INSECTICIDE RESISTANCE IN THE SOUTHERN REGION: CURRENT STATUS, FUTURE RISK AND BEST MANAGEMENT PRACTICES

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SOUTHERN REGION

The current status and future risk of insecticide resistance in the southern region and best management guidelines to minimise reliance on chemicals, pest damage, impact on beneficials and resistance selection.

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Title: Insecticide resistance in the southern region: current status, future risk and best management practices
The current status and future of insecticide resistance in the southern region and best management guidelines to minimise reliance on chemicals, pest damage, impact on beneficials and resistance selection.

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COVER: Diamondback moth.
PHOTO: Andrew Weeks, **cesar**

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The status of insecticide resistance in the southern grains region

What is insecticide resistance?

Insecticide resistance has been documented as far back as 1914, as reported by Axel Melander in a research article entitled ‘Can insects become resistant to sprays?’ In this paper the author describes the increasing difficulty of controlling an apple orchard pest, San Jose scale, with sulphur-lime. By the mid-1940s, 11 cases of resistance to inorganic insecticides had been documented and, with the introduction of the first organic insecticide (DDT) to the market in 1942, it was not long before housefly resistance was documented in 1947. Since that time, resistance to organic synthetic insecticides has been reported at an increasing rate for the majority of chemicals introduced to the market.

This is known as the insecticide treadmill and, due to the nature of genes and mutation, selection of beneficial traits, and often short invertebrate generation times, this trend is likely to continue in the absence of significant practice change. Globally, there are more than 580 documented cases of invertebrate pests evolving resistance and 325 unique chemicals for which one or more species have evolved resistance.

The Australian grains industry has an ongoing reliance on limited chemical control methods – particularly cheaper broad-spectrum chemistries. Therefore, managing insecticide resistance is a major challenge. Currently, insecticide resistance in Australian grains (excluding the grain storage pests) is established in redlegged earth mites (*Halotydeus destructor*), green peach aphid (*Myzus persicae*), diamondback moth (*Plutella xylostella*) and corn earworm (*Helicoverpa armigera*). These pests also cross over into other industries (such as the horticultural, cotton or grazing industries) meaning resistance selection can also be driven by chemical practices within these industries (Table 1). In light of this occurrence, a resistance management strategy was developed for the region. An understanding of insecticides registered for use in other industries, and therefore with potential for cross-industry issues, can be found by referring to the ‘Science behind the RMS’ documents on the IPM Guidelines for Grains website.

Other species considered minor pests of Australian grain crops that have evolved resistance include silverleaf whitefly (*Bemisia tabaci*), two spotted mite (*Tetranychus urticae*), western flower thrips (*Frankliniella occidentalis*) and onion thrips (*Thrips tabaci*), however these tend to be more prominent in the northern region.

All insecticides belong to a particular ‘Mode of Action’ (MoA) group. Each MoA group results in the same functional or anatomical change in an invertebrate at the level of the cell. The MoA group is listed on the chemical label. Resistance occurs when repeated applications of an MoA insecticide group removes susceptible insects from successive populations, leaving increasing numbers of individuals that are resistant.

Under selective pressure from insecticides, resistant individuals are more genetically ‘fit’ than their susceptible counterparts. Mating between these resistant individuals gradually increases the proportion that are resistant in the pest population as a whole. Eventually this can render an insecticide ineffective, leading to control failures in the field. Resistance can arise due to selection for:

- a heritable trait *already present* in a small portion of the pest population that provides resistance, or
- a *completely new* heritable trait (a mutation) in an individual or individuals that provides resistance.

The main mechanisms of resistance are target site resistance, metabolic resistance, penetration resistance, extraction and sequestration, altered behaviour and cross-resistance.

Target site resistance often evolves from a genetic modification affecting a channel protein or receptor protein that is important to pest survival and also used as an insecticide binding site. In a normal situation an insecticide will attach to that protein at a target site and block its function, leading to invertebrate death. Mutation can lead to a target site that is a different shape to the usual configuration, making it more difficult for the insecticide to bind to the protein and block the function. When this happens, the interaction of the insecticide with its target site is impaired and the insecticide loses its efficacy. The effect of target site resistance results in an on/off scenario. If a pest carries target site resistance to a particular insecticide it will not be controlled with that insecticide.

Another common type of resistance, metabolic resistance, occurs when a pest already has some detoxifying enzymes that will degrade the insecticide and it builds up a higher number of those enzymes. This uses a mechanism that is already naturally at play within the pest and it can result in variable levels of resistance. Therefore, it can be difficult to predict the outcome of using an insecticide on a pest that has metabolic resistance.

When a pest becomes resistant to one insecticide (for example, dimethoate), the resistance can often extend to other chemically related insecticides (for example, omethoate and chlorpyrifos); these related insecticides are labelled with a common Mode of Action (MoA) group number (for example, Group 1B, the organophosphates). This is because insecticides within a common MoA target a common site within the pest. In this case, dimethoate, omethoate and chlorpyrifos all act by binding to, and blocking the activity of, an important nervous system enzyme in invertebrates termed acetylcholinesterase.

As all insecticides within a group share a common MoA, there is a high risk of cross-resistance to many insecticides in the same group. Although less common, cross-resistance can also occur across two (or more) MoA groups. MoA groups are referred to throughout this document because of their central role in understanding resistance management.

TABLE 1 Resistance in key Australian grain pests has been reported in the following insecticide groups.

Species with resistance	Insecticide group	Mode of Action (MoA) group[§]	Industries impacted
Redlegged earth mite (*Halotydeus destructor*)	Organophosphates Synthetic pyrethroids	1B 3A	Grains, grazing, horticulture
Green peach aphid (*Myzus persicae*)	Carbamates Organophosphates Synthetic pyrethroids Neonicotinoids	1A 1B 3A 4A	Horticulture, grains, forage
Diamondback moth (*Plutella xylostella*)	Carbamates Organophosphates Synthetic pyrethroids Spinosyns (low level) Avermectins (low level) Diamides	1A 1B 3A 5 6 28	Horticulture, grains, forage
Corn earworm *(Helicoverpa armigera)*	Carbamates Organophosphates Synthetic pyrethroids Spinosyns *Bacillus thuringiensis* (Bt) Indoxacarb Diamides	1A 1B 3A 5 11A 22A 28	Cotton, grains, horticulture

§ For details on each chemical group in the IRAC classification, see Appendix 3.

