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

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Authors: Dr Siobhan de Little and Dr Paul Umina (**cesar**)

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Table 1: 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.	Umina et al. 2014a, 2014b;

	• 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).	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.)

Table 2: 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, stonefruit, tomato, tuber vegetable	canola, wheat - up to early flag leaf only, cotton
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

Table 3: 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

Table 4: 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. The summary below is based 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 drenched with imidacloprid before being transplanted into the field, although this can vary with crop type and region. Soil treatments are also common in certain crops (in some regions), especially cucurbits. Foliar insecticides are sprayed on 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 & minimisation 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 and staggered planting. 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.

Table 5: Chemical control recommendations for the green peach aphid in vegetable crops

	Spray Windows				**Rationale**
Seedling Treatment	Neonicotinoids (Group 4A) used only in seedling drenches and drip irrigation.				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.
Rotate through products for duration of window	**Autumn Window** (Mar – May)	**Winter Window** (Jun – Aug)	**Spring Window** (Sept – Nov)	**Summer Window** (Dec – Feb)	**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 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.
	Pymetrozine (Group 9C)	Spirotetramat (Group 23)	Pymetrozine (Group 9C)	Spirotetramat (Group 23)	
	Sulfoxaflor (Group 4C)	Cyantraniliprole (Group 28) Or Flonicamid (Group 29)	Sulfoxaflor (Group 4C)	Cyantraniliprole (Group 28) Or Flonicamid (Group 29)	**Autumn and Spring spray windows:** 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.
Clean-up only	Carbamates (Group 1A) - IPM compatible (see Table 6)				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.
Notes	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 for 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.				

Virus-specific and general control recommendations

Papaya ring spot and cucumber mosaic viruses are both non-persistent. 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. 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.

Table 6: Impact of insecticides on beneficial insects of relevance to vegetable crops.

Insecticide	Predatory beetles[1]				Predatory bugs					Predatory mites	Spiders	Hymenoptera[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	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.