

Insecticide resistance and implications for future aphid management in Australian grains and pastures: a review

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Abstract. Aphids can cause substantial damage to cereals, oilseeds and legumes through direct feeding and through the transmission of plant pathogenic viruses. Aphid-resistant varieties are only available for a limited number of crops. In Australia, growers often use prophylactic sprays to control aphids, but this strategy can lead to non-target effects and the development of insecticide resistance. Insecticide resistance is a problem in one aphid pest of Australian grains in Australia, the green peach aphid (*Myzus persicae*). Molecular analyses of field-collected samples demonstrate that amplified E4 esterase resistance to organophosphate insecticides is widespread in Australian grains across Australia. Knockdown resistance to pyrethroids is less abundant, but has an increased frequency in areas with known frequent use of these insecticides. Modified acetylcholinesterase resistance to dimethyl carbamates, such as pirimicarb, has not been found in Australia, nor has resistance to imidacloprid. Australian grain growers should consider control options that are less likely to promote insecticide resistance, and have reduced impacts on natural enemies. Research is ongoing in Australia and overseas to provide new strategies for aphid management in the future.

Additional keywords: biological control, host plant resistance, predictive modelling.

Introduction

Aphids cause damage to plants by direct removal of nutrients, by secreting bioactive compounds into the plant in their saliva, by the transmission of plant pathogenic viruses, and by secreting honeydew that can cause secondary fungal growth and inhibit photosynthesis. Aphids are specialised to feed from a single cell type, the phloem sieve element, and can feed from the same cell for hours and even days. As such, aphids have an intimate association with their host plants that is perhaps better described as parasitism rather than predation. While substantial damage can result from plant viruses transmitted by relatively few aphids on a plant, except for those species such as Russian wheat aphid (*Diuraphis noxia*), that inject toxic compounds in their saliva, aphids generally will only cause direct feeding damage when they achieve high population densities.

Aphids can be considered as the weeds of the insect world. When they find a suitable host, they reproduce quickly until the plant can no longer support the growing population, at which point they produce winged morphs that disperse randomly with the wind and of which some will find suitable hosts to support subsequent generations. In agricultural monocultures, virtually all individuals dispersing during the cropping season will find a suitable host – an ideal situation for unencumbered population growth. This population growth is aided by asexual reproduction and telescoping of generations: female aphids give birth to live

young in which embryos of the next generation are already developing (Moran 1992).

In temperate climates, most aphid species exhibit alternation of generations. In the late autumn, sexual females and males are produced, which migrate to an alternative woody host plant where they mate and produce eggs that can survive the winter frosts (Moran 1992). In warmer climates, like those prevailing in Australia, the sexual phase is often lost and aphids reproduce asexually throughout the year (Moran 1992). In milder Australian regions where the climate supports plant growth all year round, such as southern Victoria (Vic.) and Tasmania, aphids can be found throughout the year. In Mediterranean climates such as those of Western Australia (WA), South Australia (SA) and southern New South Wales (NSW), aphid populations all but disappear during the summer months and must reestablish populations each year after autumn rainfalls (Thackray *et al.* 2004). Many aphid species are also adapted to cooler temperatures, able to grow and reproduce at temperatures close to freezing. These species are, therefore, able to thrive during winter cropping seasons.

Aphid pests and management practices

Cereals

Several aphid species feed on cereals in southern Australia, the most common being oat aphids (*Rhopalosiphum padi*), corn

aphids (*R. maidis*), rose-grain aphids (*Metapolophium dirhodum*, except in WA), and *Sitobion miscanthi* and *S. frageriae* grain aphids. Direct feeding damage from aphids occurs when colonies develop on stems, leaves and heads, usually in the tillering and later stages of crop growth through to head filling. Another aphid species, *R. rufiabdominalis*, can be quite abundant on belowground parts of winter cereals, particularly during periods of moisture stress. In WA, the management threshold for cereal aphid feeding is when 50% of cereal tillers have 15 or more aphids and crops are expected to yield 3 t/ha or more. Under these circumstances, feeding damage may cause reductions in yields by up to 10% and also reduce seed size, leading to a possible downgrading of grain quality (Michael 2002). *R. rufiabdominalis* cannot be controlled using contact insecticides because of its belowground location on the plants.

