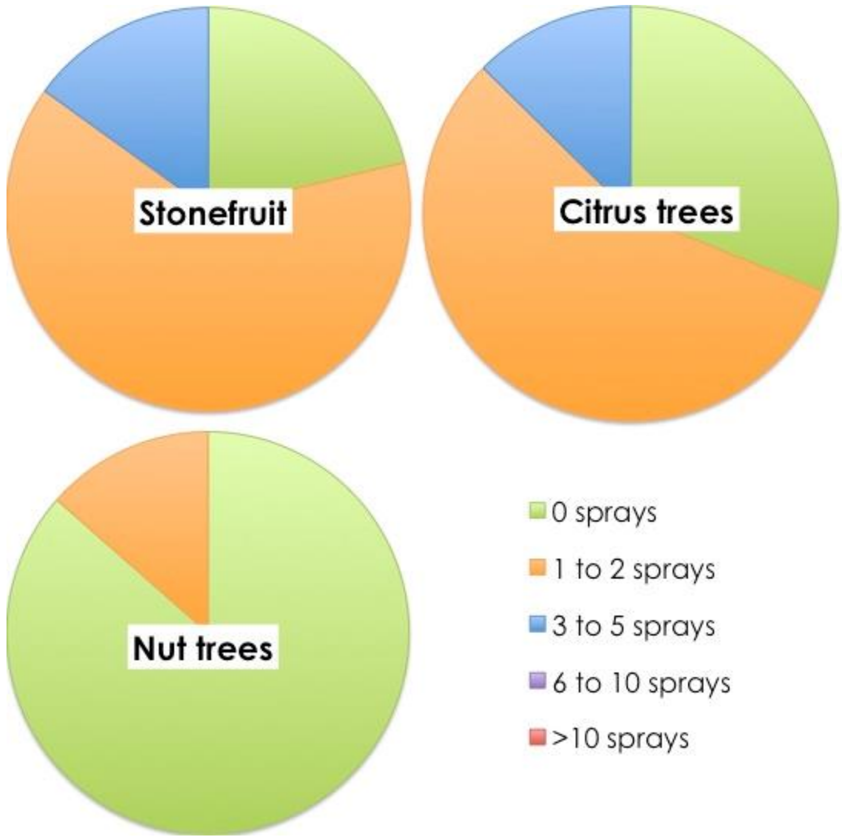

Figure 9. Number of sprays per season applied for fruit and nut trees

- For the majority of vegetable crops grown, around 1-2 sprays are applied to control GPA during a cropping season (Figs. 6-8).
- For some crops the number of sprays per season were higher. In lettuce, tomato and capsicum/chilli crops, many growers apply 3-5 sprays, while some apply 6-10 sprays or more, per season (Figs. 6 & 7).
- The number of sprays applied per season is lower in fruit and nut trees (Fig. 9).
- Corn and strawberry crops, reported separately, are sprayed 3–5 or more sprays per season to control GPA.

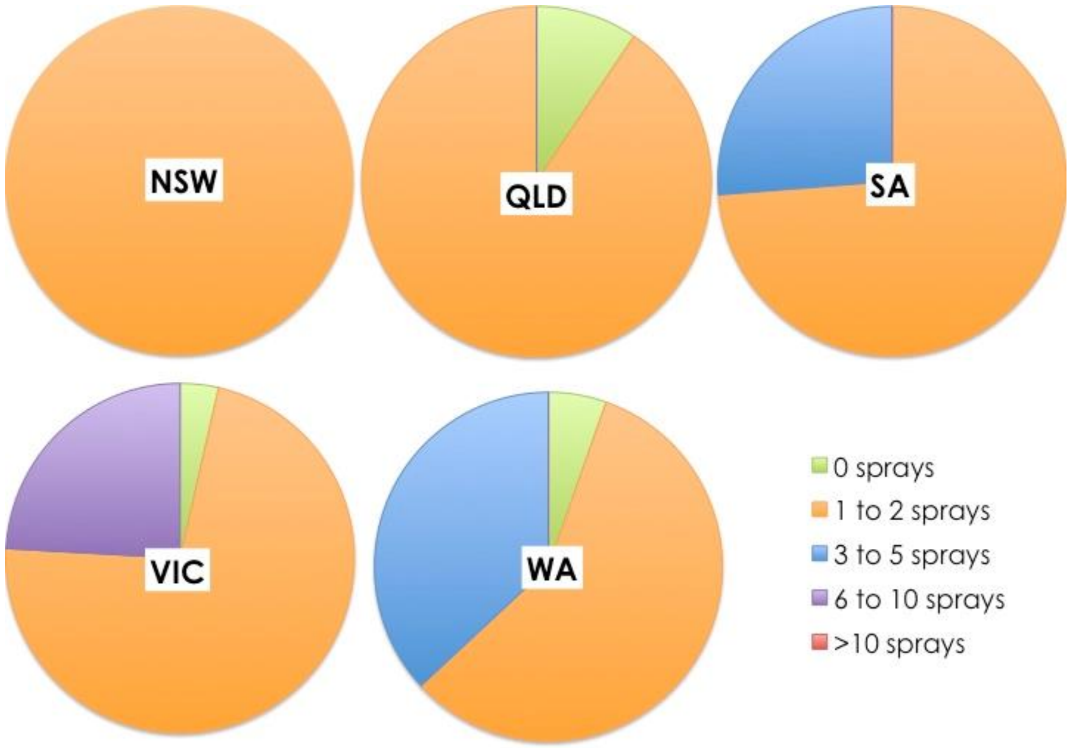

Figure 10. Number of sprays per season applied for potatoes across different states

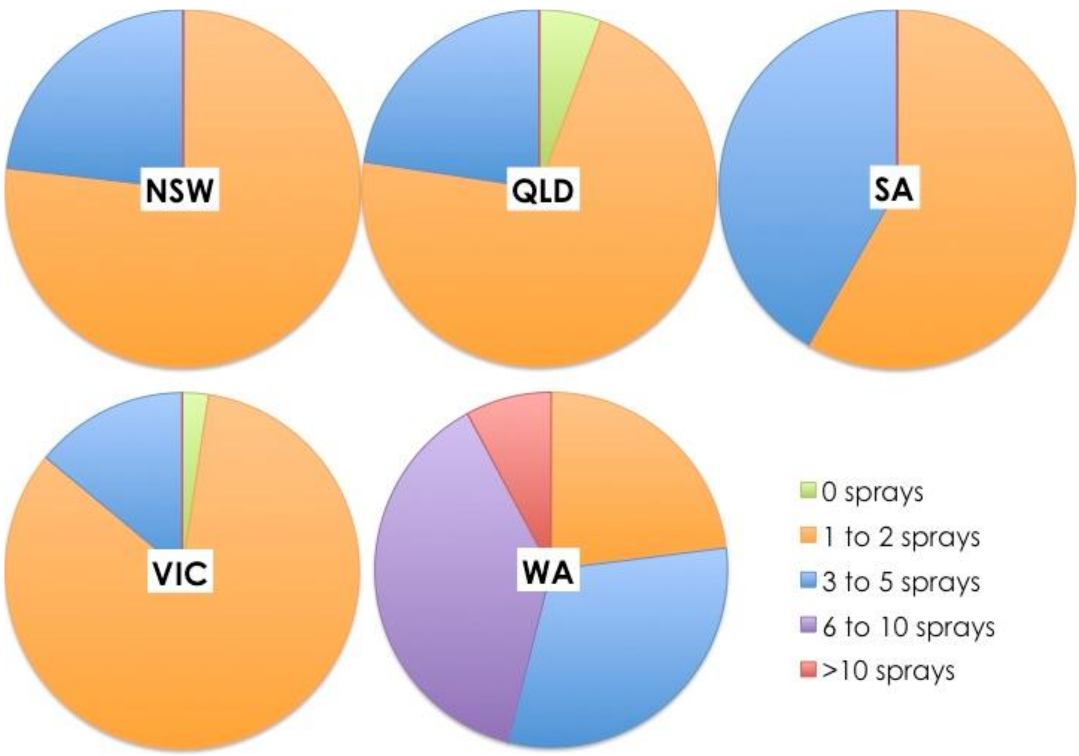

Figure 11. Number of sprays per season applied for tomatoes across different states

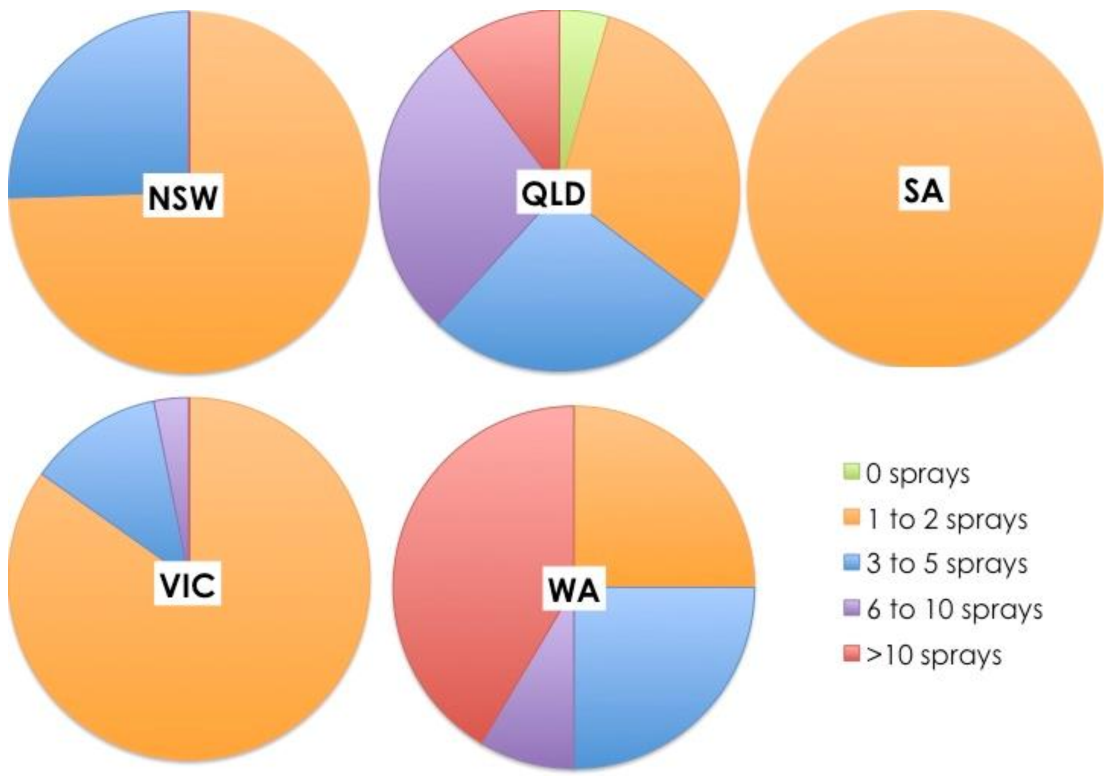

Figure 12. Number of sprays per season for capsicum/chilli across different states

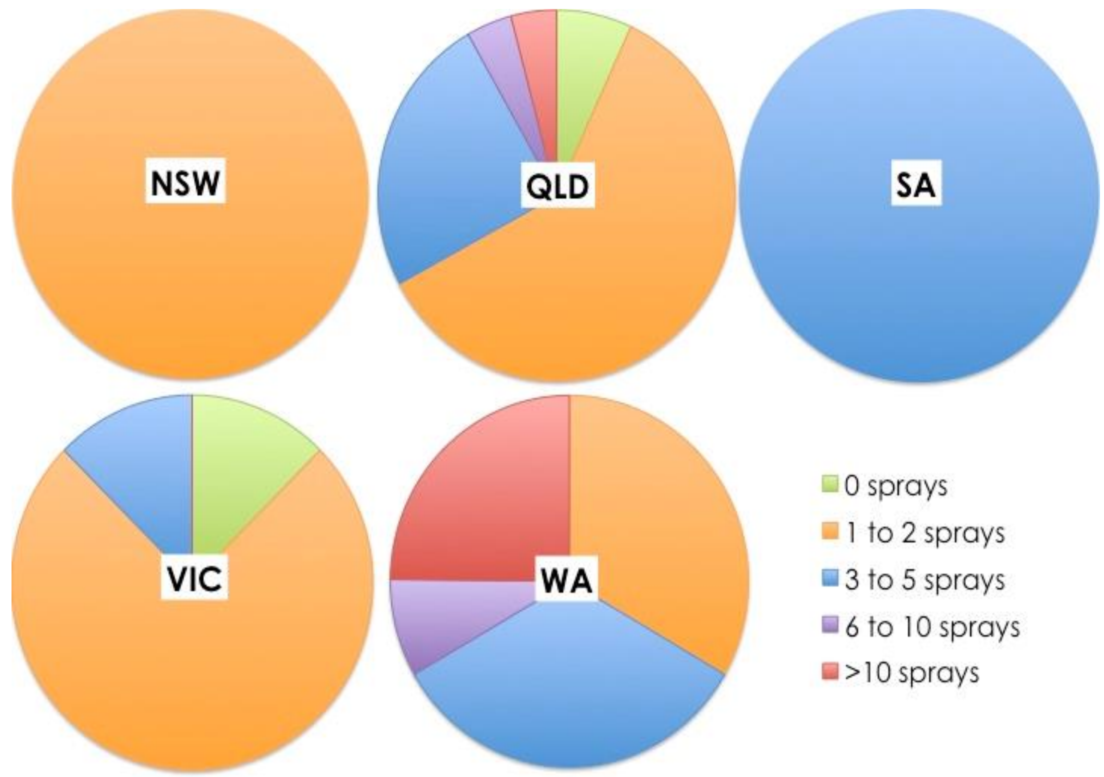

Figure 13. Number of sprays per season applied for cucurbits across different states