SOURCE: UMINA *ET AL*. (2019)

Diamondback moth (*Plutella xylostella*) larva. When DBM larvae are disturbed they will wriggle, and may drop from the plant by a silken thread.

PHOTO: DPIRD

Managing insecticide resistance

Sustainable pest management strategies are required for the stewardship of newer and older chemistries used in grains. Successful resistance management, in Australia and internationally, has been based on the implementation of insecticide resistance management strategies (IRMS) and central to these, the application of integrated pest management (IPM) tactics and the rotation of MoA groups. Greater adoption of IPM tactics, including the careful management of beneficials, cultural practices and monitoring, along with chemical rotation, can effectively reduce selection pressures on currently applied chemistries.

Effective and sustainable insecticide management aims to minimise the selection pressure on invertebrates to evolve insecticide resistance. By rotating chemicals from groups with different MoA, successive generations of the pest are not repeatedly treated with the chemicals working on the same target site. This particularly applies to pests with multiple generations in the one season that may require several spray applications.

Selection for resistance can occur as a result of repeated applications of the same MoA group against that pest, or if the pest is present when the MoA group is used against other pests in the same crop/paddock the latter is called non-target exposure. Table 2 presents a typical rotation from the southern region and highlights the non-target sprays to which typical crop pests are exposed. The most effective method of reducing this non-target selection is to:

- rotate insecticide (MoA groups) used across a crop, and
- reduce the need for insecticides where possible through IPM practices.

In broadacre farming, rotating use of the commonly used synthetic pyrethroid (3A) and organophosphate (1B) groups with other groups (where possible) will help to minimise evolution of resistance in target and non-target pests.

TABLE 2 A typical rotation, with some possible pest and insecticide scenarios, and prospects for non-target resistance selection.

Season	Crop	Crop stage	Target pests	Insecticides scenario	Target pests that may evolve resistance	Non-target pests that may evolve resistance
Winter	Wheat	Pre-seeding	Lucerne flea, mites	Dimethoate 1B	Redlegged earth mite, lucerne flea	Other establishment pests
		Seeding	Grain storage pests, aphids	SD: flutriafol + cypermethrin 3A SD: imidacloprid 4A	Redlegged earth mite/blue oat mite, cutworm	Aphids
		Vegetative	Russian wheat aphid Other aphids	Chlorpyrifos 1B (under permit PER83140) Chlorpyrifos 1B, dimethoate 1B, gamma-cyhalothrin 3A	Green peach aphid on weeds	Corn earworm, lucerne flea, redlegged earth mite/blue oat mite, European earwig
Summer		**GRAZED or FALLOW**	**No selection pressure**			
Winter	Lentils	Pre-seeding	Lucerne flea, mites	Dimethoate 1B	Redlegged earth mite, lucerne flea	Other establishment pests
		Seeding	Aphids, mites	SD: imidacloprid 4A	Aphids	
		Vegetative	Aphids	Gamma-cyhalothrin 3A	Aphids	Redlegged earth mite, European earwig
		Flowering	Native budworm, etiella, blue green aphid	Gamma-cyhalothrin 3A, dimethoate 1B	Aphids	Corn earworm, European earwig Cereal aphids on volunteer cereals. These can be common in lentils Diamondback moth in cases where brassica weeds are present in crop
		Seed set	Etiella, budworm	Gamma-cyhalothrin 3A		Corn earworm, European earwig

SD = seed dressing

The resistant pests of southern grains

The following section provides details on four key resistant pests in the Australian grains industry and factors that contribute to the continuing selection of resistance, or that are important in the management of resistance in these pests.

Redlegged earth mites (RLEM)

THE PEST

Redlegged earth mites (RLEM), *Halotydeus destructor*, a pest originally from South Africa, is widespread in the southern cropping region. It is a major and common pest of pastures and grain crops, particularly during seedling establishment when the crop is most vulnerable, resulting in the potential for considerable economic losses. The economic impact varies across years. The mites have a very broad host range which includes canola, wheat, barley, oats, lupins, sunflower, faba beans, field peas, poppies, lucerne and vetch, as well as pasture legumes and grasses. While RLEM are less of a concern in cereal crops and in some pulses (for example, lentils and chickpeas) they do cause some damage.

THRESHOLD GUIDELINES

Compensation for damage can occur in some crops, highlighting the importance of applying thresholds prior to the use of insecticides. For example, canola and wheat are susceptible to feeding damage caused by RLEM at early growth development stages (canola – cotyledon, first and second true-leaf stage; wheat – Zadoks (Z) 10 and Z12). In contrast, both crops can tolerate damage at the later growth stages (canola – third true-leaf stage; wheat – Z14). Wheat tolerates and compensates for mite feeding damage to a larger extent than canola.

Economic thresholds for RLEMs vary across crops, although most is known about canola:

At the cotyledon stage: If visual mite feeding damage (silvering or whitening) extends to 20 per cent of plants or more and mites are present, treatment is warranted. If not, recheck at the first true-leaf stage.

At the first true-leaf stage: If there are 10 mites per plant, treatment is warranted. If there are fewer mites, do not spray. Recheck paddock in five days if crop growth is slow, or in 10 days if crop growth is rapid.

At the second true-leaf stage: If there are fewer than 30 plants per square metre and the presence of mites, treatment is warranted. If there are greater than 30 plants/m^2 and the majority of plants show no visual mite feeding damage, then do not spray. Recheck paddock in five days if crop growth is slow, or in 10 days if crop growth is rapid.

Beyond the third true-leaf stage: There is no benefit in spraying, except when plants are under severe stress (moisture stress or waterlogging) coupled with mite numbers greater than 2000/m^2.

Nominal thresholds for other crops include:

- wheat and barley: 50 mites per 100cm^2;
- linseed: 10 mites per 100cm^2;
- pulses: 50 mites per 100cm^2; and
- establishing annual medic pastures: 20 to 30 mites per 100cm^2.