If aphids are at threshold levels, the decision to spray needs to be weighed up against the potential yield of the crop (Michael 2002). If the crop is dense then higher rates of insecticides are required to reduce high aphid populations and to minimise their feeding damage. Low yielding crops are unlikely to produce an economic benefit from control.

Though cereal aphids can cause yield losses through direct feeding, the primary source of damage from aphid feeding is through the transmission of viruses – in particular *Barley yellow dwarf virus* (BYDV). A rough guide is 1% early BYDV infection leads to 0.55% yield loss in a cereal crop expecting to yield 3 t/ha or more (Thackray *et al.* 2005). BYDV incidence at the end of the season seldom reaches more than 50%, unless aphids arrived immediately after crop emergence. In many years, and in many areas, the incidence does not rise above 10% and there is little yield loss because this infection occurs late when plants are less susceptible to damage.

There are no wheat varieties resistant to BYDV, but there is good resistance available in barley and some tolerance available in oats. Growers in historically high-risk areas, generally high rainfall zones, are encouraged to consider utilising these. Decision support systems can help growers determine whether the risk of BYDV warrants protective actions (Knight and Thackray 2007; Thackray *et al.* 2008). Although predictions (made from April onwards) are generally too late to influence the variety decisions of growers, they can be used to determine the necessity and timing of insecticide applications after emergence.

Seed dressings containing the insecticide imidacloprid have been shown to decrease the incidence of aphids and BYDV (Jones *et al.* 2003); however, a follow-up foliar spray of a synthetic pyrethroid at 7 weeks after crop emergence is recommended. If no seed dressings are used and there is a risk of BYDV spread then two synthetic pyrethroid applications are recommended, at 3 and 7 weeks after crop emergence.

In growing areas in the north of Australia [central NSW to central Queensland (Qld)] the oat aphid and the corn aphid can always be found in cereal crops though generally in low numbers. About every 5–7 years enormous numbers develop in early spring, particularly in barley, and these may cause yield reductions. Because BYDV is not a significant problem in this area the threat is from feeding damage only. If left untouched, most aphid populations are reduced to subeconomic levels by parasitoids and predators. If spraying is economic, growers generally use dimethoate, chlorpyrifos or pirimicarb.

Canola

Two species of aphids, the cabbage aphid (*Brevicoryne brassicae*) and the turnip aphid (*Lipaphis erysimi*), can cause considerable damage by feeding on canola growing shoot tips, causing wilting, flower abortion and reduced pod set. Canola is most sensitive to aphid damage during bud formation through to late flowering. However, as aphid colonies develop on single flowering spikes, canola compensates for the damage by producing more spikes. Control options need to be considered if plants are suffering from moderate drought stress. These stressed plants are targeted by aphids and are less able to compensate for aphid feeding damage than healthy plants. In marginal areas where drought stress is more likely, there is an increased risk of aphid feeding damage (Berlandier and Valentine 2003; Berlandier 2004a) and yield losses of up to 33% have been recorded (Berlandier 2004b). Some canola cultivars are more susceptible than others to aphid colonisation. Cultivars such as Hyden and Beacon appear to be the least susceptible to aphid colonisation (Berlandier and Valentine 2003).

The threshold for aphid feeding damage is 20% of flowering heads infected with aphids, and pirimicarb is the only chemical registered. It has the advantage of being kinder to beneficial insects such as hover flies, lacewings, ladybirds and aphid parasitoids. These predators and parasitoids will be building up in crops along with the aphids and they can reduce or contain aphid populations to below threshold levels. Pirimicarb is registered at 500–1000 g/ha, but a lower, more economical rate of 200–300 g/ha is often sufficient (Berlandier 2004b). Pirimicarb should not be applied using a mister and where cabbage aphids are present added to the spray mix can help the insecticide penetrate the aphid's waxy surface.