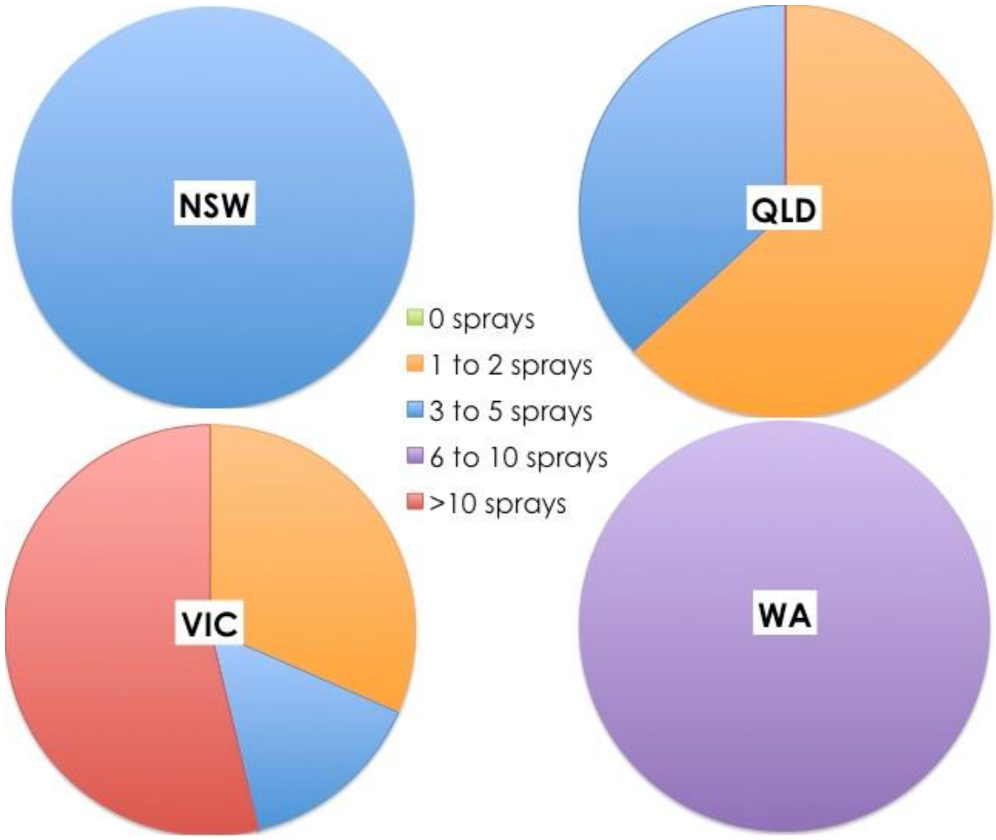

Figure 14. Number of sprays per season for Asian vegetables across different states

- Higher rates of spraying (>5 sprays per season) were more commonly reported from Western Australia, Queensland and Victoria (Figs. 10-14).
- More insecticide sprays are applied to tomato crops in Western Australia than other states (Fig. 10). The same is true for capsicum/chilli crops and cucurbits, although these two crops are also heavy sprayed in Queensland (Figs. 12-13).
- When grown, Asian vegetable crops have the highest number of sprays per season across all states (New South Wales, Queensland, Victoria and Western Australia) (Fig. 14). GPA is a major pest in this crop.

7. Reasons for applying multiple sprays per cropping season

For those growers who reported applying (or in the case of advisors, recommending) more than one insecticide per season to control GPA, respondents were asked to choose one or more reasons for spraying multiple times in a cropping season. These were: 1) it is common in the crop/region, 2) based on results from regular monitoring, 3) concern about viruses transmitted by GPA, and 4) based on my past experience controlling GPA. This was not a crop-specific question, and as both advisors and growers work with multiple crops, we cannot comment on spraying practices by crop type, only across professions and regions. Respondents could also provide qualitative responses, and reported a small number of other reasons for applying multiple sprays per season. These included spraying similar chemicals for other pest aphids (e.g. cabbage aphid), quality management, and due to very long crop seasons requiring control over a long period.

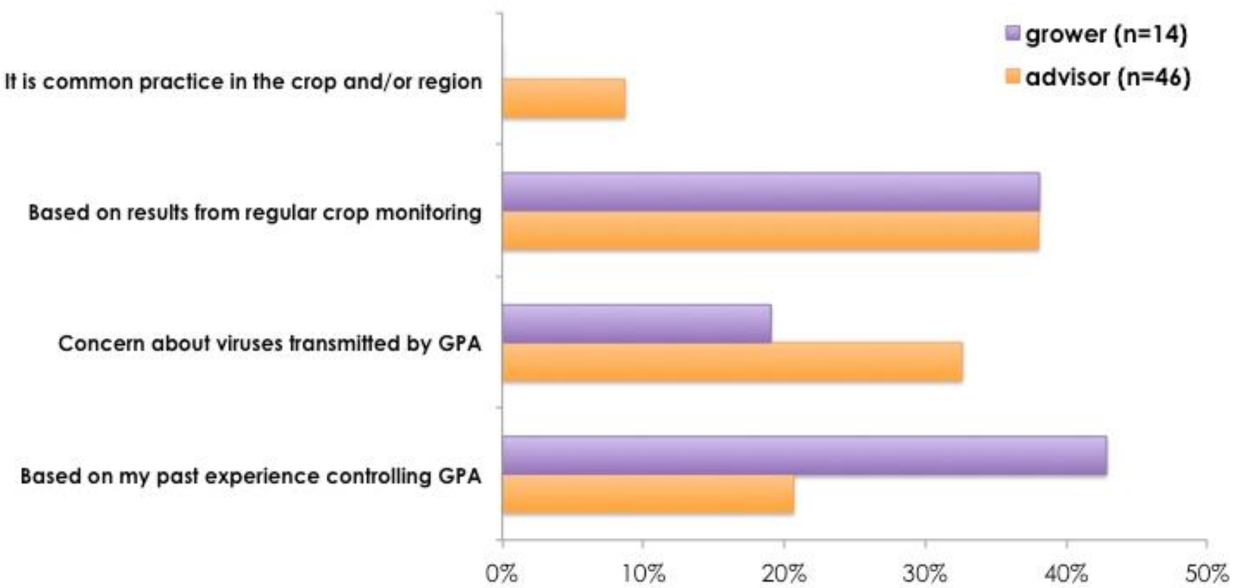

Figure 15. Reasons for applying multiple sprays in a single season

- The most likely reason for applying multiple sprays differed between growers and advisors. Growers were more likely to rely on their past experiences controlling GPA, while advisors were more likely to respond to crop monitoring (Fig. 15).

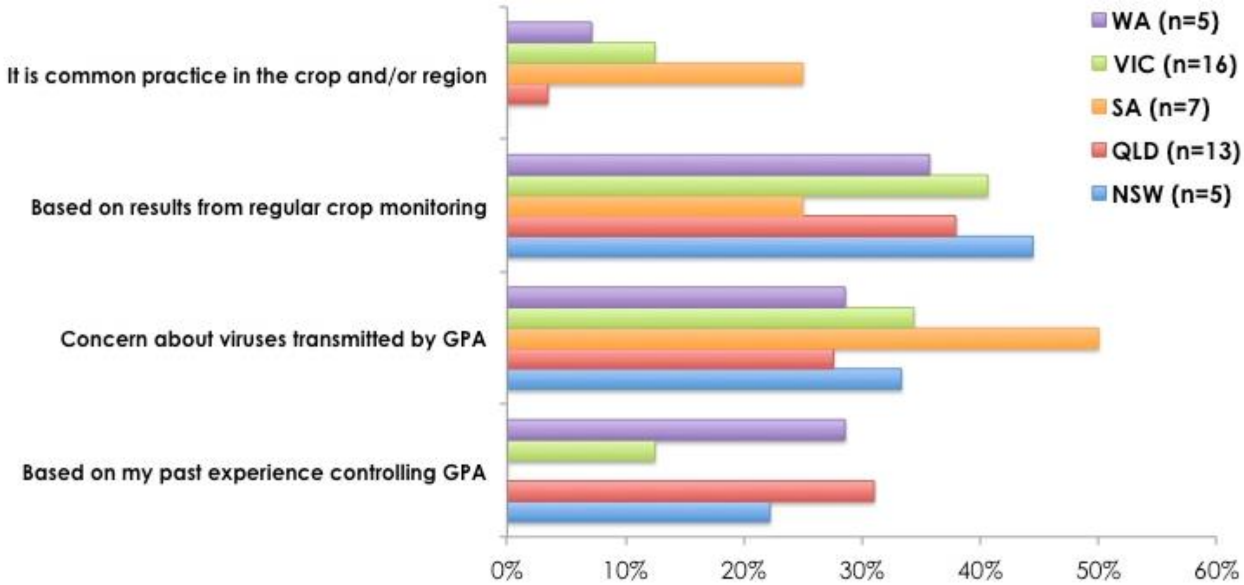

Figure 16. Advisor reasons for applying multiple sprays in a single season

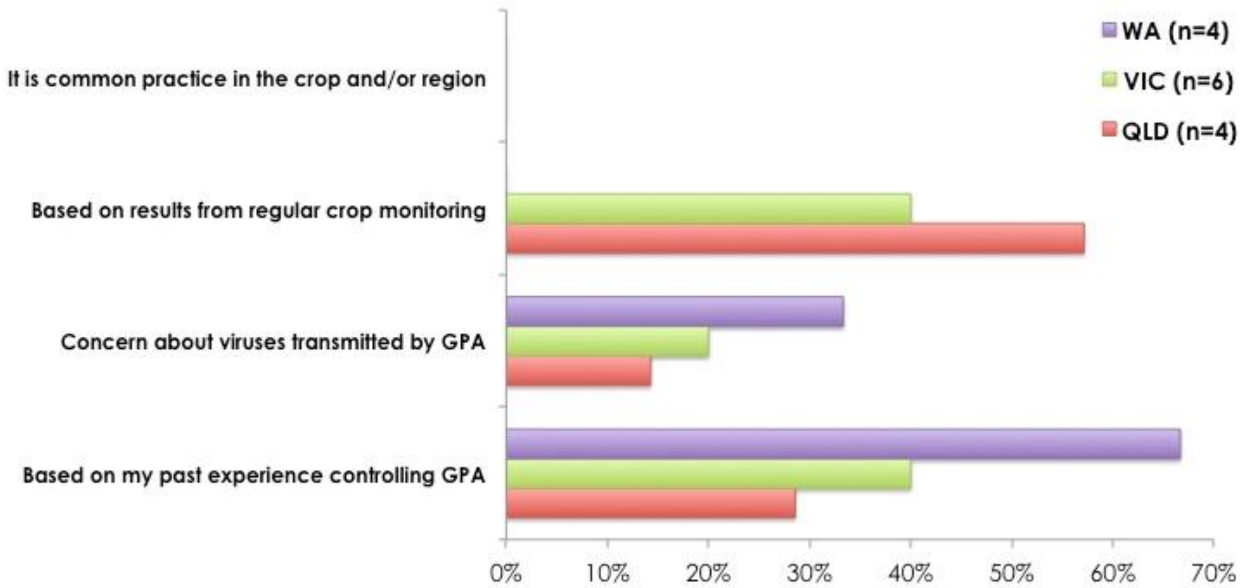

Figure 17. Grower reasons for applying multiple sprays in a single season

- Queensland and Victorian growers were more likely to apply multiple sprays based on crop monitoring, whereas Western Australian growers were more likely to spray multiple times based on past experience controlling GPA (Fig. 17).
- Some growers and advisors sprayed multiple times per season out of concern for virus transmission by GPA. In South Australia this was the most common reason for multiple sprays given by advisors (Fig. 16 & 17).

8. Insecticide selection

We asked respondents which chemical(s) they use to control GPA. They were asked to select from a list of chemicals that are currently registered to control GPA in Australia:

- Organophosphates (e.g. chlorpyrifos, dimethoate, diazinon, maldison)
- Pyrethroids (e.g. lambda-cyhalothrin, permethrin, Tau-fluvalinate)
- Neo-nicotinoids (e.g. imidacloprid, thiamethoxam, clothianidin, thiacloprid)
- Carbamates (e.g. methomyl, pirimicarb)
- Pymetrozine (e.g. Chess)
- Sulfoxaflor (e.g. Transform)
- Tetronic/Tetramic acid derivatives (e.g. spirotetramat)
- Oils (e.g. Canopy, Eco-oil)

For this question, there was no option to select non-registered products, and this may be happening in some crops and regions. Respondents volunteered some comments on chemical selection including:

- Chemical choice is based on GPA as a secondary pest
- Transform is a newer chemical and hasn't been used a lot as yet
- Durivo (Chlorantraniliprole) is used to control GPA
- Softer chemistry is recommended for control initially

The majority of growers stated that they select insecticides by referring to an agronomist or consultant (68.8%), and/or insecticide labels (68.8%). 25% of growers also referred to magazine or journal articles and a few also use the APVMA website and mobile phone app.

Chemicals use to control GPA differed between growers and advisors, and across states.

Table 17. Chemicals used for GPA control by growers and advisors
(Note: values do not necessarily add upto100% as respondents were able to provide multiple responses)

	Advisors (n=48)				Growers (n=14)			
	Never	Occasionally	Mostly	Always	Never	Occasionally	Mostly	Always
Organophosphates	22.9%	52.1%	6.3%		14.3%	42.9%	7.1%	
Pyrethroids	29.2%	31.3%	16.7%		14.3%	7.1%	28.6%	
Neo-nicotinoids	2.1%	27.1%	43.8%	12.5%	7.1%	28.6%	14.3%	
Carbamates	18.8%	37.5%	22.9%	4.2%	14.3%	35.7%	14.3%	
Pymetrozine	12.5%	35.4%	18.8%	4.2%	14.3%	7.1%	7.1%	
Sulfoxaflor	10.4%	37.5%	22.9%	12.5%	14.3%	21.4%	14.3%	
Tetronic/Tetramic acid	27.1%	20.8%	25.0%	4.2%	21.4%	7.1%	7.1%	
Oils	22.9%	35.4%	14.6%		7.1%	28.6%	7.1%	

- Advisors were most likely to recommend Neo-nicotinoids and least likely to recommend Oils or Pyrethroids (Table 17).
- Growers were most likely to use Carbamates and least likely to use Pymetrozine or Tetronic/Teramic acid derivatives (Table 17).
- Use of Organophosphates was most likely to be occasionally, or not at all (Table 17).

Table 18. Chemicals used for GPA control in Victoria
(Note: values do not necessarily add upto100% as respondents were able to provide multiple responses)

	VIC (n=24)			
	Never	**Occasionally**	**Mostly**	**Always**
Organophosphates	29.2%	54.2%	4.2%	
Pyrethroids	29.2%	33.3%	16.7%	
Neo-nicotinoids	4.2%	25.0%	41.7%	8.3%
Carbamates	16.7%	50.0%	12.5%	
Pymetrozine	8.3%	25.0%	16.7%	
Sulfoxaflor	12.5%	45.8%	12.5%	
Tetronic/Tetramic acid	29.2%	16.7%	12.5%	
Oils	25.0%	37.5%	4.2%	

- Neo-nicotinoids are the most common chemicals used to control GPA in Victoria, followed by Carbamates, Organophosphates and Sulfoxaflor (Table 18).