CHEMICAL CONTROL

There are approximately 200 insecticide products registered in Australia for RLEM, but these are primarily from three chemical groups – organophosphates (Group 1B, for example, dimethoate), pyrethroids (Group 3A, for example, alpha-cypermethrin) and neonicotinoids (Group 4A, for example, imidacloprid) – very much narrowing the options to rotate MoA for managing resistance.

There are continuing risk factors influencing the ability to minimise evolution of resistance. Most canola crops are sown with insecticide-treated seed (mainly imidacloprid) applied prior to sale. In many instances, growers are not offered an alternative of bare seed where seed is purchased. Insecticide seed dressings have also become more widely used in wheat, oats and barley, as well as on pastures. Most perennial pastures receive relatively few insecticide applications except Timerite® (Ridsdill-Smith and Pavri, 2015) directed applications in spring, which can be applied prior to the cropping phase.

Selection for resistance can result from targeted or non-targeted applications. That is, applications are either specifically targeted to control RLEM or broad-spectrum products are applied to control a variety of pests at seedling establishment. Towards the end of the season, pyrethroids applied at the mature crop growth stages typically target caterpillars and aphids, but invariably affect RLEM if applied before the diapause stage commences. In pastures and pulse crops, lucerne flea is often a co-target, resulting in combination (tank mix) or repeat applications and more prominent use of organophosphates that target both mites and fleas. Tank mixes are not advised due to a lack of information about the efficacy of mixed products and the need to rotate chemicals between subsequent generations.

The complexity of dealing with one pest while influencing another can result in unintentional resistance evolution and needs to be considered with all insecticide applications.

RESISTANCE STATUS

The incidence of RLEM resistance is increasing in Western Australia and South Australia, as shown in Figure 1.

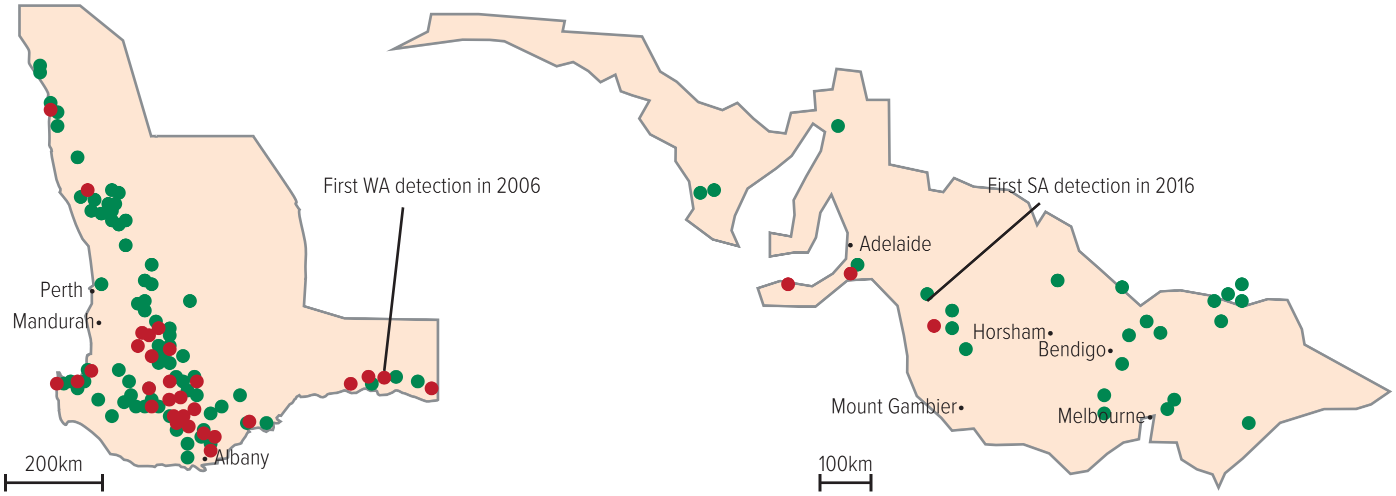
Repeated insecticide applications of the same MoA group within and between seasons has led to the relatively rapid evolution and spread of RLEM resistance, which now includes the two main chemical groups: synthetic pyrethroids (Group 3A) and organophosphates (Group 1B). Both are routinely applied against this pest in the grains and grazing industries.

RLEM is most problematic during emergence in grain crops.

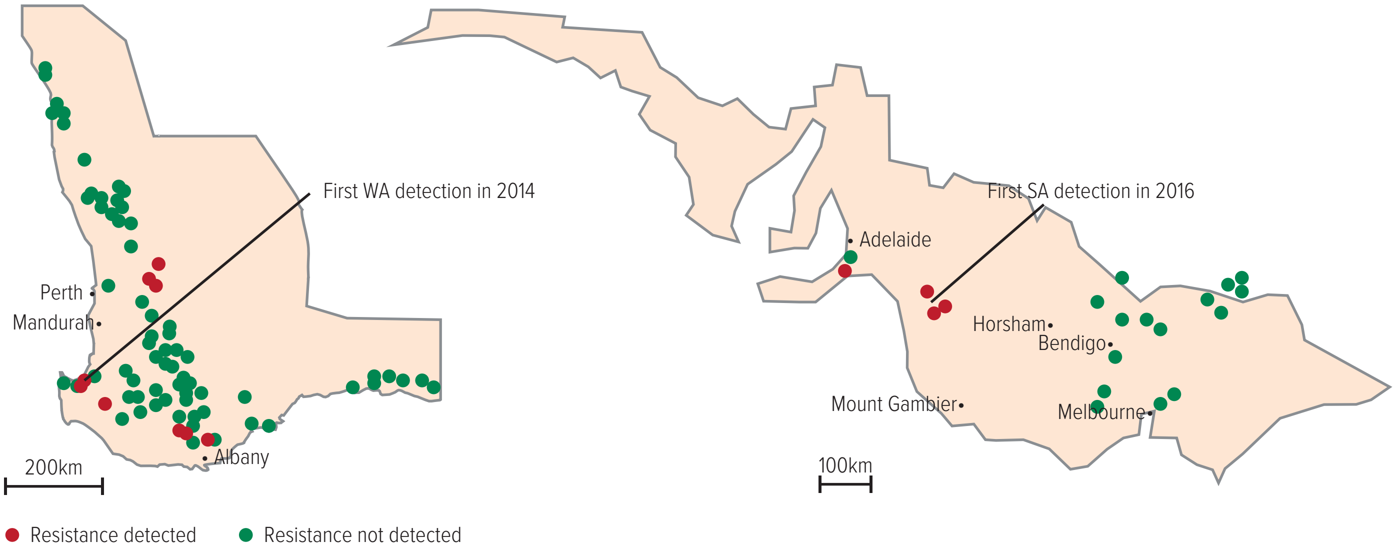
PHOTO: ANDREW WEEKS, **cesar**

FIGURE 1

Pyrethroid resistance (Group 3A) in 2018 in Western Australia, South Australia and Victoria.