The green peach aphid (*Myzus persicae*) can cause significant early season crop loss in the 2–4-leaf stage if conditions are suitable. The green peach aphid is also the most important vector of Beet western yellows virus, which may grow to be a serious problem in southern Australia in the near future (Jones *et al.* 2007).

Lupins and pulses

Three aphid species commonly feed on cultivated lupins in Australia: (i) the blue-green aphid (*Acyrtosiphon kondoi*); (ii) the cowpea aphid (*Aphis craccivora*); and (iii) the green peach aphid. Aphids may be present on seedlings but more commonly occur on lupins during budding and flowering. Aphid feeding can reduce yields especially in low rainfall areas (<325 mm) when plants are stressed and less vigorous. Stressed plants favour aphid growth, and unlike plants in higher rainfall zones, cannot easily compensate for the damage caused by aphids. The extent of yield loss is influenced by lupin variety. Yellow lupin varieties, such as Wodjil, are mostly very susceptible to aphid colonisation whereas most narrow-leaved lupin varieties, such as Kalya and Tanjil, are not (Berlandier *et al.* 1998; Edwards 2001). However, glasshouse assays indicate that green peach aphid may be able to feed successfully on some resistant varieties (Edwards *et al.* 2003) and there have been reports of green peach aphid colonising resistant narrow-leaved lupins in the field in recent years (O. Edwards, unpubl. data).

Chickpeas are not generally colonised by aphids (Edwards 2001). Overseas, field peas are often colonised by pea aphid (*Acyrtosiphon pisum*). This is not common in Australia, suggesting that there are no pea-specific races of this aphid in Australia. Both faba bean and lentils are susceptible to aphid attack, particularly by cowpea aphid (Edwards 2001).

Thresholds for treatment against aphid damage on lupins have been determined (Berlandier *et al.* 1998), and these have been extrapolated to other pulses (Evans *et al.* 2005). Control measures should be implemented if more than 30% of growing tips are colonised by aphids from the flower bud stage through to podding, particularly in aphid-susceptible varieties (Berlandier *et al.* 1998). Recommended insecticides for aphids on pulses include dimethoate, methidathion, omethoate, and pirimicarb but registration varies among states.

Aphids can also transmit viruses in pulses including *Cucumber mosaic virus* (CMV) and *Bean yellow mosaic virus* (BYMV). CMV can cause yield losses of up to 60% in lupins, but like BYDV in cereals, the risk is highly dependent on the timing of aphid arrival, and unlike BYDV, which is not seedborne, infection of sown lupin seed with CMV is the main source (Thackray *et al.* 2000). Sowing tested clean seed is the best control method but decision support systems can be effective in some areas in helping growers assess the risk of epidemics in any given year and consequently the need for control measures (Thackray *et al.* 2004).

Sorghum

The corn aphid is universally associated with sorghum production in Australia. Occasionally, very large numbers are found on plants in the vegetative stage, within the plant whorl. These populations are rarely sprayed as they have little effect on yield and they usually disappear about the time of panicle emergence. The aphid is, however, an occasional pest of sorghum panicles. Honeydew excreted by the aphid causes sticky grain, which interferes with harvesting and grain handling. Natural enemies are very important in reducing panicle infestations by the corn aphid (B. Franzmann, unpubl. data).

Soybean

The soybean aphid (*Aphis glycines*) was discovered in Australia in 2000. It can mainly be a problem in coastal NSW and Qld. High populations can reduce plant vigour, height and yield. Heavily infested plants may be covered in sooty mould growing on honeydew secreted by the aphids. Predators play an important role in suppression of populations (Brier 2007).

Pastures

Legume pastures are an important component of ley-farming systems of southern Australia (Reeves and Ewing 1993). Depending on soil type and climate, these pastures are usually dominated by annual medics (*Medicago* spp.) or clovers (*Trifolium* spp.). Aphids have been key pests of legume pastures since the 1980s, when most pasture legume pest aphid species were first introduced into Australia (Walters and Dominiak 1988). Cowpea aphid and blue-green aphid will colonise both medics and clovers, though host suitability varies among the different pasture species (Berlandier *et al.*

1999; Nair *et al.* 2003). An additional species, *Therioaphis trifolii*, has two different forms: (i) spotted alfalfa aphid (*T. trifolii* f. *maculata*), which attacks lucerne and some medic species; and (ii) spotted clover aphid (*T. trifolii*), which in some parts of southern Australia can cause substantial damage on clovers. Aphid-transmitted viruses can also be a problem in pasture legumes, in particular BYMV in clover and Alfalfa mosaic virus in medics.