Table 19. Chemicals used for GPA control in Queensland
(Note: values do not necessarily add upto100% as respondents were able to provide multiple responses)

	QLD (n=16)			
	Never	**Occasionally**	**Mostly**	**Always**
Organophosphates	18.8%	43.8%	6.3%	
Pyrethroids	31.3%	18.8%	6.3%	
Neo-nicotinoids		25.0%	37.5%	12.5%
Carbamates	18.8%	31.3%	18.8%	6.3%
Pymetrozine	6.3%	37.5%	18.8%	
Sulfoxaflor		18.8%	31.3%	31.3%
Tetronic/Tetramic acid	12.5%	18.8%	37.5%	12.5%
Oils	6.3%	43.8%	18.8%	

- In Queensland, the most commonly used chemical for GPA control is Sulfoxaflor. Neo-nicotinoids and Tetronic/Tetramic acids are also highly used chemicals (Table 19).

Table 20. Chemicals used for GPA control in Western Australia
(Note: values do not necessarily add upto100% as respondents were able to provide multiple responses)

	WA (n=8)			
	Never	**Occasionally**	**Mostly**	**Always**
Organophosphates		62.5%	12.5%	
Pyrethroids		37.5%	25.0%	
Neo-nicotinoids		25.0%	50.0%	
Carbamates		25.0%	50.0%	
Pymetrozine	12.5%	25.0%	25.0%	
Sulfoxaflor		12.5%	50.0%	
Tetronic/Tetramic acid	12.5%	12.5%	37.5%	
Oils	12.5%	25.0%	12.5%	

- In Western Australia, Carbamates, Sulfoxaflor and Neo-nicotinoids are the most highly used chemicals to control GPA, followed by Organophosphates (Table 20).

Table 21. Chemicals used for GPA control in South Australia
(Note: values do not necessarily add upto100% as respondents were able to provide multiple responses)

	SA (n=8)			
	Never	**Occasionally**	**Mostly**	**Always**
Organophosphates	12.5%	37.5%	12.5%	
Pyrethroids	12.5%	12.5%	37.5%	
Neo-nicotinoids		50.0%	25.0%	
Carbamates		37.5%	37.5%	12.5%
Pymetrozine	12.5%	37.5%	12.5%	12.5%
Sulfoxaflor	25.0%	62.5%		
Tetronic/Tetramic acid	25.0%	37.5%		
Oils		25.0%	25.0%	

- In South Australia, the most commonly used chemicals against GPA are Carbamates, followed by Neo-nicotinoids (Table 21).

Table 22. Chemicals used for GPA control in New South Wales
(Note: values do not necessarily add upto100% as respondents were able to provide multiple responses)

	NSW (n=5)			
	Never	**Occasionally**	**Mostly**	**Always**
Organophosphates	20.0%	60.0%		
Pyrethroids	40.0%	20.0%	40.0%	
Neo-nicotinoids		20.0%	20.0%	40.0%
Carbamates	60.0%	20.0%		
Pymetrozine	40.0%	20.0%		20.0%
Sulfoxaflor	20.0%	20.0%	20.0%	20.0%
Tetronic/Tetramic acid	60.0%		20.0%	
Oils	60.0%	20.0%	20.0%	

- In New South Wales, Neo-nicotinoids are the most commonly used chemicals for GPA control, followed by Pyrethroids, Organophosphates and Sulfoxaflor (Table 22).

9. Beneficial insects

We asked respondents how often they considered beneficial insects in the crop when selecting insecticides for GPA control

- 36.7% of advisors and 43.8% of growers reported always considering beneficial insects when selecting insecticides (Fig. 18)
- 50% of growers either never, or only occasionally, considered beneficial insects (Fig. 18)
- Only 6.1% of advisor respondents would never consider beneficial insects when selecting insecticides, whereas 25% of grower respondents would never consider beneficial insects (Fig. 18)
-

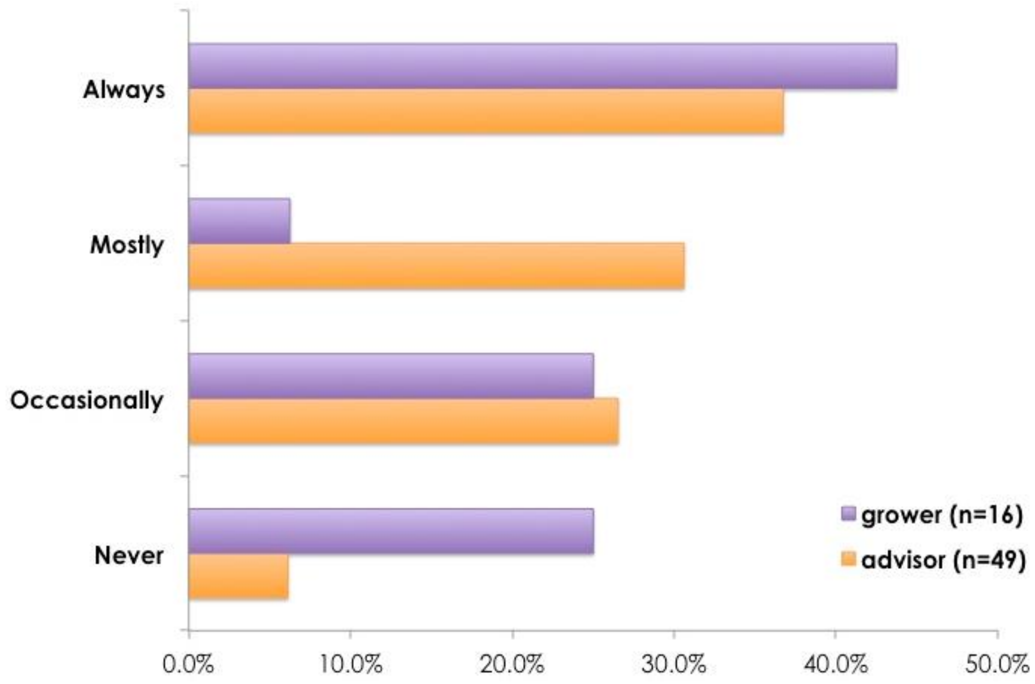

Figure 18. Frequency beneficial insects are considered when selecting insecticides

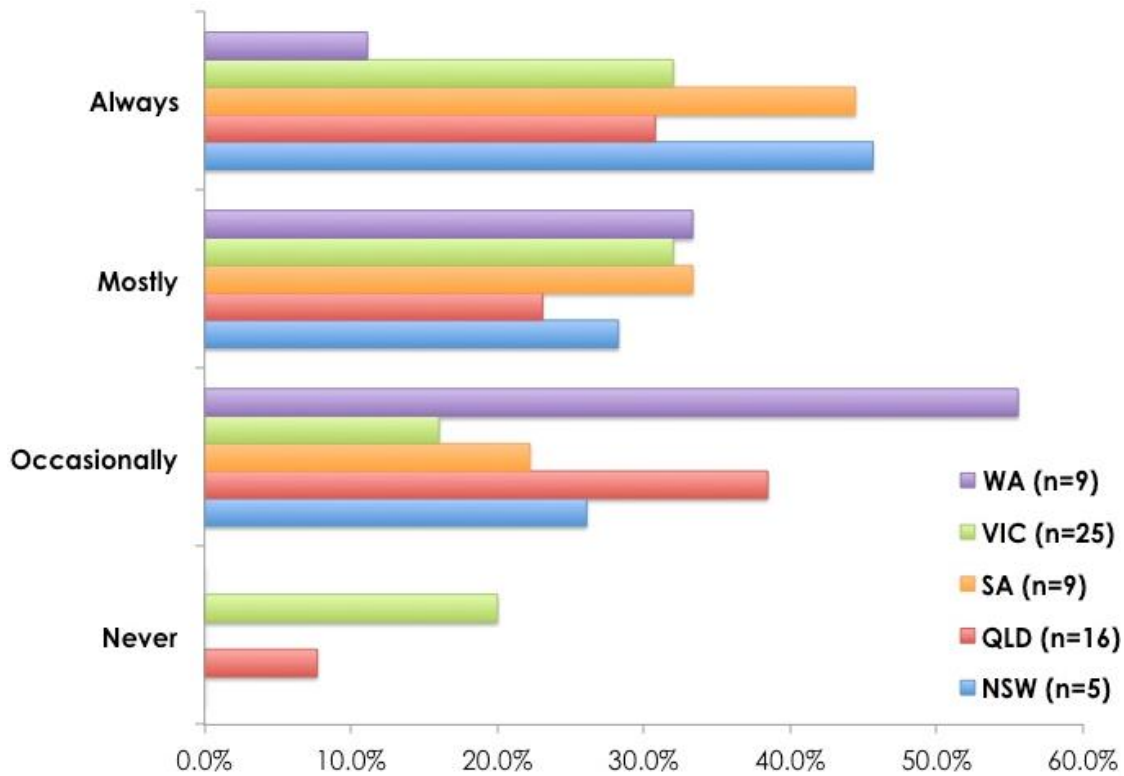

Figure 19. Frequency beneficial insects are considered when selecting insecticides by state

- In South Australia, New South Wales and Victoria, the majority of respondents always and/or mostly consider beneficial insects when selecting insecticides (Fig. 19).
- In Queensland and Western Australia, a number of respondents only consider beneficial insects occasionally (Fig. 19).
- Victoria and Queensland where the only two states were respondents reported they would never consider beneficial insects when selecting an insecticide to spray GPA (Fig. 19).

10. Insecticide rotations

Rotation of chemical groups when applying multiple sprays in a single growing season is a common resistance management strategy. Respondents were asked to comment on their insecticide rotation practices.

- 93.8% of growers reported that they rotate between chemical groups when applying more than one spray within a single growing season of a crop.
- Advisors reported that the growers they worked with either always (38.8%) or mostly (46.9%) rotated chemical groups within a single growing season.
- Across all the states, it was common to either always or mostly rotate chemical groups when spraying more than once within a single growing season (Fig. 20).

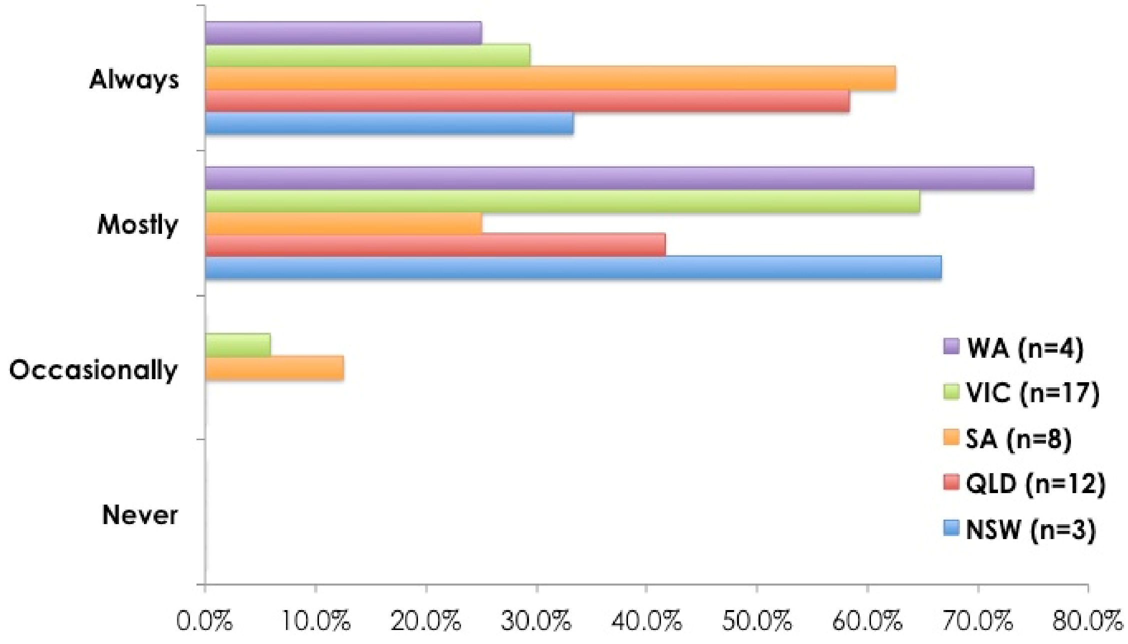

Figure 20. Frequency insecticides are rotated between chemical groups when spraying multiple times in a single season

Respondents were asked to select the reasons for rotating chemical groups from the following list:

- Concerns about insecticide resistance
- Advice from agronomist/consultant (grower-only option)
- Industry guidelines
- Price of the insecticide
- Label restrictions
- Weather conditions
- Previous insecticides didn't work as well as expected
- Part of a regular practice

The main reason respondents gave for rotating chemical groups was due to concerns about insecticide resistance. Advisors and growers also commonly reported rotating chemical groups as part of a regular practice. Growers commonly rotate chemical groups based on agronomist/consultant advice. The price of insecticide was rarely reported as being a reason for rotating between chemical groups (Fig. 21).