Organophosphate resistance (Group 1B) in 2018 in Western Australia, South Australia and Victoria.



In SA, high levels of resistance to synthetic pyrethroids and moderate levels of resistance to organophosphates have been recorded. At the time of publication, insecticide resistance has not been detected in other parts of SA, Victoria, NSW or Tasmania. In the short to medium- term, resistance is likely to become more prevalent in SA, and is expected to arise in other states. It is notable that, at the time of writing, resistance profiling of RLEM populations is continuing through GRDC investment and collaboration between **cesar**, the Western Australian Department of Primary Industries and Regional Development, and CSIRO. These activities will help us continue to build a picture about the current status of insecticide resistance in the grains industry.

The resistance management strategy for RLEM in Australian grains and pastures can be found on the GRDC website – https://grdc.com.au/FS-RLEM-Resistance-strategy.

ECOLOGICAL AND BIOLOGICAL CONSIDERATIONS LINKED TO IPM/RM OPTIONS

RLEM are generally active from late April until early November and typically complete three generations per season. The summer is passed as a diapausing egg in the body of a dead female mite on the soil surface. The majority of diapause eggs are produced in spring; the Timerite® control strategy makes use of the pre-diapausing stages of mites. Summer dormancy is broken, and egg hatch is triggered, by autumn rainfall accompanied by cool temperatures (range 16 degrees C to 20.5°C).

Outbreaks of resistance can be somewhat contained. RLEM movement across the farm is mostly through gradual dispersal as they walk, and typically only by tens of metres in a mite's lifetime. However, longer-range dispersal occurs during the summer via airborne movement of diapause eggs in summer dust storms. Eggs may also be dispersed on soil adhering to livestock and farm machinery and through transportation of plant material, particularly fodder/hay during periods of drought.

Natural enemies of RLEM do exist but their impact, particularly at the beginning of the season, can be limited. A predatory mite, the whirly gig mite (*Anystis wallacei*) was introduced from France in 1965 into WA pastures for the biological control of RLEM. This predator does not spread rapidly and has poor survival under continuous cropping systems and heavy grazing of pastures. Other native predatory mites, for example snout mites, are known to attack RLEM and have been shown to be effective in pasture systems. Strategic manipulation of shelterbelts containing grasses and shrubs can provide a suitable habitat for RLEM natural enemies, which can then move into adjacent paddocks and aid in control.

Green peach aphid (GPA)

THE PEST

In Australia, the green peach aphid (GPA), *Myzus persicae*, primarily attacks canola and pulse crops. It affects all grain growing regions, typically occurring every year or, in some locations, every two to three years. Canola is more vulnerable to GPA attack than pulse crops. It is also a major pest of horticulture (hosts include a variety of vegetables and some fruit tree crops).

The aphids feed by sucking sap from leaves and flower buds. In grains crops, GPA typically cause less direct feeding damage than other aphid species. Direct feeding impacts can occur when populations become large and where they cover most foliage, resulting in retarded growth of young plants. This is uncommon, however, with their status as a disease vector posing a more significant threat.

Young vegetative canola is most susceptible to GPA damage during autumn when GPA increase in numbers in the milder conditions and aphid flights are common. Large infestations of GPA on seedling crops can cause leaf distortion, wilting of cotyledons, stunting of growth, premature leaf senescence and seedling death. Although GPA may be found in canola at later stages, their numbers are usually insufficient to cause significant yield loss.

The aphids' capacity to transmit viruses to early establishing crops is an ongoing challenge for the industry. GPA can transmit more than 100 plant viruses, such as turnip yellows virus (TuYV) – previously known as beet western yellows virus (BWYV) – and cucumber mosaic virus (CMV). Aphids need to feed on the plant to acquire TuYV as well as to transmit the virus. Hence, correctly timed insecticide application can prevent virus transmission.

Aphids' asexual reproductive cycle means all offspring are clones of the mother. For this reason, new GPA resistances can appear widespread in a single season and may occur across Australia over a couple of seasons.

THRESHOLD GUIDELINES

Thresholds for managing aphids to prevent the incursion of aphid-vectored virus have not been established. In practice, few aphids are needed to transmit a viruses to a crop and this may occur before the aphid population is readily detectible.

Economic thresholds for direct feeding damage by GPA have also not been established. In most situations, GPA insecticide treatment to prevent direct feeding damage will not be economic and is not recommended.

Monitor young vegetative canola for GPA. PHOTO: **cesar**

CHEMICAL CONTROL

Five chemical sub-groups are registered to control GPA in grain crops:

- **carbamates (Group 1A, e.g. pirimicarb);**
- **synthetic pyrethroids (Group 3A, e.g. alpha-cypermethrin);**
- **organophosphates (Group 1B, e.g. dimethoate);**
- **neonicotinoids (Group 4A, e.g. imidacloprid); and**
- **sulfoxaflor (Group 4C).**

Paraffinic spray oils are also registered for suppression of GPA.

The majority of canola crops are sown with imidacloprid-treated seed. Only a small proportion of pulse crops are sown with imidacloprid-treated seed.

RESISTANCE STATUS

GPA has evolved resistance to a large number of insecticides globally (over 70 actives across a range of MoA groups).

High levels of resistance to carbamates and pyrethroids are now widespread across Australia, with populations displaying target site resistance. Widespread moderate levels of resistance to organophosphates have been detected, as well as widespread low levels of neonicotinoid resistance. In these cases, populations display metabolic resistance. Sensitivity shifts to sulfoxaflor have recently been found in a small number of GPA populations in Western Australia, showing the potential of low-level resistance evolution to this product.