Breeders have had some success breeding aphid resistance into Australian pasture legume varieties. Most current varieties of the barrel medic (*M. truncatula*) have resistance to both blue-green aphid and spotted alfalfa aphid, with some limited protection also against pea aphid and spotted clover aphid (Gao *et al.* 2007a). Aphid-resistant lines are also available for the strand medic, *M. littoralis* (Nair *et al.* 2003). Breeders have not been as successful identifying resistance in clovers; moderate tolerance to blue-green aphid is available in some varieties of subterranean clover, but no resistance exists against spotted clover aphid.

Organophosphate (dimethoate) and carbamate (pirimicarb) insecticides are registered for use against aphids in legume pastures. Growers in high aphid risk areas should consider aphid-resistant varieties rather than relying on insecticide treatments. If no aphid-resistant options are available, growers should consider seed treatments when the aphid risk is high. If insecticide sprays are necessary, growers should survey the pasture for predators and parasitoids (see below) before treating, to determine whether the aphid populations might be controlled naturally. More natural enemy-friendly insecticides such as pirimicarb should be favoured. Because of their anti-feeding effects, pyrethroid insecticides are likely to be most effective at preventing aphids from introducing viruses into pastures, but this practice should be avoided unless absolutely necessary because of the high risk of selecting for insecticide resistance in both aphids and other pasture pests.

Biological control

Biological control of aphids in Australian cropping systems is achieved to a varying degree by a combination of exotic parasitoids and indigenous predators. The abundance of aphid parasitoids in a crop is easiest to gauge from the presence of mummified aphids rather than observing the foraging wasps. During the late stages of parasitoid development, the aphid cuticle becomes hardened and darkened (black or grey). Such 'mummies' are easily visible within a colony of feeding aphids, and under these circumstances growers can reasonably assume that most other aphids in the colony are also parasitised and will not reproduce. All aphid parasitoids will only attack aphids, but most will attack more than one aphid species. Aphidiid parasitoids (e.g. *Aphidius* spp., *Lysiphlebus* spp., *Diaraietella rapae*) are the most abundant and effective parasitoids in Australian grains, while aphelinid parasitoids (e.g. *Aphelinus* spp.) are generally restricted to summer crops, such as sorghum. Some exotic parasitoids (e.g. *D. rapae*) appeared in Australia by unknown means, perhaps arriving as part of aphid incursions, whereas others have been introduced intentionally by practitioners of classical biological control. For example, a large number of introductions occurred during the 1980s in response to

the accidental introduction of the pea aphid, blue-green aphid, and spotted alfalfa aphid (Hughes *et al.* 1987; Waterhouse and Sands 2001). Aphid populations can be suppressed substantially by both specialist and generalist predator species, the most important of which are ladybird adults and larvae (Coleoptera: Coccinellidae), hoverfly larvae (Diptera: Syrphidae), and lacewing larvae (Neuroptera: Chrysopidae and Hemerobiidae).

Before using insecticides, growers should always make an effort to survey their crops for natural enemies, which may already be suppressing any further aphid population growth. When natural enemies are present, insecticide treatments can in fact lead to increased aphids because predators and parasitoids are generally more sensitive to contact insecticides than are pest aphid species. If insecticide treatments are necessary, there are insecticide options that have less of an impact on natural enemies. Seed treatments, such as imidacloprid, are particularly friendly to natural enemies because only plant-feeding insects are exposed to the toxins. Of the contact insecticides registered for use against aphids in Australian grains, pirimicarb has the lowest impact on natural enemy populations. The choice of these insecticides is enhanced by the absence of any reported resistance to imidacloprid or pirimicarb in aphid pests of Australian grains.