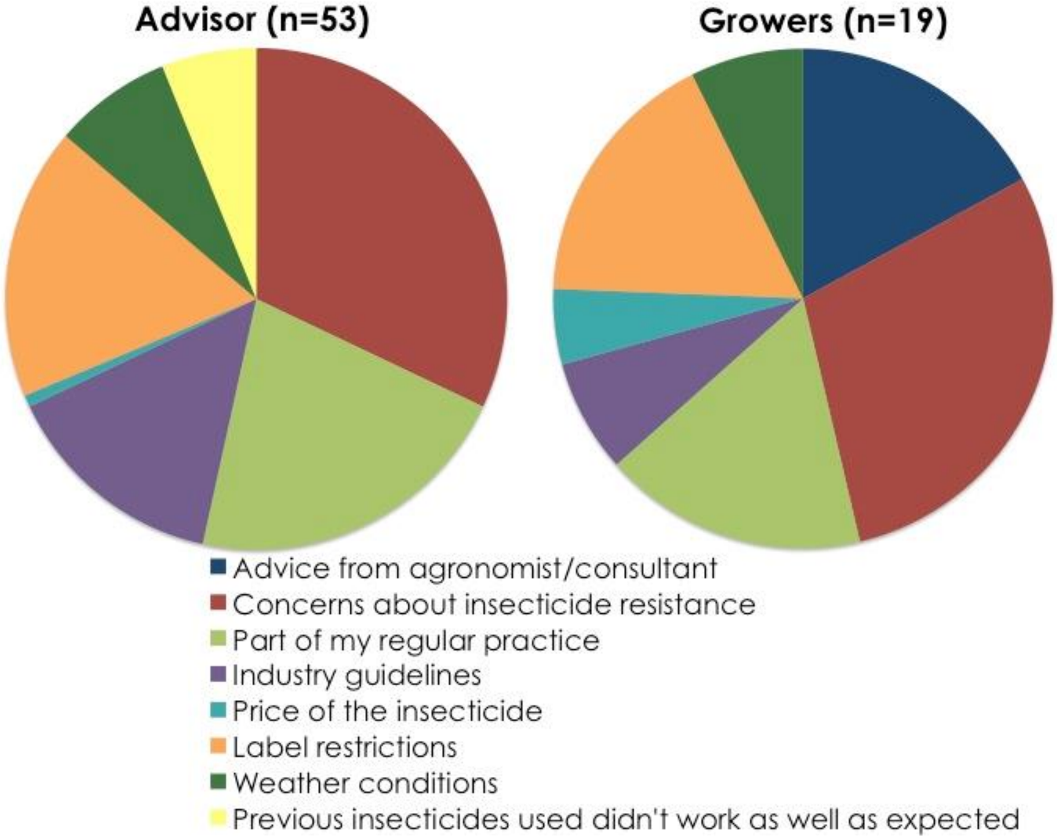

Figure 21. Reasons for rotating insecticides between different chemical groups in a single season

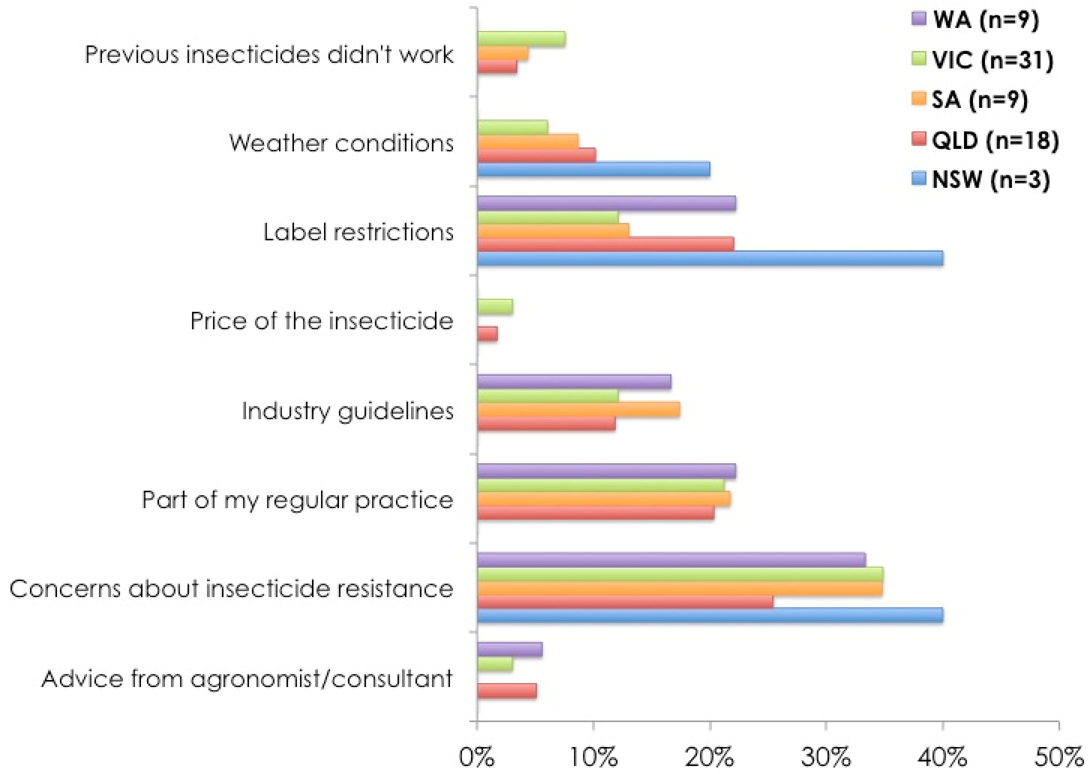

Figure 22. Reasons for rotating insecticides between different chemical groups in a single season by state

Reasons for rotating insecticides between different chemical groups were fairly consistent across the different states (Fig. 22). Several respondents provided other reasons for rotating chemical groups, including IPM practices/programs that involve beneficial insects, environmental safety issues, maximum residue limits and withholding periods.

11. Chemical control failures

A large number of respondents have experienced chemical control failures involving GPA. Respondents reported the highest number of control failures in Victoria, however the ratio of failure to no failures was relatively equal across Australia (approximately twice as many control failures reported as those with no experience of control failures) (Table 23).

Table 23. Respondents who have experience a GPA control failure

	NSW (n=5)	**QLD** (n=16)	**SA** (n=9)	**VIC** (n=25)	**WA** (n=9)
Experience of Failure	60.0%	62.5%	55.6%	64.0%	44.4%
No Experience of Failure	20.0%	31.3%	22.2%	32.0%	22.2%
Not sure	20.0%	6.3%	22.2%	4.0%	33.3%

When a control failure occurred, all but one grower (who was from Victoria) believed the failure was due to insecticide resistance, whereas only 53% of advisors thought that the failure was due to resistance. 43% of advisors were unsure whether control failures they had experienced were due to insecticide resistance (Fig. 23).

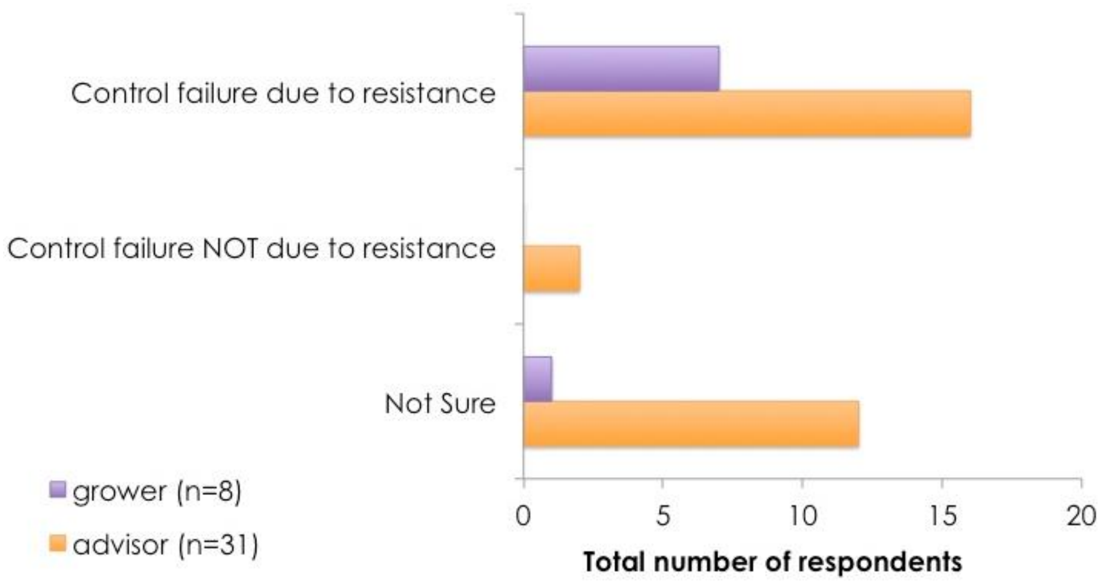

Figure 23. Grower and advisor beliefs about the reasons for a control failure

In New South Wales, Queensland and South Australia, advisors were more likely to think a control failure was due to resistance, whereas in Victoria and Western Australia, advisors were more likely to be unsure of the reason for control failures they had experienced.

12. Other invertebrate crop pests

Insecticides used to control other pests will increase section pressure on GPA to develop insecticide resistance if they are also present in the crop at the time of application. Respondents reported controlling for other pests as well as GPA in the same crops. The most commonly reported pests targeted with insecticides were mites, thrips and *Helicoverpa* spp. Respondents reported using a range of chemicals to control these pests (Table 24).

Table 24. Number of respondents that spray insecticides to control pests other than GPA

Pest	Responses	Species	Control Methods
Mites	54.72%	Two-spotted, Redlegged earth mite, *Bryobia*, Red Spider	Maldison, Eco-Oil, Omite, Acramite, Vertimec, Imidacloprid, Bifenthrin, Omethoate, Dimethoate, Abermectin, Milbemectin, Wettable sulphur, Paramite
Thrips	47.17%	Onion, Western Flower, Plague,	Methomyl, Movento, Success, Klartan, Dimethoate, Hy-mal, Transform, Dichlorvos, Maverick, Aza Maz, BioPest Oil
Helicoverpa	36.19%	*H. armigera* *H. puntigera*	Lannate, Pyganic, Belt, Coragen, Avatar, Success, Methomyl, Proclaim, Dipel, pyrethroids
Diamondback moth	26.42%	Plutella	Belt, Coragen, Dipel, Avatar, Success, Methomyl, Proclaim
Moths	26.42%	Carob, Codling, Light Brown Apple, Oriental Fruit, Potato	Altacor, Lannate, Thiacloprid, Samurai, Methoml, Alpha-cypermethrin, Success, Avatar, Delegate, Lorsban
White Fly	18.87%	Greenhouse, Silverleaf	Agri50NF, Admiral, BioPest Oil, Lorsban, Confidor, Movento, Chess, Talstar, Transform
Aphids	15.09%	Black, Citrus, Cow, Lettuce, Wooly	Neo-nicotinoids, Movento, Chess
Mealy Bug	7.55%		Tokuthio, Transform, Applaud, Samurai, Bio Pest, Lannate, Suprathion, Lorsban, oils

Key Findings

The majority of survey respondents were from Victoria (45.3%) and Queensland (20.9%) followed by Western Australia (11.6%), South Australia (11.6%), and New South Wales (7.0%). The majority of respondents had 11+ years experience and worked with more than one crop in 2013. The majority of growers have properties between 10 and 80 Ha, and the majority of advisors manage more than 30 growers each.

The most common crops grown or managed by respondents in 2013 were cucurbits, tomatoes, lettuce, capsicum/chilli, broccoli and potatoes. In Victoria, Western Australia and South Australia, the majority of crops grown or advised on were potatoes, while the main crops in Queensland were capsicum/chillis and cucurbits. In New South Wales, the main crop grown or advised on was capsicum/chillis.

Advisors were more likely to rate GPA as a pest in the majority of crops compared with growers. Both growers and advisors report that GPA is more likely to be a major pest than a minor pest in capsicum/chilli crops. GPA is considered a major pest in potatoes in New South Wales, South Australia, Victoria and Western Australia. In lettuce crops, GPA is a major pest in New South Wales, Queensland and Victoria, and a minor pest elsewhere. All growers in Victoria, Western Australia and Queensland, and advisors in New South Wales, rate GPA as a major pest in Asian vegetable crops. GPA is not widely considered a pest of citrus trees and nut trees.

Both growers and advisors reported that the most likely monitoring frequency for GPA was once a week, followed by once a fortnight. No growers, and only a few advisors reported not monitoring for GPA at all. The most likely monitoring frequency was at least once a week in most crops where GPA was either a minor or major pest. In citrus trees and nut trees monitoring was more likely to occur once a fortnight. The only region that did not monitor at all for GPA in vegetable crops was Victoria, and this was only 15.4% of respondents from this state.

Although there was some variation in GPA control methods across different crops and different regions, the most common control method was to spray once GPA reached threshold levels in crop. Victorian and Queensland advisors work across a greater variety of crops than advisors from other regions, and also reported using a variety of control methods. The most common method used in both these states was spraying once GPA reached a threshold, particularly in crops where GPA is a minor pest or not a pest at all (i.e. beans/peas or fruit and nut trees). In South Australia, spraying once GPA reached a threshold was most likely in capsicum/chilli, broccoli and cauliflower crops. In Western Australia, spraying GPA once they reached a threshold was not a common control method for most crops, apart from broccoli, cauliflower and some fruit and nut trees.

In crops where GPA is a pest, growers and advisors from all regions are more likely to follow routine/calendar spraying or to apply insecticides when spraying other chemicals. Routine/calendar spraying for GPA was the most common control method used in Western Australia across most crops. In other regions, routine spraying specifically for GPA was less common, but applying insecticides for GPA control during crop sprays for other reasons was more likely.

Other control methods used across all regions are reliance on biological control agents and the removal of host plants. In particular, removal of host plants is a common control method used in brassica crops (i.e. broccoli, cabbage and cauliflower). Although there was some indication that growers and advisors rely on biological control agents or host plant removal in many fruit and vegetable crops, these control methods were less likely to be used than insecticide application.

For the majority of vegetable crops grown, around 1-2 sprays are applied to control GPA within a single cropping season. For some crops the number of sprays per season was higher – particularly in lettuce, tomato and capsicum/chilli crops. In these crops, many growers reported applying 3–5 sprays, 6–10 sprays, and in some cases 10+ sprays per season. Higher rates of spraying (>5 sprays per season) occurred in Western Australia, Queensland and Victoria. When grown, Asian vegetable crops had the highest number of sprays per season across all states. Fruit and nut trees had the lowest number of sprays per season, and bean/pea crops and potato crops also had relatively low numbers of sprays per season across all states.

The most likely reason for applying multiple sprays differed between growers and advisors. Growers were more likely to rely on their past experiences controlling GPA while advisors were more likely to respond to crop monitoring outcomes. Queensland and Victorian growers were more likely to apply multiple sprays based on crop monitoring, whereas Western Australian growers were more likely to spray multiple times based on past experience controlling GPA. Some growers and advisors sprayed multiple times per season out of concern for virus transmission by GPA. In South Australia this was the most common reason for multiple sprays given by advisors.

The vast majority of respondents stated they rotate between chemical groups when applying more than one spray per growing season. The number one reason respondents gave for rotating chemical groups was due to concern about insecticide resistance. Advisors and growers also reported rotating chemical groups as part of a regular practice, and in the case of growers, based on advice received from their agronomist/consultant. Only advisors in Victoria, Queensland and South Australia reported rotating chemical groups because the previous chemical control didn't work.

Chemicals used to control GPA differed across regions. Neo-nicotinoids are the most commonly used chemical group, followed by Sulfoxaflor and then Carbamates. Pymetrozine is used occasionally, while Organophosphates and Pyrethroids are likely to be used only occasionally or not at all. Tetronic/Tetramic acid derivatives and mineral spray oils are also only applied occasionally to control GPA or were not used at all. In Victoria and New South Wales, Neo-nicotinoids are the most common chemicals used to control GPA. In Queensland, the most commonly used chemical for GPA control is Sulfoxaflor and in South Australia and Western Australia, Carbamates are the most commonly used chemicals for GPA control.