There are GPA populations found overseas that carry resistance mutations not found in Australia and these represent a biosecurity risk. An economic analysis undertaken by CSIRO in 2015 estimated that an incursion of dual imidacloprid/sulfoxaflor-resistant GPA could lead to economic impact of more than $500 million, based on additional management costs in canola and yield losses (Edwards, 2015).

GPA populations move readily between grains and horticultural crops, especially in regions where both industries operate. In horticulture, application rates of insecticides are much higher than in grains, creating extra selection pressure for resistance evolution.

Ultimately, the use of chemicals to control GPA in oilseed, pulses and horticulture crops continues to grow in Australia, placing strong selection pressure on the evolution of resistance in GPA. As aphids produce cloned offspring, resistant individuals can soon dominate a landscape if there is widespread use of the same insecticide group across paddocks and farms. The grains industry Resistance Management Strategy for GPA takes into account grain grower proximity to horticultural regions and gives advice accordingly.

The resistance management strategy for GPA in Australian grains can be found on the GRDC website – www.grdc.com.au/GPAResistanceStrategy.

ECOLOGICAL AND BIOLOGICAL CONSIDERATIONS LINKED TO IPM/RM OPTIONS

GPA is present all year round with populations typically peaking in autumn and spring in southern grain growing areas. They have many generations each year. Under ideal conditions, the generation time can be less than two weeks. Females give birth to live young (typically five instars before reaching adulthood). The optimum temperature for GPA is about 22°C, with most activity occurring during the warmer, milder months of the year.

Although it has not been measured, it is likely there is broad-scale, wind-assisted movement of winged GPA across Australian regions. However, there is still strong local movement. For example, in winter grain crops, infestations start when winged aphids fly into crops from autumn weeds (for example, roadside vegetation). The spread of viruses occurs when infected aphids disperse and feed on uninfected plants. Limited aphid flight occurs below 17°C, hence there is typically little risk of virus spread during winter.

There are many effective natural enemies of aphids. Hoverfly larvae, lacewings, ladybird beetles, spiders and damsel bugs are common predators that suppress populations in the southern region. Aphid parasitic wasps lay eggs inside bodies of aphids and evidence of parasitism is seen as bronze-coloured, enlarged aphid 'mummies'. Entomopathogenic fungal diseases are also known to be important in causing rapid colony decline in cropping situations where large aphid populations exist.

A mummified aphid. PHOTO: ANDREW WEEKS, **cesar**

Diamondback moth (DBM)

THE PEST

The diamondback moth (DBM), *Plutella xylostella*, is a pest of canola, mustard, brassica vegetables and forage crops. DBM larvae feed on plant foliage, stems, flower heads and pods. The larvae can be found at any stage of canola development, with their numbers often increasing in the lead-up to flowering. Canola can tolerate considerable leaf damage before causing yield loss, but feeding on developing flower buds can be economically damaging. Severe infestations can cause complete defoliation and yield losses of up to 80 per cent in canola.

THRESHOLD GUIDELINES

- **Rosette stage:** more than 50 per cent leaf area damage.
- **Pre-flowering stem extension:** 50 larvae per 10 sweeps (30 larvae per 10 sweeps when crop is under moisture stress).
- **Early to mid-flowering:** more than 50 larvae per 10 sweeps.
- **Mid to late flowering:** more than 100 larvae per 10 sweeps.
- **Pod maturation:** 200 larvae per 10 sweeps.

(NB: all stages of moisture-stressed crops are more susceptible to insect damage.)

CHEMICAL CONTROL

Chemicals remain central to DBM control in canola and also in the forage and vegetable brassica industries. Five chemical sub-groups are registered to control DBM in Australian canola crops: synthetic pyrethroids, organophosphates, spinosyns, avermectins and *Bacillus thuringiensis*.

There are approximately 170 insecticide products registered in Australia for DBM control, but these are primarily from the organophosphates and synthetic pyrethroids. Four newer insecticides with different MoAs are registered for DBM control in brassica vegetable crops.

RESISTANCE STATUS

The use of chemicals in canola and vegetable crops continues to grow in Australia, placing strong selection pressure on the evolution of resistance. DBM has a high propensity to evolve resistance and there are more than 82 insecticide compounds recorded globally to which DBM has evolved resistance.

In Australia, there are high and widespread levels of resistance to pyrethroids and organophosphates (which are generally ineffective), low levels of resistance to avermectins and spinosyns and moderate levels of resistance to diamides in DBM in canola production regions. Higher levels of resistance to the avermectins, spinosyns, and diamides occur in DBM in vegetable production regions.

Because DBM moths can disperse over large distances, resistant individuals can soon dominate a landscape if there is widespread use of the same insecticide group. The movement of DBM between industries and crops including canola (grains), vegetables (horticulture) and forage brassicas (grazing industries) increases the pressure for resistance selection in any one industry. Resistance management is further complicated because, for each of these industries, there is a great disparity in the number of registered MoAs.

The resistance management strategy for DBM in Australian canola can be found on the GRDC website – https://grdc.com.au/fs-resistancestrategydiamondbackmoth.

There are only two synthetic insecticides (spinetoram (Group 5) and emamectic benzoate (Group 6)) and several *Bacillus thuringiensis* var. *kurstaki* products currently registered for use in canola and capable of reliably providing efficacious control of DBM. Even so, resistance to these synthetic MoAs has also been recorded occasionally.

ECOLOGICAL AND BIOLOGICAL CONSIDERATIONS LINKED TO IPM/RM OPTIONS

DBM is a cosmopolitan pest. The Australian climate supports DBM development and reproduction year-round in the cropping zone. Between cropping seasons, resistant DBM populations can persist in local areas on wild brassicaceous plants. DBM typically completes three to five generations per canola growing season, and eight to 12+ generations per year in brassica vegetable crops. DBM infestations in canola generally peak in early to mid-spring. By this time all life stages overlap, making it a difficult insecticide target.

As a pest of brassica crops (canola, mustard, forage brassicas, vegetable brassicas) not surprisingly it also occurs commonly on Brassicaceae weeds, for example, Lincoln weed, mustard weed, turnip weed, Ward's weed, dog weed and other native Brassicaceae.