In areas of Australia with more consistent rainfall, predator populations are sustained year-round and aphid populations can be suppressed by natural enemies throughout the year. In these areas, natural enemies should be monitored before insecticide treatments are considered. In some crops, guidelines are available to monitor natural enemies. For example, in barley in the northern region, it is recommended that growers check for aphids by choosing six widely spaced positions in the crop and at each position, examine five consecutive plants in a row. If 27 out of 30 plants are covered with aphids and if there are less than two ladybird beetles, ladybird larvae, hoverfly larvae or lacewing larvae per plant on each of the infested plants, then an insecticide treatment is recommended (Franzmann *et al.* 1992).

In Mediterranean climates, characterised by wet winters and long, dry summers, aphid and natural enemy populations crash during the summer when green plant material is scarce. During the subsequent autumn and winter, aphids are able to escape parasitism and predation due to a higher reproductive rate at lower temperatures. Once the warmer temperatures arrive in spring, natural enemies often gain the upper hand and aphid populations are suppressed – but this is often too late to prevent significant crop damage.

Predictive modelling

In the Mediterranean-style climate of the WA wheatbelt, aphids survive the summer in low numbers on perennial grasses, summer weeds, or volunteer crops that may appear after periodic rain events. The timing of aphid flights into crops in the winter growing season is correlated with the occurrence and extent of rainfall events during the late summer and early autumn (Fig. 1) (Thackray *et al.* 2004; Knight and Thackray 2007). These rainfall events support the growth of alternative weedy or volunteer hosts on which aphid populations can multiply before moving to crops. Because the weeds and volunteers are often also reservoirs for aphid-transmitted viruses, the same rainfall data are also correlated with the risk of virus outbreaks.

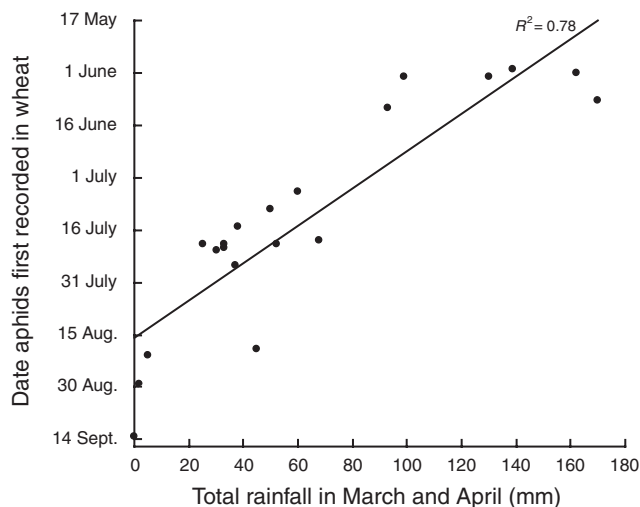


Fig. 1. Effect of rainfall in March and April on the date aphids were first recorded in wheat validation blocks from 1998 to 2002 at five different sites in the Western Australian grainbelt. The equation of the line is: $y = -0.5355x + 371.19$; ($R^2 = 0.7839$; $P < 0.05$).

The association between rainfall and aphid/virus risk has been used as the basis for the development of simulation models to forecast aphid outbreaks and virus (BYDV, CMV and BYMV) epidemics in the WA wheatbelt (Thackray *et al.* 2004, 2008; Knight and Thackray 2007; Maling *et al.* 2008). The models use daily regional temperature and rainfall data to predict aphid population development on weeds and crop volunteers, and the subsequent movement of dispersing aphids into paddocks. Virus incidence can be estimated and potential yield losses due to virus infection can be calculated.

The models now form the basis for three decision support systems (DSS) used extensively by WA farmers and advisers to optimise choice of cultural control measures for CMV and BYMV in lupins and the need for and timing of insecticide sprays against BYDV aphid vectors in cereal in medium and high rainfall zones. The DSS are available online through the Department of Agriculture and Food, WA website (<http://www.agric.wa.gov.au>, verified 10 October 2008). Regional risk predictions for yield losses for different sowing dates are provided in the form of colour-coded maps. Ongoing improvements to the DSS include automated climate data retrieval and map generation (Maling *et al.* 2008).