The role of beneficial insects in controlling GPA varied between survey respondents. In South Australia, New South Wales and Victoria, the majority of respondents always and/or mostly considered beneficial insects. In Queensland and Western Australia, the majority of respondents stated they only occasionally consider beneficial insects when managing GPA. 50% of growers either never, or only occasionally, considered beneficial insects while only 6.1% of advisor respondents stated they would never consider beneficial insects when selecting insecticides.

Respondents reported the highest level of chemical control failures for GPA in Victoria, but all states reported control failures. When a control failure occurred, all but one grower believed the failure was due to insecticide resistance, whereas only 53% of advisors believed the chemical control failures they had experienced were due to resistance. 43% of advisors were not sure whether control failures they experienced were due to insecticide resistance or not. In New South Wales, Queensland and South Australia, advisors were more likely to think a control failure was due to resistance, whereas in Victoria and Western Australia, advisors were more likely to be unsure of the reason(s) for chemical control failures.

Appendix IV

Science Behind the Resistance Management Strategy for the green peach aphid (*Myzus persicae*) in Bundaberg field vegetable crops

Public Report

Dr Paul Umina
cesar pty ltd

Project Number: VG12109

Author: Dr Siobhan de Little & Dr Paul Umina

VG12109

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Australia

Contents

Background information on the green peach aphid (GPA), *Myzus persicae*

Attribute	What is known about GPA?	References
Mode of reproduction	• In Australia nearly always asexual (anholocyclic) forms. • Populations are occasionally composed of a mixture of holocyclic (sexual/asexual, host-alternating) and anholocyclic (asexual, non host-alternating) clones.	Blackman 1974; Vorburger et al. 2003; Moran 1992
Life cycle (incl. # generations)	• Present year round, populations predominately peak in spring and autumn. Many generations per year. Under ideal conditions generation time is < 2 weeks. • Parthenogenic females give birth to live young (typically 5 instars before reaching adulthood). • In sexual clones, mating takes place on the primary host (*Prunus*), where the eggs are laid and undergo diapause over winter (this is rare in Australia). • The optimum temperature for green peach aphids is about 22°C, with most activity occurring during the warmer milder months of the year. Threshold minimum and maximum temperatures for their development are approximately 5°C and 33°C respectively.	Van Emden et al. 1969; Moran 1992
Crop hosts	• Polyphagous. Includes oilseeds, pulses, brassicas, leafy vegetables, citrus, pome/stone fruits, cut flowers. • In field vegetables they are known to attack crucifers, solenacea, beans and peas, lettuce, asian greens and cucurbits • Some plant-host preferences among *M. persicae* clones/biotypes	Van Emden et al. 1969; Weber 1985; Nikolakakis et al. 2003; Zitoudi et al. 2001
Non-crop hosts	• Many. Weeds include capeweed, wild radish, wild turnip, fathen, nightshade and other cruciferous weeds.	Van Emden et al. 1969; Bailey 2007
Distribution	• Australia wide, very common across all horticultural and grain growing regions as well as being a cosmopolitan species.	Bailey 2007; Bellati et al. 2010
Dispersal/movement	• Infestations start when winged aphids fly into crops from adjacent crops or weeds (e.g. roadside vegetation). Large infestations of GPA on seedling crops can cause leaf distortion, wilting of cotyledons, stunting of growth, premature leaf senescence and seedling death. • Likely to be broad-scale movement across Australia.	Vorburger et al. 2003; Bailey 2007; Berlainder et al. 2010
Feeding behaviour	• Sucking pest, mostly on the underside of older plant leaves. Also found on growing tips in young plants and on developing and mature flowers. • GPA also transmit many important plant viruses, including papaya ringspot virus, cucumber mosaic virus, bean yellow mosaic virus and turnip yellow mosaic virus (previously beet western yellows virus). • Secretion of honeydew can cause secondary fungal growth (i.e. sooty moulds), which inhibits photosynthesis and can decrease plant growth. When deposited on fruit, honeydew and sooty mould greatly reduces the marketability of horticulture produce.	Van Emden et al. 1969
Chemical controls	• Chemicals remain key to control within vegetable crops as well as other industries. • There are approximately 200 insecticide products registered in Australia, but these are mostly from only 4 chemical subgroups (group 1 Acetylcholinesterase (AChE) inhibitors (organophosphates & carbamates), group 3 Sodium channel modulators (pyrethroids) and group 4 Nicotinic acetylcholine receptor (nAChR) competitive modulators (neonicotinoids).	Umina et al. 2014a, 2014b; APVMA; IRAC

Biological control options	• There are many effective natural enemies of aphids. Hoverfly larvae, lacewings, ladybird beetles and damsel bugs are known predators that can suppress populations. Aphid parasitic wasps lay eggs inside bodies of aphids and evidence of parasitism is seen as bronze-coloured enlarged aphid ‘mummies’. If mummified aphids make up 10% of the total aphid population within a paddock, it is likely that the majority of remaining aphids have also been parasitised. This is an indication that the population is likely to crash within 2 weeks. Entomopathogenic fungi are also known to be important in causing rapid colony decline in cropping situations where large aphid populations develop.	Volkl et al. 2007; P. Mangano (Pers. Comm.)

Insecticide products with label claims for green peach aphid control in Australia

Source: APVMA-Public Chemical Registration Information System Search (PUBCRIS), Australian Pesticides & Veterinary Medicines Authority; accessed February 2016.

Note: Crops in red are vegetable crops of most relevance to this strategy.

Mode of action	Pesticide category	Example trade names	Active ingredient	Plant hosts for pesticide registration against GPA	Plant hosts for pesticide registered for general aphids
Group 1A	Carbamates	Marlin, Lannate, Electra	Methomyl	peaches, nectarines	
Group 1A	Carbamates	Pirimicarb, Pirimor, Aphidex	Pirimicarb	almond[1], beetroot, brassica leafy vegetables[3], brussels sprouts, cabbage, canola, cauliflower, celery[2], chicory, radicchio[3], chinese cabbage, cotton, kale, lupin, radish, rocket[3], stonefruit, sweet potato[3], swedes, turnip	asparagus, blueberry, broad bean, capsicum, celeriac[4], chilli[5], citrus, cucurbit, cut flowers[6], dubosia, endive, eggplants[7], garden cress, globe artichoke, honey-dew melon, horned melon, leek, lettuce, lima bean, nasturtium, okra, ornamental, pea, pepino, potkin, rockmelon, shallot, silver beet, spinach, spring onions[2], squash, strawberry, sweet corn[2], tomato, watermelon, watercress, wild flowers[8]
Group 1B	Organophosphates	Lorsban, Strike-out, Chlorpyrifos	Chlorpyrifos	tomatoes, fruiting and cucurbit vegetables	
Group 1B	Organophosphates	Diazol, Diazinon	Diazinon	cabbage, cauliflower, broccoli, brussel sprouts, kale, kohlrabi, stone fruit	nursery plants
Group 1B	Organophosphates	Danadim, Dimethoate	Dimethoate	adzuki beans, cowpeas, mung beans, navy beans, pigeon peas, chickpeas, lupins, borlotti beans, cabbage, cauliflower, brussels sprouts, broccoli	apple, bean, berry fruit, beetroot, bilberry, blackberry, blueberry, capsicum, carrot, cherry, chickpea, citrus fruit, cotton, cowpea, cucurbit, grain legume, grape, leafy vegetable, lupin, melon, mung bean, navy bean, nectarine, onion, ornamentals, parsnip, passionfruit, pawpaw, pea, peach, peanut, pear, pigeon pea, plum, potato, protea, quince, radish, raspberry, root vegetable, sesame, sorghum, stone fruit, strawberry, sweet potato, tomato, turnip, vegetables, watermelon, wildflowers, zucchini
Group 1B	Organophosphates	Fyfanon, Maldison	Maldison	stonefruit	bean, cabbage, carrot, cauliflower, celery, cucurbit, flowers, lettuce, ornamentals, proteas, tomato, wildflowers
Group 1B	Organophosphates	Nitofol	Methamidophos	dubosia[9]	
Group 1B	Organophosphates	Fokus, Sentineal	Omethoate	lupins	callistemon, carnation, chrysanthemum, citrus, cotton, eucalyptus, geranium, grevillea, myrtle, tree tea, paperbark, potato, rose, wattles

Group 1B	Organophosphates	Thimet	Phorate		eggplants[10], peppers (chillies, capsicums & paprika)[10], shallots[10], spring onions[10], sweet potato[11]
Group 1B + 3A	Pyrethroid + Organophosphate	Pyrinex super	Bifenthrin + Chlorpyrifos	tomatoes	
Group 3A	Pyrethroids	Alpha Duo, Apparent, Kenso Agcare	Alpha-cypermethrin		winter cereals, non-food nursery stock[12]
Group 3A	Pyrethroids	Stakeout, Ambush, Axe	Permethrin	broccoli, brussels sprouts, cabbage, cauliflower, rhubarb[13]	
Group 3A	Pyrethroids	Amgrow pyrethrum insect spray	Piperonyl butoxide / Pyrethrins	apricot, cabbage, cherry, cucumber, flower, lettuce, peach, rose, strawberry, tomato	
Group 3A	Pyrethroids	Klartan, Mavrik aquaflow	Tau-fluvalinate	tomatoes	rose, ornamentals
Group 3A	Pyrethroids	Richgro beat-a-bug naturally based insect spray	Piperonyl butoxide / Chilli / Garlic extract / Pyrethrins	fruit crop or tree, vegetables (except capscium and lettuce), cut flowers, grapevines, nursery plants, ornamentals, roses, trees, greenhouse and glasshouse crops	
Group 4A	Neonicotinoids	Intruder, Supreme	Acetamiprid	potatoes	
Group 4A	Neonicotinoids	Samurai	Clothianidin	peaches, nectarines	Indian/tropical sandalwood & associated trees in mixed species plantation forest[14]
Group 4A	Neonicotinoids	Confidor, Nuprid, Titan, Novaguard	Imidacloprid	Asian root vegetables[15], apricot, broccoli, brussles sprouts, cabbage, capsicum, carrot[16], cauliflower, cucurbit, dubosia, eggplant, hazelnuts[17], kohlrabi, melon, nectarine, peach, peppers (chillies and paprika only)[18], plum, potato, stonefruit, tomato, tea[17], zucchini	cape gooseberry[18], celery[18], cotton, culinary herbs[17], beetroot[19], brassica leafy vegetables[20], roses, rhubarb[21], shrubs, plants and ornamental plants, non-bearing citrus tree, non-food nursery stock[22], ornamental citrus
Group 4A	Neonicotinoids	Calypso	Thiacloprid	stonefruit	camellias, maybush, rose
Group 4A	Neonicotinoids	Actara	Thiamethoxam	tomatoes	
Group 4C	Sulfoximines	Transform	Sulfoxaflor (Isoclast™ active)	barley (up to early flag leaf only), brassica - asian, brassica vegetables, canola, capsicum, chilli, cotton, cucumber, cucurbits, eggplant, fruiting vegetable, lettuce, leafy vegetable, melon, okra, pumkin, root vegetable, silver beet, squash,	canola, wheat - up to early flag leaf only, cotton

				stonefruit, tomato, tuber vegetable	
Group 9B	Pymetrozine	Chess, Endgame, Eurochem	Pymetrozine	almond[23], beetroot, brassica – Asian, broccoli, brussels sprouts, cabbage, capsicum or pepper, cauliflower, chard, chinese cabbage, cress, cut flower, eggplant, endive, green mustard, kale (chou moellier), lettuce, nursery stock in pots or field, pistachio, potato, rocket, silver beet, spinach, stonefruit, tomatoes, tomatoes (greenhouse only)[24]	celery[25], cut flowers[26]
Group 12A	Diafenthiuron	Pegasus	Diafenthiuron		non-food nursery stock[27]
Group 23	Tetronic and Tetramic acid derivatives	Movento	Spirotetramat (iso)	bean, brassica leafy vegetables, brassica vegetables, broccoli, broccolini, brussels sprout, cabbage, capsicum, chilli, cauliflower, celery, chicory, cucurbit, eggplant, endive, herb, kohlrabi, leafy vegetable, lettuce, pea, potato, snow pea, stonefruit, sugar snap pea, tomato	non-food nursery stock[28]
Group 28	Diamides	Benevia	Cyantraniliprole	capsicum, eggplant, fruiting vegetable, tomato	
Group 28 + 4A	Diamides + Neonicotinoids	Durivo insecticide	Chlorantraniliprole + Thiamethoxam	broccoli, brussels sprouts, cabbage, cauliflower, brassica leafy vegetables, tomatoes, capscium, cotton, eggplant, lettuce, endive, silver beet, spinach	
Group 29	Flonicamid	Mainman	Flonicamid	cucumber, cucurbit, potato, pumpkin, rockmelon, squash, zucchini	
		Eco-oil	Emulsifiable botanical oils		capscium, crop - commercial, cucumber, floriculture crops, home garden use - general, ornamental crops, tomato, strawberries
		Canopy	Paraffinic oil	adzuki bean, canola, chickpea, faba bean, field pea, lentil, linola, linseed crop, lucerne, lupin, mung bean, navy bean, pigeon pea, safflowers, soybean, sunflower, vetch	

		Richgro lime sulfur	Sulphur		fruit trees
		Natrasoap	Fatty acid - K salts		fruit crop, home garden use - general, nursery, nut crop, ornamental, potted plant, vegetable

1. Minor use permit for almonds. Valid until 31/03/2017
2. Minor use permit for sweet corn, celery, and spring onions. Valid until 30/06/2019
3. Minor use permit for sweet potato, brassica leafy vegetables, chicory radicchio, and rocket. Valid until 30/06/2019
4. Minor use permit for celeriac. Valid until 30/09/2020
5. Minor use permit for chili peppers. Valid until 31/03/2021
6. Minor use permit for cut flowers. Valid until 30/09/2017
7. Minor use permit for eggplants. Valid until 31/03/2019
8. Minor use permit for wildflowers. Valid until 30/06/2018
9. Minor use permit for dubosia. Valid until 31/03/2018
10. Minor use permit for eggplant, peppers, shallots and spring onions. Valid until 31/07/2016
11. Minor use permit for sweet potato. Valid until 31/03/2018
12. Minor use permit for nursery stock (non-food). Valid until 30/09/2020
13. Minor use permit for rhubarb. Valid until 31/03/2017
14. Minor use permit for sandalwood plantation and associated trees. Valid until 30/06/2016
15. Minor use permit for Asian root vegetables. Valid until 30/09/2020
16. Minor use permit for carrot, leafy lettuce, silverbeet and spinach. Valid until 31/05/2018
17. Minor use permit for date palms, ginger, hazelnuts, culinary herbs, tea and tea tree. Valid until 31/03/2017
18. Minor use permit for celery, cucumber, peppers and cape gooseberry. Valid until 31/05/2020
19. Minor use permit for beetroot. Valid until 30/09/2020
20. Minor use permit for brassica leafy vegetables. Valid until 31/03/2019
21. Minor use permit for rhubarb. Valid until 30/06/2018
22. Minor use permit for nursery stock (non food). Valid until 30/09/2020
23. Minor use permit for almonds. Valid until 31/03/2017
24. Minor use permit for tomatoes (protected). Valid until 31/05/2018
25. Minor use permit for celery. Valid until 30/06/2017
26. Minor use permit for cut flowers. Valid until 30/09/2017
27. Minor use permit for nursery stock. Valid until 30/04/2017
28. Minor use permit for nursery stock. Valid until 31/07/2018

Withholding periods for harvesting vegetable crops after insecticide application

Source: APVMA-Public Chemical Registration Information System Search (PUBCRIS), Australian Pesticides & Veterinary Medicines Authority; accessed February 2016.