As canola flowering commences, DBM larvae move to and cause loss of floral buds, flowers and young pods, and later cause scarring of the outer walls of maturing pods. The damage to these reproductive parts can reduce seed number and size. Nonetheless, canola has significant capacity to compensate for defoliation loss. Severe infestations can cause complete defoliation and substantial yield losses (although losses have not been quantified).

There is large scope for the role of invertebrate natural enemies to regulate DBM populations. Three parasitoid wasp species have been successfully introduced to Australia for the biological control of DBM. They supplement a range of native parasitoids and various polyphagous predators (for example, predatory bugs, ladybird beetles, lacewings, spiders, etc.) that provide biotic regulation of DBM.

Outbreaks of the fungal pathogen *Zoophthora radicans* can cause spectacular reductions in DBM populations in canola crops.

DBM numbers increase towards the end of flowering in canola.

PHOTO: DAVID McCLENAGHAN

Corn earworm (also knows as cotton bollworm)

THE PEST

In south-eastern Australia, the corn earworm (*Helicoverpa armigera*) is only an occasional pest of pulses, oilseeds and winter cereals. In comparison to the better known and closely related native budworm (*H. punctigera*), it is responsible for fewer crop issues. Nonetheless it represents a significant challenge for the grains industry given the ongoing reliance on chemical control methods and its resistance status. In addition, the incidence of the pest appears to be gradually increasing in some areas, according to anecdotal information.

Larvae feed directly on flowers, pods and seed heads, for which there are economic thresholds. For high-value consumption pulses, grain quality may also be downgraded at receivals through relatively low levels of damage. The species is most prevalent across all northern grain growing regions of eastern Australia and is usually in lower abundance in the south.

CHEMICAL CONTROL

There are over 200 insecticide products registered in Australia against corn earworm for grain, cotton and vegetable crops. The majority of available insecticides are from three chemical groups with broad-spectrum activity: carbamates, organophosphates and synthetic pyrethroids. There are an additional three registered insecticide MoAs that are selective for *Helicoverpa* spp. and to which there is low or no resistance: emamectin benzoate, indoxacarb and diamides (chlorantraniliprole). These have become more widely used in pulses due to their high efficacy and relatively low impact on beneficial insects.

RESISTANCE STATUS

Corn earworm has evolved some level of resistance to the three chemical groups with broad-spectrum activity (organophosphates, carbamates and pyrethroids).

Historically, it is this resistance that caused devastation in the cotton industry prior to the introduction of genetically modified (GM) cotton. The use of chemicals to target *H. armigera* in grain crops continues to grow in Australia, placing strong selection pressure for the evolution of resistance in some of the more selective products. There have been resistances detected (low to very low incidence) in other registered MoAs including spinosyns, *Bacillus thuringiensis* (Bt), indoxacarb and the diamides. The fact that resistances are present is a concern, even though they are not yet resulting in widespread chemical control failures.

The resistance management strategy for *Helicoverpa armigera* in Australian grains can be found on the GRDC website – https://grdc.com.au/GRDC-FS-Helicoverpa-resistance-management.

Corn earworm larvae feed directly on flowers, pods and seed heads.

PHOTO: ANDREW WEEKS, **cesar**

ECOLOGICAL AND BIOLOGICAL CONSIDERATIONS LINKED TO IPM/RM OPTIONS

In temperate and cool climate zones, the majority of corn earworm overwinter (diapause) from mid-March until mid-spring. Emergence from diapause in October onwards initiates the first of two to four generations per season in southern regions. The lifecycle (egg to adult) is typically 42 days at 25ºC. In spring and autumn, it takes over eight weeks to complete a single generation.

Unlike the native budworm, corn earworm infestations more typically arise from local dispersal, although the species is capable of long-range migration. Corn earworm is thought to breed locally in southerly or coastal regions of SA and Victoria. Corn earworm moth immigrants are occasionally reported in northern Tasmania, but they are not known to establish beyond one or two generations.

Common weed hosts for corn earworm include Paterson's curse (*Echium plantagineum*), Verbenaceae spp., Malvaceae spp. and great mullein (*Verbascum virgatum*).

There are many effective natural enemies of corn earworm. These include predatory beetles such as ground beetles and the larvae of various species of lady beetles; predatory bugs such as assassin bugs and various species of shield bugs; lacewing larvae; spiders; hoverfly larvae; larval parasitoids including various species of wasps, and tachinid flies; and egg parasitoids including Trichogramma wasps.

Pathogens available commercially as biopesticides include formulated products of nuclear polyhedrosis virus (NPV) and the bacterial toxins from Bt. Entomopathogenic fungi are also being investigated for future commercialisation.

There is significant pressure on chemicals for corn earworm given resistance status. PHOTO: ANDREW WEEKS, **cesar**

Risk analysis of future resistance threats to the industry

Estimating resistance risk in grains pests

The risk of resistance arises from the evolutionary or genetic basis of resistance and the extent to which a pest species may be exposed to insecticides. Therefore, this analysis of future risks used several steps of filtering and ranking to estimate resistance risk for 80 common Australian grains pests in Australia. The steps included consideration of evolutionary potential, targeted and off-target insecticide pressure, and the availability of pest refuges. Resistant pests were included in this analysis to ground truth the predictions.

Firstly, **evolutionary potential** for resistance was considered using a recently developed model for pests in the US. The model estimates evolutionary potential using biological traits of pests such as pest taxonomy, host plant feeding patterns and rate of reproduction. This helped to identify 26 of the highest-ranking grains pests that occur in the southern grains region.

Secondly, **targeted insecticide usage** was considered through pest severity, which was assumed to be an indicator of the number of insecticides the pest would attract. Here, pest incidence/severity was based on the total number of pest reports recorded on the PestFacts Map database (where all pest reports to **cesar** or SARDI from SA, Victoria and NSW have been recorded since 2006).