These models are particularly useful where the necessary input data are readily available from existing databases. In New Zealand, aphid flights cannot be predicted from weather data and similar models require aphid suction trap catch data to generate effective DSS tools (Bicknell *et al.* 2000). Such an investment can be justified only when it results in substantial benefits to the growers, and this limits the utility of these models in other parts of Australia where the relationship between climate data and aphid arrival is less strong, but suction traps are not available.

Insecticide resistance

The use of prophylactic spraying to control aphids and aphid-transmitted viruses increases the risk of insecticide resistance

development, both in target and non-target species (McKirdy and Jones 1996). DSS systems, as described in the previous section, allow growers to evaluate risk and use insecticides more strategically (Knight and Thackray 2007). Unfortunately, such tools are the exception rather than the rule and as long as inexpensive insecticides are effective and available, growers will use them as a risk management tool.

Some aphid species are renowned for developing insecticide resistance. For example, the green peach aphid has developed resistance to more classes of insecticide than any other insect species (Anstead *et al.* 2005). Unfortunately for Australian grain growers, green peach aphid is common in the grainbelts of Australia. It is a more serious pest of vegetables, but can cause damage to canola (Berlandier 2004a) and narrow-leafed lupins (Berlandier *et al.* 1998). It is the only one of three aphid species attacking narrow-leafed lupins that can feed on resistant varieties (Cardoza *et al.* 2006). The good news is that this aphid species does not feed extensively on cereals – and cereal aphids, for some unknown reason, do not develop insecticide resistance as readily as other aphid pest species. There is no evidence for insecticide resistance in Australian cereal aphids (O. Edwards, unpubl. data).

In addition to being the target of insecticide applications on canola and lupins as well as in vegetables, green peach aphid will often be exposed to insecticide treatments in other crops while feeding on broad-leafed weeds interspersed among crop plants. Insecticide resistance in Australian populations of green peach aphid has been present since at least the early 1990s (Herron *et al.* 1993). Several mechanisms of insecticide resistance have been found to be widespread in European populations of this pest (Anstead *et al.* 2007). Amplified carboxylesterase (E4) was first inferred to be present in Australia by the presence of an associated chromosomal translocation (Wilson *et al.* 2002). Since then, surveys of green peach aphid insecticide resistance mechanisms have been conducted, covering the grain-growing regions of WA, SA, NSW, Vic., and Qld (Tables 1–3). Almost every aphid collected had organophosphate resistance due to

amplification of the esterase gene E4. This mechanism also provides some cross-resistance to pyrethroid insecticides (Devonshire 1989). Unlike the situation in Europe, the related mechanism of amplified FE4 esterase has not been found in Australia (Edwards and Lawrence 2003a, 2003b, 2006). The amplified esterase resistance mechanism is unusual because it is regulated by DNA methylation, and can be ‘switched on’ in response to pesticide exposure (Field 2000). As a result, aphid populations can quickly adapt to survive insecticide treatments, in particular organophosphates such as dimethoate, which may recently have been used effectively. The presence of amplified E4 esterase in a high proportion of green peach aphid clones sampled indicates that organophosphate insecticides are not likely to be a good option for future control of this pest.

Knockdown resistance (kdr) to pyrethroids is also prevalent in green peach aphids collected from grain-growing regions around Australia (Tables 1–3). The frequency of this resistance varies from around 25 to 100% of sampled aphids, which probably reflects the recent history of pyrethroid insecticide applications in each area. In northern Vic. and southern Qld (Table 2), kdr was found to be particularly frequent, perhaps as a result of recent exposure to pyrethroid applications in vegetables in these areas. The frequency of kdr in green peach aphid populations is sufficiently high that any application of pyrethroid insecticide would quickly lead to populations dominated by resistant individuals. Any green peach aphids feeding on broad-leafed weeds within cereal crops are likely to respond in a similar fashion to prophylactic pyrethroid sprays targeting cereal aphids, possibly leading to control problems in adjacent canola or lupin crops. Prophylactic spraying can also select for insecticide resistance in non-target organisms. Recent reports in WA of high level resistance to synthetic pyrethroids in the redlegged earth mite (*Halotydeus destructor*) (Umina 2007) must certainly be the result of the use of synthetic pyrethroids for prophylactic aphid control in cereals and other crops, since historically pyrethroids have not been registered for use against this mite.