Insecticide	Cucurbit crops[1]	Cucumbers	Capsicum	Chilli	Eggplant	Tomato	Potato	Beans/Peas	Strawberries	Sweet potato	Asian vegetables	Lettuce
Pirimicarb	2 days	2 days	2 days					2 days			2 days	2 days
Chlorpyrifos	5 days	5 days	5 days	5 days	5 days	3 days						
Diazinon			14 days									
Maldison	3 days	3 days				3 days		3 days				3 days
Omethoate							7 days					
Phorate			10 weeks	10 weeks	10 weeks							
Bifenthrin + Chlorpyrifos						3 days						
Piperonyl butoxide/ Pyrethrins		1 day				1 day			1 day			1 day
Tau-fluvalinate						2 days						
Acetamiprid							7 days					
Imidacloprid	1 day	1 day	7 days		7 days	3 days	7 days					
Thiamethoxam						6 weeks						
Sulfoxaflor	1 day	1 day	1 day	1 day	1 day	1 day	7 days			7 days	3 days	
Pymetrozine							14 days				14 days	
Flonicamid	1 day	1 day					14 days					
Spirotetramat	1 day	1 day	1 day	1 day	1 day	1 day	7 days	7 days[2]			3 days	1 day
Cyantraniliprole		1 day	1 day	1 day	1 day	1 day						
Chlorantraniliprole + Thiamethoxam			NIL		NIL	NIL					4 weeks	4 weeks
Emulsifiable botanical oils		NIL	NIL			NIL						
Fatty acid K salts	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL

1. Including pumpkin, squash, rockmelon, watermelon and zucchini,

2. 3 days only for sugar snap and snow peas

Current status of insecticide resistance in green peach aphids within Australia

Attribute	What is known for *Myzus persicae*?	References
Resistance status	• Confirmed widespread resistance to pyrethroids, organophosphates and carbamates. • Evidence that resistance to neonicotinoids is emerging. • Reported chemical control failures involving spirotetramat (Movento) in northern Qld vegetables, but no confirmed resistance detected.	Umina et al. 2014a, Edwards et al. 2008, de Little et al. In Prep.
Mode of action of resistance & cross-resistance	• Synthetic pyrethroids: parasodium channel (mutations at kdr, superkdr loci), some cross-resistance from E4/FE4 • Organophosphates: amplified esterases (E4, FE4) • Carbamates: modified acetylcholinesterase (MACE), some cross-resistance from E4, FE4 • Neonicotinoids: Amplified P450, modified AChR receptor	Martinez-Torres et al. 1999; Field & Devonshire 1998; Moores et al. 1994; Puinean et al. 2010; Bass et al. 2011
Known fitness costs	• Synthetic pyrethroids: reduced motility/responsiveness to alarm pheromone, parasitoid avoidance all at low temperatures (initially attributed to E4/FE4) • Carbamates: reduced response to alarm pheromone, parasitoid avoidance.	Foster et al. 1996, 1997, 2003, 2010
Genetic basis for resistance	• Synthetic pyrethroids: kdr and Super-kdr are codominant • Organophosphates: E4 and FE4 co-dominant and induced. • Carbamates: MACE thought to be co-dominant • Neonicotinoids: P450 co-dominant, modified AChR thought to be recessive (only found homozygous)	Criniti et al. 2008; Field 2000; Field et al. 1999; Puinean et al. 2010

Industry chemical use and secondary chemical exposure

The use (and motivations for use) of insecticides to control GPA varies from region-to-region. A survey of 104 horticultural advisers (agronomists and consultants), growers, and researchers from Queensland, New South Wales, Victoria, South Australia, Tasmania and Western Australia was completed in 2014. Cropping practice and GPA control methodology varies widely from region to region, so the following information is based only on results from Queensland, with a focus on the Bundaberg region. GPA is regarded as a common pest, typically occurring every year. The majority of vegetable seedlings (~80%) are reportedly drenched with imidacloprid before being transplanted into the field, although this varies considerably with crop type and region. Soil treatments are also common in certain crops (in some regions), especially cucurbits. Foliar insecticides are sprayed in the majority of vegetable crops monthly, although many of these applications do not specifically target GPA. It is not uncommon for some crops to be sprayed with 8-10 separate applications of insecticides from the vegetable seedling stage through to harvest (often with 2-4 plantings in a single paddock per year). When insecticides are being applied for GPA, many of the sprays are used prophylactically. With the exception of imidacloprid seedling drenches, Group 4C (sulfoxafor) and Group 23 (spirotetramat) products are among the most commonly used chemistries to combat GPA in vegetable crops. Group 1A (carbamates), Group 1B (organophosphates), Group 3A (synthetic pyrethroids) and Group 4A (neonicotinoid) products are also applied regularly.

Resistance management & minimization strategy

The aim of this strategy is to minimise the selection pressure for resistance to the same chemical group across consecutive generations of Myzus persicae. We have relied upon the latest (2014-2015) resistance surveillance activities, as well as those published by Umina et al. 2014a, 2014b. Pyrethroid, carbamate and organophosphate resistance is now commonplace across Australia, in both horticultural and grains crops, therefore the use of these chemicals for control of GPA should be restricted. Resistance to imidacloprid has recently been confirmed in horticultural crops from Queensland (de Little et al. in prep). This strategy has been specifically developed to deal with the Bundaberg vegetable growing region. In this region, vegetable crops are grown all year round, with no/little seasonal break. Crops have staggered planting, with sowing and harvesting occurring almost all year round. It is not uncommon for growers to have adjacent fields that have the same crop at different growth stages. The main focus of this strategy is Cucurbit crops (e.g. melons, pumpkins, zucchinis) that are vulnerable to virus spread by green peach aphid, and Solenacea crops (e.g. capsicum, chill, eggplant and tomatoes) where green peach aphid is considered a major pest. Other crops grown in the region such as sweet potatoes, potatoes, peas and beans, and leafy greens are also host crops for green peach aphid and are included in this management strategy.

In the future, resistance management strategies for GPA should ideally establish resistance levels on early-autumn aphid populations (especially in years where they are anticipated to reach damaging levels). This would provide a scientifically valid approach for the selection of chemicals to be used against these pest populations (i.e. confidence in the selection of chemical groups based on known resistance levels, allowing for a wider selection and rotation of chemicals in some seasons). A spray window approach is recommended to avoid exposure of successive aphid generations to the same chemical group (IRAC 2010). The most important element of the strategy is to rotate chemical compounds from different IRAC mode of action groups (Table 1). Repeated use of insecticides from the same chemical group will increase selection pressure for resistance development. It is also essential to comply with product label directions and spray rates. Do not spray any chemicals at reduced rates as this can increase selection pressure for resistance development.

Chemical control recommendations for the green peach aphid in vegetable crops

<table>
<tr><th></th><th colspan="4">Spray Windows</th><th>Rationale</th></tr>
<tr><td>Seedling Treatment</td><td colspan="4">Neonicotinoids (Group 4A)
used only in seedling drenches and drip irrigation.</td><td>Resistance recently confirmed to neonicotinoid (Group 4A) insecticides in Queensland. Minimising the number of applications will minimise further resistance development and increase the longevity of this chemical group.</td></tr>
<tr><td rowspan="3">Rotate through products for duration of window</td><td>Autumn Window
(Mar – May)</td><td>Winter Window
(Jun – Aug)</td><td>Spring Window
(Sept – Nov)</td><td>Summer Window
(Dec – Feb)</td><td rowspan="2"><u>Winter and Summer spray windows:</u>
Cyantraniliprole is likely to be commonly used in summer to control silverleaf whitefly and western flower thrips.
Use Spirotetramat as the first spray following a seedling treatment, as this chemical is relatively soft on beneficial insects (see Table 6). Cyantraniliprole should not be used as the first spray following a seedling treatment involving Durivo® as this product also contains a Group 28 active ingredient (chlorantraniliprole). Cyantraniliprole should only be used as a first spray following a seedling treatment involving imidacloprid or thiamethoxam.
In non-cucurbit crops, rotate between applications of Spriotetramat and Cyantraniliprole. In cucurbit crops, rotate between applications of Spirotetramat and Flonicamid.</td></tr>
<tr><td>Pymetrozine (Group 9C)</td><td>Spirotetramat (Group 23)</td><td>Pymetrozine (Group 9C)</td><td>Spirotetramat (Group 23)</td></tr>
<tr><td>Sulfoxaflor (Group 4C)</td><td>Cyantraniliprole (Group 28)
Or
Flonicamid (Group 29)</td><td>Sulfoxaflor (Group 4C)</td><td>Cyantraniliprole (Group 28)
Or
Flonicamid (Group 29)</td><td><u>Autumn and Spring spray windows:</u>
Sulfoxaflor is relatively fast acting, and thus has a fit in the spray window with the slower acting product Pymetrozine.
Sulfoxaflor should not be used as the first spray following a seedling treatment due to possible cross-resistance with neonicotinoids (Group 4A).
Rotate between applications of Sulfoxaflor and Pymetrozine.</td></tr>
<tr><td>Clean-up only</td><td colspan="4">Carbamates (Group 1A) - IPM compatible (see Table 6)</td><td>Resistance to carbamates (Group 1A) is relatively widespread within Australia and thus the expected field efficacy against GPA is inconsistent. The use of this chemical group is only recommended as a last resort, despite the fact it is soft on beneficial insects.</td></tr>
<tr><td>Notes</td><td colspan="5">Assess aphid and beneficial populations over successive checks to determine if chemical control is warranted, particularly following seedling drenches (which should provide control for 4-6 weeks).
Use economic spray thresholds where available and do not spray if pest pressure is considered low. Comply with all directions for use on product labels. Ensure spray rigs are properly calibrated and sprays achieve good coverage. If adjacent paddock crop stages are staggered, consider area wide sprays using the same chemical group.
Avoid the use of Synthetic Pyrethroids (SPs) and Organophosphates (OPs). There is nation-wide resistance to these chemical groups in GPA, and the use of these two chemical groups are likely to be disruptive to beneficial insects and/or flare whitefly populations.
Avoid repeated use of insecticides from the same chemical group against GPA or other pests, as this will increase selection pressure for resistance development, not only in GPA, but also in other species such as whiteflies and diamondback moths.
Do not re-spray a paddock in the same season where a known spray failure has occurred using the same product or another product from the same chemical group, or if a spray failure has occurred where the underlying cause is unidentified.</td></tr>
</table>

Virus-specific and general control recommendations

Papaya ring spot and cucumber mosaic viruses are both non-persistent viruses. The movement of non-persistent viruses is difficult to control because transmission by aphids (including GPA) occurs within a short time period (typically within a few seconds to minutes once aphids have begun to feed on an uninfected plant). Do not spray crops 'prophylactically' as insecticidal sprays are generally ineffective in managing non-persistent viruses and may enhance virus spread through increased vector activity (Budnik et al. 1996, Thackray et al. 2000).

- Be aware of edge effects; aphids will often move in from weeds around paddock edges. Where GPA are colonising crop margins and fence-lines in the early stages of population development, consider a border spray with insecticides to prevent/delay the build-up of GPA and retain beneficial insects.
- Consider planting wind barriers (such as sugar cane) around paddocks and plant new crops upwind of old crops, to avoid wind-assisted movement of winged aphids.
- Use reflective mulches to reduce landing rates of winged aphids on crops.
- Use herbicides or other tactics to eliminate weed hosts for common viruses (e.g. Papaya ringspot virus). This includes weeds from the Cucurbitaceae family such as wild melon (*Citrullus lanatus* var. *lanatus*), prickly paddy melon (*Cucumis myriocarpus*), bitter paddy melon/wild gourd (*Cirullus colocynthis*), and ivy gourd (*Coccinia grandis*).
- Ensuring plant diversity through mixed or inter-cropping will reduce virus incidence (Hooks et al. 1998). Non-virus host cover or barrier crops can also reduce non-persistent virus incidence as aphids land on these plants (that don't host the virus) and clean virus particles from their mouthparts whilst probing the plant. It is important to select the cover/barrier crop in relation to the expected rotation of crops in neighboring paddocks to prevent other pest and disease build-up.

Interactions with insecticide resistance in other pest species

Insecticides used to control other pests will increase selection pressure on GPA if they are also present in the crop at the time of application.
Similarly, insecticide applications aimed at GPA will expose other insect pests to selection pressure for resistance. Repeated chemical exposure to the same chemical group(s) should be avoided wherever possible, regardless of the pest being targeted. The risk of resistance developing to Group 4C (e.g. sulfoxaflor) and 4A (e.g. imidacloprid) chemicals in other pests as a result of the recommendations of this Strategy is likely to be relatively low. Insecticides that are less harmful to beneficial insects (such as lady beetles, and parasitoid wasps) are recommended as the first options for GPA control.

Table 6 has been collated from information found in the Cotton Pest Management Guide (2015), the Biobest side-effects manual (2015), The Good Bug Book (2002), and through discussion with experts. The impact rating gives the % reduction in beneficial species following chemical application: VL (very low), less than 10%; L (low), 10–20%; M (moderate), 20–40%; H (high), 40–60%; VH (very high), > 60%. '–' indicates no data available for specific local species.

Impact of insecticides on beneficial insects of relevance to vegetable crops.