Thirdly, an alternative measure of insecticide usage was used that was assumed to reflect both **targeted and non-target insecticide usage**. The value of commodity production was used as a proxy for chemical usage; this assumes a higher-value crop is associated with higher insecticide usage. This chemical usage proxy was scaled by the frequency of association between the crop type and pest to estimate selection pressure and thus resistance risk. To estimate the association between each grains crop (commodity) and pest, a matrix of pests by commodities was built and assigned a score for the frequency (1–10) of the pest–commodity association, to account for variation in the regularity a pest is found in a given commodity at levels relevant to selection (for example, RLEM is only occasionally problematic on wheat).

Finally, the availability of non-sprayed plant hosts (**pest refuges**) was estimated for each pest by classifying them into either exotic/cosmopolitan or native classes, assuming native pests have a broad native host range outside the cropping zone where insecticides are rarely, if ever, applied (and susceptible gene refuges are maintained). Table 3 provides the individual ranking or assessment against each of these steps.

To rank the pests from highest resistance potential to lowest, the mean ranking of the first three steps was taken and then filtered by step four. Not surprisingly, the rankings placed pests that have already acquired resistance at the top (within the top four), which supports the rationale behind the analysis. These were GPA (rank 1), RLEM (rank 3) and diamondback moth (rank 4). The exception was corn earworm, probably because the effect on cotton production was not considered in this grains-specific analysis.

Native budworm and Rutherglen bug were initially rank 7 and rank 11 respectively, however using step four, native invertebrates were omitted from the final list because they breed so commonly on native and weed hosts which are not subjected to any insecticide selection pressure, thereby diluting resistance selection.

Pests at risk of evolving resistance

The analysis conducted here is preliminary and should not be viewed as a definitive list of pests at risk of resistance evolution in Australian grains. More sophisticated approaches that consider other biological and agronomic variables, as well as the interplay between insecticide exposure across different commodities in Australia, are warranted. Nonetheless, there are useful predictions that serve as an important reminder that resistance is an incredibly dynamic evolutionary process in invertebrates. From within the top nine ranked pests (Table 3), those that are at greatest risk of acquiring resistance are oat aphid, lucerne flea, cabbage aphid, cowpea aphid and the European earwig. Oat aphid ranks highly because of the sheer area of wheat (and other crops) that can receive non-selective aphid sprays. Cowpea aphid (pulses) and cabbage aphid (canola) are also strong resistance candidates because they can be unintentionally sprayed when crops are sprayed for other pests like native budworm, Etiella and diamondback moth. Lucerne flea and earwigs (poor dispersers) are invariably present in or under most crops, sometimes in low numbers, but would regularly be exposed to insecticides when a crop is sprayed for other pests.

TABLE 3 The top nine grains pests selected for their evolutionary potential to acquire resistance. These pests are assessed against four criteria.

Common name	Scientific name	Dominant crop stage	Evolutionary potential rank[§]	Targeted insecticide rank[§]	Target and off-target insecticide rank[§]	Mean rank
Green peach aphid*	*Myzus persicae*	Establishment	1	5	3	3.0
Oat aphid	*Rhopalosiphum padi*	Vegetative	7	7	1	5.0
Redlegged earth mite*	*Halotydeus destructor*	Establishment	17	1	2	6.7
Diamondback moth*	*Plutella xylostella*	Flower/seed	4	4	13	7.0
Lucerne flea	*Sminthurus viridis*	Establishment	14	2	7	7.7
Cabbage aphid	*Brevicoryne brassicae*	Vegetative	8	9	8	8.3
Cowpea aphid	*Aphis craccivora*	Vegetative	2	8	16	8.7
Corn earworm*	*Helicoverpa armigera*	Repro	3	18	9	10.0
European earwig	*Forficulia auricularia*	Establishment	19	12	4	11.7

§ Numbers provide the pest ranking for each of the three criteria.
*These pests have already acquired resistance to some MoAs.

Cabbage aphid *(Brevicoryne brassicae)* on canola. Adult and nymphs.

PHOTO:ANDREW WEKS, cesar

Best management practices for control

3.1 Integrated pest management and resistance management

IPM, in its simplest form, is a control strategy that combines a variety of biological, cultural and chemical control practices to manage and prevent pests (invertebrates) from reaching damaging levels in crops. The integration of a range of effective, economic and sustainable pest management tactics to deal with pests replaces the reliance on any single control method, particularly chemical use, to give stable long-term pest control. The sole reliance on chemical control for pest management is not a sustainable long-term solution. The most effective way to minimise and/or manage insecticide resistance is through the adoption of IPM and strategically rotating chemicals (between different MoAs) when they are warranted.

IPM does not mean the abandonment of insecticides – it aims to reduce the frequency of insecticide applications. In this way it reduces the chance of resistance arising in a pest population. Insecticides within an established IPM framework are tools used to assist in pest control when biological and cultural control methods are insufficient.

IPM principles involve a sound understanding of pest biology, the natural enemies of pests, and pest interactions within the farming system to allow the most appropriate use of a variety of control tactics. These control tactics generally fall into the following categories:

- Assessing **pest identity** and risk prior to seeding, in the previous season or in early autumn, enables IPM tactics to be applied consistently with the risk.
- Making best use of **natural enemies and biological control** involves the conservation of natural enemies (predators, parasites and pathogens) that feed on or attack pests (for example, control of canola aphids by ladybird beetles and lacewing predators).
- Suppressing pests through **cultural and physical control** – tactics such as crop rotation, trap cropping (using 'sacrifice' crops to attract pests), crop hygiene, removal and destruction of weeds (for example, 'green bridge') and volunteer plants, planting/harvest date selection, site selection, resistant cultivar and variety selection and nutrient management. Tactics can also include the incorporation of nectar-producing plants to encourage natural enemies and the use of barriers such as windbreaks and physical disturbances of the system (for example, mowing, grazing, ploughing and inter-row cultivation).
- Using **insecticides strategically** means decisions on the use of chemicals to control pests should be made after pest monitoring and the use of economic thresholds. Where applicable, the use of selective chemical options that are specific to target pests and relatively harmless to natural enemies (for example, pirimicarb for aphids, Bt for caterpillars and insecticide baits for beetle pests) should be used in preference to broad-spectrum insecticides.