Table 1. Insecticide resistance status of *Myzus persicae* clones collected in Western Australia in 2001 and 2002

Carboxylesterase [susceptible (S), E4 type, FE4 type], knockdown resistance (kdr) and modified acetylcholinesterase (MACE) genotypes were detected according to methods described in Field *et al.* (1999) and Cassanelli *et al.* (2005). Imidacloprid resistance (R) or susceptibility (S) was evaluated using bioassays following the aphid-dip method described by Devine *et al.* (1996). All samples were tested for carboxylesterase resistance, but some samples were not available for further testing

Host plant	n	Carboxylesterase			kdr			MACE			Imidacloprid	
		S/S	S/E4	E4/E4	+/+	+/-	-/-	+/+	+/-	-/-	S	R
<i>M. persicae</i> clones collected in 2001												
Broccoli	1			1		1				1		1
Wild radish	2		1	1		2				2		2
Canola	11		3	8		9				9		9
Capeweed	3		1	2		1				1		1
Field pea	1		1							1		1
Narrow-leafed lupin	1			1		1				1		1
Yellow lupin	1					1				1		1
<i>M. persicae</i> clones collected in 2002												
Cauliflower	1		1			1				1		1
Wild radish	5		3	2		3	2			5		5
Canola	12		6	6	1	6	5			12		12

Table 2. Insecticide resistance status of *Myzus persicae* clones collected in Victoria, New South Wales and Queensland in 2005
Carboxylesterase [susceptible (S), E4 type, FE4 type], knockdown resistance (kdr), and modified acetylcholinesterase (MACE) genotypes were detected according to methods described in Field *et al.* (1999) and Cassanelli *et al.* (2005). Imidacloprid resistance (R) or susceptibility (S) was evaluated using bioassays following the aphid-dip method described by Devine *et al.* (1996)

Host plant	<i>n</i>	Carboxylesterase			kdr			MACE			Imidacloprid	
		S/S	S/E4	E4/E4	+/+	+/-	-/-	+/+	+/-	-/-	S	R
<i>Queensland</i>												
Swinecress	1			1	1					1	1	
Broccoli	2		2			1	1			2	2	
Cabbage	1			1		1				1	1	
Wild radish	3		1	2						3	3	
<i>New South Wales</i>												
Wild radish	6			6	1	4	3			6	6	
Cabbage	1	1								1	1	
Canola	3		6	6	1	6	5			12	12	
<i>Victoria</i>												
Canola	3	1		2		2	1			3	3	

Table 3. Insecticide resistance status of *Myzus persicae* clones collected in South Australia in 2006
Carboxylesterase [susceptible (S), E4 type, FE4 type], knockdown resistance (kdr), and modified acetylcholinesterase (MACE) genotypes were detected according to methods described in Field *et al.* (1999) and Cassanelli *et al.* (2005). Imidacloprid resistance (R) or susceptibility (S) was evaluated using bioassays following the aphid-dip method described by Devine *et al.* (1996)

Host plant	<i>n</i>	Carboxylesterase			kdr			MACE			Imidacloprid	
		S/S	S/E4	E4/E4	+/+	+/-	-/-	+/+	+/-	-/-	S	R
Canola	15		11	4		11	4			15	15	
Cabbage	2		2				2			2	2	
Wild radish	6		5	1		4	2			6	6	

Like amplified E4 resistance, kdr was almost always found in heterozygous form (Tables 1–3). In Europe, heterozygotes also predominate and it is believed there could be fitness costs to homozygosity at the kdr locus (Anstead *et al.* 2007). In Australia, the low levels of sexual reproduction in this species would also limit the appearance of homozygotes. A second, stronger kdr mechanism, super-kdr, is widespread in Europe (Anstead *et al.* 2007) but has not been found in any Australian populations (O. Edwards, unpubl. data).