Insecticide	Predatory beetles[1]				Predatory bugs					Predatory mites	Spiders	Parasitic Wasps						Lacewing adults	Thrips[6]	Toxicity to bees[9]
	Total[2]	Red & Blue beetle	Minute 2-spotted lady beetle	Other lady beetles	Total[3]	Damsel bugs	Big-eyed bugs	Other Predatory bugs	Apple Dimpling			Total	*Eretmocerus*[7]	*Encarsia formosa*	*Trichogramma*	*Aphytis*	*Aphidius*			
Paraffinic oil	VL	L	L	VL	VL	VL	VL	VL	VL	-	L	VL	-	-	VL	-	VL	VL	VL	VL
Petroleum oil	-	-	-	L	-	-	-	-	-	M	-	-	-	H	-	M	-	-	-	-
Cyantraniliprole	M	M	VL	L	M	M	M	H	L	-	M	VL	L	-	VL	-	VL	VH	H	-
Spirotetramat	M	L	H	H	VL	VL	VL	VL	M	-	M	M	L	-	M	-	M	VH	M	-
Pirimicarb	H	VL	VL	L	M	L	M	VL	VL	L	VL	VL	M	H	H	L	VL	L	L	VL
Flonicamid	L	VL	VL	VL	H	H	VH	H	H	-	M	M	L	-	H	-	M	L	H	-
Diafenthiuron	M	H	VL	M	L	M	VL	L	H	-	L	L	H	-	L	-	L	L	L	M
Pymetrozine	M	M	M	M	M	L	L	VL	H	L	L	L	L	M	L	L	L	M	VL	VL
Sulfoxaflor	H	L	M	H	L	VL	L	M	VH	-	L	M	-	-	H	-	M	H	H	-
Chlorantraniliprole/ Thiamethoxam	-	-	-	-	-	-	-	-	-	-	-	-	M	-	-	-	-	-	-	-
imidacloprid (irrigating)	H[4]	-	-	-	VH	-	-	-	-	-	-	-	L	-	L	-	-	L	-	-
Acetamiprid	H	M	VH	H	H	M	H	M	VH	-	VL	L	H	-	H	-	L	L	VH	M[10]
Imidacloprid (spraying)	H	L	VH	H	H	M	H	L	VH	M	L	L	VH	VH	H	H	L	M	H	M
Thiamethoxam	H	H	H	H	H	M	M	H	H	-	VL	M	M	-	H	-	M	M	H	H
Organophosphates[5]	H	M	H	H	H	M	H	H	VH	H	M	H	VH	VH	VH	H	H	M	H	H
Tau-fluvalinate	VH	-	-	-	VH	-	-	-	-	-	-	-	VH	-	VH	-	-	M	-	-
Piperonyl Butoxide / Pyrethrins	VH	-	-	-	VH	-	-	-	VH	-	VH	VH	VH	-	VH	-	VH	H	VH	H
Bifenthrin/ Chlorpyrifos	VH	-	-	-	VH	-	-	-	VH	-	VH	VH	VH	-	VH	-	VH	VH	VH	H
Permethrin	VH	-	-	H	VH	-	-	-	VH	H	VH	VH	VH	VH	VH	H	VH	VH	VH	H

1. Toxicity ratings for predatory beetles and Hymenoptera are for adults only.
2. Total predatory beetles – ladybeetles, red and blue beetles, other predatory beetles.
3. Total predatory bugs – big-eyed bugs, minute pirate bugs, brown smudge bugs, glossy shield bug, predatory shield bug, damsel bug, assassin bug, apple dimpling bug.
4. This rating is for the larval stage of predatory beetles because irrigating affects soil organisms.
5. Organophosphates: diazinon, chlorpyrifos, dimethoate, maldison, methamidophos, omethoate, phorate.
6. Toxicity ratings for Hymenoptera are for adults only.

7. Rankings for Eretmocerus based on data from Jamie Hopkinson in semi-laboratory replicated experiments (QDAF) and on ranking for E. mundus (P. De Barro, CSIRO, unpublished) and for E. eremicus (Koppert Biological Systems, The Netherlands (http://side-effects.koppert.nl/#).
8. Effects on thrips are for populations found on leaves. This is relevant to seedling crops, where thrips damage leaves, and to mid-late season when thrips adults and larvae help control mites by feeding on them as well as on leaf tissue.
9. Data Source: British Crop Protection Council. 2003. The Pesticide Manual: A World Compendium (Thirteenth Edition). Where LD50 data is not available impacts are based on comments and descriptions. Where LD50 data is available impacts are based on the following scale: very low = LD50 (48h) > 100 ug/bee, low = LD50 (48h) <100 ug/bee, moderate = LD50 (48h) < 10 ug/bee, high = LD50 (48h) < 1 ug/bee, very high = LD50 (48h) < 0.1 ug/bee.
10. Wet residue of these products is toxic to bees, however, applying the products in the early evening when bees are not foraging will allow spray to dry, reducing risk to bees the following day.

References

APVMA – Australian Pesticides and Veterinary Medicines Authority, *Public Chemical Registration Information System Search* (https://portal.apvma.gov.au/pubcris)

Bass, C., Puinean, A. M., Andrews, M., Cutler, P., Daniels, M., Elias, J., Paul, V.L., Crossthwaite, A.J., Denholm, I., Field, L. M., Foster, S. P., Lind, R., Williamson, M. S. and R. Slater. 2011. Mutation of a nicotinic acetylcholine receptor β subunit is associated with resistance to neonicotinoid insecticides in the aphid *Myzus persicae*. BMC Neurosci. 12: 51-62.

Bailey, P. T. (Ed.). 2007. Pests of field crops and pastures: Identification and control. *CSIRO Publishing.*

Bellati, J., Mangano, P., Umina, P. and Henry, K. 2010. I SPY: Insects of Southern Australian Broadacre Farming Systems Identification Manual and Information Resource. *Department of Primary Industries and Resources South Australia.* Pp. 178. ISBN: 978-0-646-53795-5.

Berlandier, F., Severtson, D. and Mangano, P. 2010. Farmnote, Aphid management in canola crops, Note 440. *Department of Agriculture and Food.*

Blackman, R.L. 1974. Life-cycle variation of *Myzus persicae* (Sulz.) (Hom., Aphididae) in different parts of the world, in relation to genotype and environment. Bull. Entomol. Res. 63: 595-607.

Biobest Side-Effects Manual. http://www.biobestgroup.com/en/side-effect-manual Accessed December 2015.

British Crop Protection Council. 2003. The Pesticide Manual: A World Compendium (Thirteenth Edition)

Budnik, K., Laing, M.D., da Graca, J.V., 1996. Reduction of yield losses in pepper crops caused by potato virus Y in KwaZula-Natal, South Africa, using plastic mulch and yellow sticky traps. Phytoparasitica 24, 119–124.

Cotton Pest Management Guide 2015-2016. http://www.crdc.com.au/publications/cotton-pest-management-guide-2015-16

Criniti, A., Mazzoni, E., Cassanelli, S., Cravedi, P., Tondelli, A., Bizzaro, D. and Manicardi, G. C. 2008. Biochemical and molecular diagnosis of insecticide resistance conferred by esterase, MACE, *kdr* and super *kdr* based mechanisms in Italian strains of the peach potato aphid, *Myzus persicae* (Sulzer). Pestic. Biochem. Physiol. 90: 168-174.

de Little, S., Umina, P., Edwards, O., Weeks, A., van Rooyen, A., (In Prep) Discovery of metabolic resistance to neonicotinoids in green peach aphids (*Myzus persicae*) in Australia.

Edwards, O., Franzmann, B., Thackray, D. and S. Micic. 2008. Insecticide resistance and implications for future aphid management in Australian grains and pastures: a review. Aust. J. Exp. Agric. 48: 1523-1530.

Field, L. M. 2000. Methylation and expression of amplified esterase genes in the aphid *Myzus persicae* (Sulzer). Biochem. J. 349: 863–868.

Field, L. M. and Devonshire, A. L. 1998. Evidence that the E4 and FE4 esterase genes responsible for insecticide resistance in the aphid *Myzus persicae* (Sulzer) are part of a gene family. Biochem. J. 330: 169–173.

Field, L. M., Blackman, R. L., Tyler-Smith, C. and Devonshire, A. L. 1999. Relationship between amount of esterase and gene copy number in insecticide-resistant *Myzus persicae* (Sulzer). Biochem. J. 339: 737–742.

Foster, S. P., Harrington, R., Devonshire, A. L., Denholm, I., Devine, G. J., et al. 1996 Comparative survival of insecticide-susceptible and resistant peach-potato aphids, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae), in low temperature field trials. Bull. Entomol. Res. 86: 17–27.

Foster, S. P., Harrington, R., Devonshire, A. L., Denholm, I., Clark, S. J., et al. 1997. Evidence for a possible fitness trade-off between insecticide resistance and the low temperature movement that is essential for survival of UK populations of *Myzus persicae* (Hemiptera: Aphididae). Bull. Entomol. Res. 87: 573–579.

Foster, S. P., Kift, N. B., Baverstock, J., Sime, S., Reynolds, K., et al. 2003. Association of MACE-based insecticide resistance in *Myzus persicae* with reproductive rate, response to alarm pheromone and vulnerability to attack by *Aphidius colemani*. Pest Manag. Sci. 59: 1169–1178.

Foster, S. P., Denholm, I., Poppy, G. M., Thompson, R. and Powell, W. 2010. Fitness trade-off in peach-potato aphids (*Myzus persicae*) between insecticide resistance and vulnerability to parasitoid attack at several spatial scales. Bull. Entomol. Res. 101: 659–666.

Hooks, C.R.R., Valenzuela, H.R., Defrank, J., 1998. Incidence of pest and arthropod natural enemies in zucchini grown in living mulches. Agric.

Ecosys. Environ. 69, 217–231.

IRAC Group 28 (Diamide) Working Group 2010. Insecticide Resistance Management Global Guidelines for IRAC Group 28 (Diamide) Insecticides. http://www.irac-online.org/wp-content/uploads/2009/09/Global_IRM_Guidelines_Group-28_v2.1.pdf.

Koppert Biological Systems. http://side-effects.koppert/ Accessed February 2016.

Llewellyn R (Ed.). (2002) The Good Bug Book, 2nd edition. Integrated Pest Management Pty Ltd.

Martinez-Torres, D., Foster, S. P., Field, L. M., Devonshire, A. L. and Williamson, M. S. 1999. A sodium channel point mutation is associated with resistance to DDT and pyrethroid insecticides in the peach-potato aphid, *Myzus persicae* (Sulzer)(Hemiptera: Aphididae). Insect Mol. Biol. 8: 339-346.

Moores, G. D., Devine, G. J. and A. L. Devonshire. 1994. Insecticide-insensitive acetylcholinesterase can enhance esterase-based resistance in *Myzus persicae* and *Myzus nicotianae*. Pestic. Biochem. Physiol. 49: 114-120.

Moran, N. 1992. The evolution of aphid life cycles. Ann. Rev. Entomol. 37: 321-348.

Nikolakakis, N. N., Margaritopoulos, J. T. and Tsitsipis, J. A. 2003. Performance of *Myzus persicae* (Hemiptera: Aphididae) clones on different host-plants and their host preference. Bull. Entomol. Res. 93: 235-242.

Puinean, A. M., Foster, S. P., Oliphant, L., Denholm, I., Field, L. M., Millar, N. S., Williamson, M. S. and C. Bass. 2010. Amplification of a cytochrome P450 gene is associated with resistance to neonicotiniod insecticides in the aphid *Myzus persicae*. PLOS Gen. 6: 1-11.

Thackray, D.J., Jones, R.A.C., Bwye, A.M., Coutts, B.A., 2000. Further studies on the effects of insecticides on aphid vector numbers and spread of cucumber mosaic virus in narrow-leafed lupins (Lupinus angustifolius). Crop Prot. 19, 121–139.

Umina, P., Edwards, O., Carson, P., van Rooyen, A. and Anderson, A. 2014a. High levels of resistance to carbamate and pyrethroid chemicals widespread in Australian *Myzus persicae* (Hemiptera: Aphididae) populations. J. Econ. Entomol. 107(4): 1626-1638

Umina, P., Edwards, O., Mangano, P. and Miles, M. 2014b. Resistance management for green peach aphid Fact Sheet. *Grains Research and*

Development Corporation.

Van Emden, H.F., Eastop, V.F., Hughes, R.D., Way, M.J. 1969. Ecology of *Myzus persicae*. Ann. Rev. Entomol. 14: 197-270.

Volkl W, Mackauer M, Pell JK, Brodeur J. 2007. Predators, Parasitoids and Pathogens. *In*: Van Emden, HF and Harrington R (eds.). Aphids as Crop Pests, CABI, Wallingford. Pp. 187-233.

Vorburger, C., Lancaster, M. and P. Sunnucks. 2003. Environmentally related patterns of reproductive modes in the aphid *Myzus persicae* and the predominance of two 'superclones' in Victoria, Australia. Mol. Ecol. 12: 3493-3504.

Weber, G. 1985. Genetic variability in host plant adaptation of the green peach aphid, *Myzus persicae*. Entomol. Exp. Appl. 38: 49-56.

Zitoudi, K., Margaritopoulos, J. T., Mamuris, Z., and Tsitsipis, J. A. 2001. Genetic variation in *Myzus persicae* populations associated with host-plant and life cycle category. Entomol. Exp. Appl. *99*: 303-311.

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Resistance Management Strategy for the green peach aphid in Bundaberg field vegetable crops

cesar

sustainability through science and innovation

Green peach aphids
Photo: A. Weeks, **cesar**

Key points

- Green peach aphids (GPA) are an important pest of vegetables, causing damage by feeding and transmitting viruses.
- Nine chemical groups are registered to control GPA in vegetables. Botanic oils are also registered for GPA control, and paraffinic oils are registered for suppression.
- High levels of resistance to carbamates, pyrethroids and organophosphates are found across Australia. Low levels of resistance to neonicotinoids have also been observed in some GPA populations.
- A strategy to manage insecticide resistance in GPA populations is available for use by vegetable growers in Bundaberg, involving rotating different chemical groups, and using alternative (IPM) methods to reduce pest and virus loads.

Colour morphs of green peach aphids
Photo: A. Weeks, **cesar**

Green peach aphids and insecticide resistance

In Australia, the green peach aphid (GPA), *Myzus persicae*, primarily attacks Cucurbit, Solenacea and Brassica crops, as well as being a common pest in broadacre crops (such as canola and pulses). The aphids feed by sucking sap from leaves and flower buds. When populations are large, the crop's entire foliage may be covered, resulting in retarded growth of young plants. GPA can transmit more than 100 plant viruses such as cucumber mosaic virus (CMV) and papaya ring spot virus (PRSV).

Despite the name, GPA are not always green in colour, ranging from shades of light and dark green, yellow, pink and red. Scientific studies have shown that there is no difference in the level of insecticide resistance between different colour morphs of GPA. A single genetic biotype or 'clone' of GPA can be made up of both green and red morphs; and these different colour morphs from a single clonal population respond in exactly the same way to insecticides.

The use of chemicals to control GPA in horticultural and broadacre crops continues to grow in Australia, placing strong selection pressure on the development of resistance. As aphids produce offspring that are clones of the mother, resistant individuals can soon dominate a landscape if there is widespread use of the same insecticide across paddocks and farms.

With resistance to three key insecticide groups already established in Australia, and resistance developing to a fourth group, vegetable growers are encouraged to understand how to minimise the further development of resistance.

Resistance management and minimization strategy

Chemicals within a specific chemical group usually share a common target site within the pest, and thus share a common mode of action (MoA). There are nine chemical groups registered to control GPA in vegetable crops (see Table 1). Botanic oils are also registered for GPA control, and paraffinic oils are registered for suppression. The basis of this strategy is to minimise the selection pressure for resistance to the same chemical group across consecutive generations of GPA.

In developing this strategy, the latest resistance surveillance results from 2014-2015 have been used. These results show that carbamate (e.g. pirimicarb), pyrethroid (e.g. permethrin) and organophosphate (e.g. dimethoate) resistance are now commonplace across Australia, in both horticultural and grains crops. Resistance to neonicotinoids (e.g. imidacloprid) has recently been confirmed in some vegetable crops.

This strategy has been specifically developed for the Bundaberg vegetable growing region, particularly Cucurbit and Solenacae crops.

Key recommendations to minimize resistance

Rotate chemical compounds from different MoA groups.

Avoid the repeated use of insecticides from the same chemical group, as this will increase selection pressure for resistance development, not only in GPA, but also in other species such as whiteflies and diamondback moths. Table 2 will help guide growers' selection of seasonal control options for GPA in Bundaberg field vegetable crops.

Implement non-chemical control tactics and consider beneficial insects when managing GPA populations.

Table 3 will help guide grower's choice of chemicals given their likely impact on beneficial insects of relevance to vegetable crops.

Other IPM recommendations include:

- assess aphid and beneficial populations over successive checks (note if aphid numbers are trending up or down) to determine if chemical control is warranted, particularly following seedling drenches (which should provide control for 4-6 weeks).
- use economic spray thresholds where available and do not spray if pest pressure is low.
- avoid the use of pyrethroids and organophosphates. There is nation-wide resistance to these chemical groups and their use is likely to be disruptive to beneficial insects and/or flare whitefly populations.
- comply with all directions for use on product labels, and ensure spray rigs are properly calibrated and sprays achieve good coverage, particularly in crops with a bulky canopy.
- do not re-spray a paddock in the same season where a known spray failure has occurred using the same product or another product from the same chemical group.

GPA can carry many different plant viruses. The movement of viruses is difficult to control because transmission by aphids can occur within a very short time period (within a few seconds to minutes once aphids have begun to feed). To minimise the spread of viruses into paddocks, recommendations include:

- do not spray crops 'prophylactically' as insecticidal sprays are generally ineffective in managing non-persistent viruses and may enhance virus spread through increased vector activity.
- be aware of edge effects; aphids can move in from weeds around paddock edges. Where GPA are colonising crop margins and fence-lines, consider a border spray with an insecticide to prevent/delay the build-up of aphids and retain beneficial insects.
- consider planting wind barriers (e.g. sugar cane) around paddocks and plant new crops upwind of old crops, to avoid wind-assisted movement of aphids.
- use reflective mulches to reduce landing rates of winged aphids on crop plants.
- use herbicides or other tactics to eliminate weed hosts for common viruses, such as wild melon, prickly paddy melon, bitter paddy melon (wild gourd) and ivy gourd.
- plant non-virus host cover (or barrier) crops; aphids land on these plants (that don't host the virus) and clean virus particles from their mouthparts whilst probing the plant. It is important to select the cover (or barrier) crop in relation to the expected rotation of crops in neighboring paddocks to prevent other pest and disease build-up.

More Information

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Useful Resources

Science behind the resistance management strategy for the green peach aphid (Myzus persicae) in Bundaberg field vegetable crops – 2016 www.cesaraustralia.com/latest-news/all/RMS-GPA-bundaberg-vegetables

Green peach aphid – Red and green colour morphs www.cesaraustralia.com/latest-news/sustainable-agriculture/insecticide-resistance-in-green-peach-aphids-red-or-green-you-re-asking-the-wrong-question

Green peach aphid – Pestnote www.cesaraustralia.com/sustainable-agriculture/pestnotes/insect/green-peach-aphid

Green peach aphid – Resistance testing service www.cesaraustralia.com/latest-news/all/new-service-to-screen-for-insecticide-resistance-in-aphids

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Horticulture Innovation Australia

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Table 1. Insecticide Resistance Action Committee (IRAC) Mode of Action classification of insecticides, including active ingredients with label claims for GPA in Australian vegetable crops, and example trade names of chemical products.

IRAC MoA group	Insecticide category	Active ingredient(s)	Example trade names
GROUP 1A INSECTICIDE	Carbamates	pirimicarb	Pirimicarb, Pirimor
GROUP 1B INSECTICIDE	Organophosphates	chlorpyrifos, diazinon, dimethoate, maldison, omethoate, phorate	Strike Out, Danadim, Fyanon, Thimet, Fokus, Pyrinex Super[1]
GROUP 3A INSECTICIDE	Synthetic Pyrethroids	permethrin, piperonyl butoxide, pyrethrins, tau-fluvalinate	Ambush, Klartan, Pyrinex Super[1]
GROUP 4A INSECTICIDE	Neonicotinoids	acetamiprid, imidacloprid, thiamethoxam	Intruder, Confidor, Nuprid, Actara, Durivo[2]
GROUP 4C INSECTICIDE	Sulfoximines	sulfoxaflor (Isoclast™ active)	Transform
GROUP 9B INSECTICIDE	Pymetrozine	pymetrozine	Chess, Endgame
GROUP 23 INSECTICIDE	Tetronic and Tetramic acid derivatives	spirotetramat (iso)	Movento
GROUP 28 INSECTICIDE	Diamides	cyantraniliprole, chlorantraniliprole	Benevia, Durivo[2]
GROUP 29 INSECTICIDE	Flonicamid	flonicamid	Mainman

1. Co-formulation containing Group 1B and 3A insecticides
2. Co-formulation containing Group 28 and 4A insecticides

Source: APVMA-PUBCRIS; accessed Feb 2016

Table 2. Chemical control recommendations for GPA in Bundaberg field vegetable crops.

<table>
<tr><th></th><th colspan="4">Spray Windows[1]</th><th>Rationale</th></tr>
<tr><td>Seedling treatment</td><td colspan="4">Neonicotinoids (Group 4A) used only in seedling drenches and drip irrigation.</td><td>Resistance recently confirmed to neonicotinoid (Group 4A) insecticides in Queensland. Minimising the number of applications will minimise further resistance development and increase the longevity of this chemical group.</td></tr>
<tr><td rowspan="3">Rotate through products for duration of window</td><td>Autumn (Mar—May)</td><td>Winter (Jun—Aug)</td><td>Spring (Sept—Nov)</td><td>Summer (Dec—Feb)</td><td rowspan="3">Winter and Summer spray windows:
Cyantraniliprole is likely to be commonly used in summer to control silverleaf whitefly and western flower thrips.
Use Spirotetramat as the first spray following a seedling treatment, as this chemical is relatively soft on beneficial insects (see Table 3). Cyantraniliprole should not be used as the first spray following a seedling treatment involving Durivo® as this product also contains a Group 28 active ingredient (chlorantraniliprole). Cyantraniliprole should only be used as the first spray following a seedling treatment involving imidacloprid or thiamethoxam.
In non-cucurbit crops, rotate between applications of Spirotetramat and Cyantraniliprole. In cucurbit crops, rotate between applications of Spirotetramat and Flonicamid.

Autumn and Spring spray windows:
Sulfoxalfor is relatively fast acting, and thus has a fit in the spray window with the slower acting product Pymetrozine.
Sulfoxaflor should not be used as the first spray following a seedling treatment due to possible cross-resistance with neonicotinoids (Group 4A).
Rotate between applications of Sulfoxaflor and Pymetrozine during these windows.</td></tr>
<tr><td>Pymetrozine (Group 9C)</td><td>Spirotetramat (Group 23)</td><td>Pymetrozine (Group 9C)</td><td>Spirotetramat (Group 23)</td></tr>
<tr><td>Sulfoxaflor (Group 4C)</td><td>Cyantraniliprole (Group 28) Or Flonicamid (Group 29)</td><td>Sulfoxaflor (Group 4C)</td><td>Cyantraniliprole (Group 28) Or Flonicamid (Group 29)</td></tr>
<tr><td>Clean-up only</td><td colspan="4">Carbamates (Group 1A) - IPM compatible</td><td>Resistance to carbamates (Group 1A) is relatively widespread within Australia and thus the expected field efficacy against GPA is inconsistent. The use of this chemical group is only recommended as a last resort, despite the fact it is soft on beneficial insects.</td></tr>
</table>

1. Botanic oils and paraffinic oils can be used to control GPA at any time.

Table 3: Likely impact of insecticides on beneficial insects of relevance to field vegetable crops.

This information has been collated from the Cotton Pest Management Guide (2015), the BioBest side-effects manual (2015), The Good Bug Book (2002), and through discussion with experts.

The scores indicate a reduction in beneficial species following chemical application: VL (very low) <10%; L (low) 10–20%; M (moderate) 20–40%; H (high) 40–60%; VH (very high) > 60%. '-' indicates no data available for species. Note: the impact of chemicals may differ between crop types.

Insecticide	Predatory beetles[1]				Predatory bugs					Predatory mites	Spiders	Hymenoptera (small wasps)[6]						Lacewing adults	Thrips[8]	Toxicity to bees[9]
	Total[2]	Red & Blue beetle	Minute 2-spotted lady beetle	Other lady beetles	Total[3]	Damsel bugs	Big-eyed bugs	Other Predatory bugs	Apple Dimpling			Total (wasps)	*Eretmocerus*[7]	*Encarsia formosa*	*Trichogramma*	*Aphytis*	*Aphidius*			
Paraffinic Oil	VL	L	L	VL	VL	VL	VL	VL	VL	-	L	VL	-	-	VL	-	-	VL	VL	VL
Petroleum Oil	-	-	-	L	-	-	-	-	-	M	-	-	-	H	-	M	-	-	-	-
Cyantraniliprole	M	M	VL	L	M	M	M	H	L	-	M	VL	L	-	VL	-	-	VH	H	-
Spirotetramat	M	L	H	H	VL	VL	VL	VL	M	-	M	M	L	-	M	-	-	VH	M	-
Pirimicarb	H	VL	VL	L	M	L	M	VL	VL	L	VL	VL	M	H	H	L	L	L	L	VL
Flonicamid	L	VL	VL	VL	H	H	VH	H	H	-	M	M	L	-	H	-	M	L	H	-
Diafenthiuron	M	H	VL	M	L	M	VL	L	H	-	L	L	H	-	L	-	VH	L	L	M
Pymetrozine	M	M	M	M	M	L	L	VL	H	L	L	L	L	M	L	L	M	M	VL	VL
Sulfoxaflor	H	L	M	H	L	VL	L	M	VH	-	L	M	-	-	H	-	-	H	H	-
Chlorantraniliprole / Thiamethoxam	-	-	-	-	-	-	-	-	-	-	-	-	M	-	-	-	-	-	-	-
Imidacloprid (Irrigating)	H[4]	-	-	-	VH	-	-	-	-	-	-	-	L	-	L	-	L	L	-	-
Acetamiprid	H	M	VH	H	H	M	H	M	VH	-	VL	L	H	-	H	-	H	L	VH	M[10]
Imidacloprid (Spraying)	H	L	VH	H	H	M	H	L	VH	M	L	L	VH	VH	H	H	VH	M	H	M
Thiamethoxam	H	H	H	H	H	M	M	H	H	-	VL	M	M	-	H	-	VH	M	H	H
Organophosphates[5]	H	M	H	H	H	M	H	H	VH	H	M	H	VH	VH	VH	H	VH	M	H	H
Tau-Fluvalinate	VH	-	-	-	VH	-	-	-	-	-	-	-	VH	-	VH	-	VH	M	-	-
Piperonyl Butoxide / Pyrethrins	VH	-	-	-	VH	-	-	-	VH	-	VH	VH	VH	-	VH	-	VH	H	VH	H
Bifenthrin / Chlorpyrifos	VH	-	-	-	VH	-	-	-	VH	-	VH	VH	VH	-	VH	-	VH	VH	VH	H
Permethrin	VH	-	-	H	VH	-	-	-	VH	H	VH	VH	VH	VH	VH	H	VH	VH	VH	H

1. Toxicity ratings for predatory beetles are for adults only.
2. Total predatory beetles – ladybeetles, red and blue beetles, other predatory beetles.
3. Total predatory bugs – big-eyed bugs, minute pirate bugs, brown smudge bugs, glossy shield bug, predatory shield bug, damsel bug, assassin bug, apple dimpling bug.
4. This rating is for the larval stage of predatory beetles because irrigating affects soil organisms.
5. Organophosphates: diazinon, chlorpyrifos, dimethoate, maldison, methamidophos, omethoate, phorate.
6. Toxicity ratings for hymenoptera are for adults only.
7. Rankings for *Eretmocerus* based on data from Jamie Hopkinson in semi-laboratory replicated experiments (QDAF) and on ranking for *E. mundus* (P. De Barro, CSIRO, unpublished) and for *E. eremicus* (Koppert Biological Systems, The Netherlands http://side-effects.koppert.nl/#).
8. Effects on thrips are for populations found on leaves. This is relevant to seedling crops, where thrips damage leaves, and to mid-late season when thrips adults and larvae help control mites by feeding on them as well as on leaf tissue.
9. Data Source: British Crop Protection Council. 2003. The Pesticide Manual: A World Compendium (Thirteenth Edition). Where LD50 data is not available impacts are based on comments and descriptions. Where LD50 data is available impacts are based on the following scale: very low = LD50 (48h) > 100 ug/bee, low = LD50 (48h) <100 ug/bee, moderate = LD50 (48h) < 10 ug/bee, high = LD50 (48h) < 1 ug/bee, very high = LD50 (48h) < 0.1 ug/bee.
10. Wet residue of these products is toxic to bees, however, applying the products in the early evening when bees are not foraging will allow spray to dry, reducing risk to bees the following day.