Modified acetylcholinesterase resistance is also common in green peach aphid populations in Europe (Anstead *et al.* 2007), yet has not been found anywhere within Australia (Tables 1–3). Consequently, applications of carbamate insecticides, such as pirimicarb, are not likely to lead to resistant populations developing in the short term, so they should continue to be an effective management tool for green peach aphid in the future.

Imidacloprid insecticides are very effective contact and systemic aphidicides. No evidence for resistance to imidacloprid was found in bioassays conducted as part of a recent survey (Edwards and Lawrence 2003a, 2003b, 2006). The use of imidacloprid insecticides in Australian grains has been limited by the high costs relative to synthetic pyrethroids, but this situation may change when the patent expires.

Future management practices

With the need for reduced inputs and the risk of increased insecticide resistance, future aphid management practices should

aim to reduce overall insecticide use. Using aphid-resistant varieties is the most economical option for growers, but aphid-resistant varieties are not always available and do not always deter virus spread. Aphids are also able to evolve biotypes that can overcome resistance, so resistant varieties are often not durable.

Research is ongoing in Australia and overseas to identify the mechanisms used by aphids to feed successfully on host plants, and the mechanisms used by plants to achieve successful defence against aphids. This research may lead to new strategies to achieve durable resistance against pest aphid species. There is growing evidence that resistance to aphids is often mediated by a class of proteins called 'R-genes', which are inherited as single, dominant genes and act in an analogous fashion to mammalian antibodies (Rossi *et al.* 1998; Klingler *et al.* 2005, 2007). These proteins appear to function by recognising a factor associated with aphid feeding, and in response elicit effective defences (Gao *et al.* 2007b). The same class of proteins is responsible for resistance to many pathogens, and researchers worldwide are investigating both the recognition and signalling processes associated with these proteins. Once these processes are better understood, it is not unreasonable to believe that in the future these R-gene proteins could be artificially engineered to function against aphid pests or other pathogens in plant species where no naturally occurring resistance can be identified.

There are also ongoing research efforts identifying aphid genes necessary for successful feeding. In narrow-leafed lupins, one phloem alkaloid (lupanine) has been implicated in conferring

resistance to the green peach aphid (Cardoza *et al.* 2006), and it appears that members of one particular class of detoxification enzymes are necessary to feed on a diet containing this alkaloid (S. Seah and O. Edwards, unpubl. data). Researchers at Kansas State University have demonstrated that eliminating one salivary gland protein of unknown function prevents the pea aphid from feeding successfully on plants, but feeding on an artificial diet is unaffected (Mutti *et al.* 2006). In the future, aphid resistance could be achieved by engineering plants to produce RNA interference constructs that effectively silence these genes and prevent successful feeding (Baum *et al.* 2007; Mao *et al.* 2007).

'High-tech' solutions such as these will take at least 10 years to reach the market. In the interim, aphid management should continue to be based on the development and use of aphid- and/or virus-resistant varieties whenever possible, natural enemy conservation, and selective use of insecticides only when necessary. Prophylactic treatment should be avoided because of their effects on natural enemies, and because they select strongly for insecticide resistance in both target and non-target species. It is important to understand better the efficacy and economics of seed treatments, which can greatly reduce non-target effects. Also, more research is needed into more strategic methods of insecticide application. One promising approach is to use border treatments of insecticides to kill immigrant aphids. This approach is similar to the strategy of using border rows of non-hosts to limit the degree to which immigrating aphids introduce non-persistent viruses into crops (Jones 2005; Hooks and Fereres 2006). Perhaps the greatest benefit could be obtained by research into improved strategies for natural enemy monitoring and conservation, as it is difficult in most cropping systems for growers to judge accurately whether aphid populations will be sufficiently suppressed by biological agents so that insecticide treatments are not necessary. These approaches should together provide Australian grain growers with effective options to manage aphids into the future.

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