3.2 IPM in the grains industry

Many growers are adopting aspects of IPM and are increasingly aware of the impact of chemicals on the environment and their negative effects on beneficial invertebrates. In general, there is an attitude to increase IPM adoption, use fewer insecticides, manage resistance risk and improve knowledge of beneficial invertebrate species and the roles they play in cropping systems. However, some growers perceive the costs and complexity of adopting IPM in a multi-pest system as a major barrier. Indeed, the relationships between agronomic practices, pests, agrichemical use and the role of beneficials are complex and often incur higher short-term operational costs than the sole use of insecticides. There are a number of constraints to the uptake of IPM among growers.

Logistical constraints

Practical and logistical constraints can limit IPM opportunities and uptake. Examples include the following:

- The pest complex at crop establishment can be particularly challenging and many insecticide decisions are often made prior to sowing (prior to pests being detected). This is sometimes based on risk assessments (for example, history of resident pests, climate and type of break crop) or just as insurance.
- Pest considerations are generally lower in priority than agronomic weed and disease management considerations (for example, rotation, sowing times, varieties), which can reduce flexibility. IPM implementation requires time and know-how to monitor the cropping system, since there are often different control methods for each pest.
- There is a lack of practical monitoring methods for large-scale farming and many growers find it challenging to monitor emerging crops during busy seeding programs.
- Low-disturbance farming systems create a more favourable habitat for some pests and reduce opportunities for mechanical disturbance (for example, stubble management) during non-crop periods. For example, 'pupae busting' for *H. armigera* pupae (used widely in the cotton industry) in soil is not a compatible tactic in no-till situations.
- Invertebrate pests can reduce grain yield but also grain quality; in some pulse crops, low market tolerance for partially chewed grain leads to a nil tolerance for certain invertebrate pests in crops, precluding a threshold-based approach.
- Selective insecticides are only available for some key pests, so when there are multiple pests in the system this can lead to the use of broad-spectrum insecticides, which are detrimental to the beneficial insects.
- Limited access to different MoAs makes it difficult to develop insecticide rotation strategies.

Knowledge/attitudinal constraints

Identified knowledge and attitudinal constraints to uptake include the following:

- Those involved in IPM need to understand the methods available and be knowledgeable about effective natural enemies for the suite of pests present on each crop.
- For some pests, only limited information exists on biology, ecology and economic thresholds.
- Many growers lack practical knowledge and/or confidence in the IPM approach or perceive the implementation of an IPM multi-pest system as too complex.
- Many large-scale growers outsource crop protection to their advisers, who can understandably take a risk-averse approach to avoid potential crop damage, the additional costs in monitoring and the use of more expensive (selective) insecticides. Thus, insecticide applications are sometimes made at non-optimal times (or unnecessarily) to coincide with the other farming operations (such as fungicide, herbicide or nutrient applications).

Despite these constraints, IPM has been successfully trialled and adopted by a small number of grain growers in the southern region (Horne et al. 2008), demonstrating these obstacles are not insurmountable.

IPM is not a cut and dried process. Given that an IPM approach seeks to draw on a variety of control practices to manage (but not necessarily eliminate) pests, taking small steps to reduce insecticide usage is a good place to start, particularly in the context of resistance management. Growers who use IPM often start on a smaller scale, splitting off an area of the property where they may test IPM principles in a low-risk situation and increasing the scale as knowledge and confidence grows.

As independent consultant, Bill Long (from Yorke Peninsula SA), says:

"Short-term economics does not need to be the main driver behind adoption of IPM principles. Many growers are keen on IPM for the social and environmental benefits it brings. For example, growers generally do not like using insecticides. They know they're dangerous chemicals to handle and apply, and recognise there is a higher health risk associated with their use. Any system which enables growers to use less insecticide less often is going to be very popular.

Growers are also very conscious of the impact of most of these chemicals in the natural environment, and as good stewards of the land, they're seeking alternatives. Growers are also increasingly aware it's not a good practice to kill beneficial insects which can prey on pest insects. In days gone by, growers pretty much saw almost every invertebrate as a pest, but many are now learning to recognise beneficial species and the roles they play in cropping environments, and how to keep the balance."

The views above are more generally recognised from grower surveys and industry workshops undertaken on behalf of GRDC. This includes a recent focus group analysis, undertaken as part of a GRDC project supporting the sustainable use of insecticides and local on-farm implementation of integrated pest management strategies in the GRDC southern region. Through these focus groups, it was recognised that the following values drive interest and uptake in IPM:

- responsibility for land and environment;
- continuity of farming and family tradition;
- rewards and demonstration of success; and
- passion for agriculture and pride in quality products.

3.3 Planning and risk assessment

A range of factors can influence the likelihood of particular pest outbreaks and the decisions about the most appropriate options for pest management. For example, paddock history and summer rainfall are both very strong predictors of many crop establishment pests. By factoring in this information, several valuable tools that are useful for IPM decision making become available.

'Best bet' management options (which utilise pest risk assessments) have been developed for earth mites, aphids (particularly GPA) and DBM (see Appendix 1). These summarise the range of IPM activities available to mitigate the risk of damage and the circumstances that may lead to low-risk situations (where insecticide usage is unnecessary).

In assessing risk, correct identification of pests is critical. Misidentification can lead to inappropriate insecticide use and a potential control failure. For detailed information and tips on key features to identify key pests, and to distinguish similar-appearing pests, see the grains industry *I SPY* manual. Within the grains industry, identification can be verified through the National Pest Information Service, a consortium of grains industry invertebrate pest experts that provide identification support. National Pest Information Service providers produce the regionally based publications *PestFacts south-eastern*, *PestFacts South Australia*, *PestFax*, and *The Beatsheet*, which provide guidelines on best methods to submit samples for identification.

3.4 The role and management of beneficials in minimising pest pressures

3.4.1 BENEFICIALS IN CROPPING SYSTEMS

There are three distinct groups of invertebrate beneficials that can be found in crop systems, each playing an important role in crop health. They include:

a) **crop pollinators** (invertebrates that pollinate oilseed and pulse crops, such as European and native bees and some flies);

b) invertebrates that **engineer** the soil (such as earthworms, ants, termites, mites and springtails) by increasing water infiltration, nutrient mobilisation and weed seed destruction; and

c) invertebrates that are the **natural enemies** of crop invertebrate pests. Natural enemies include predators such as spiders, lady beetles, ground beetles (carabids) and hoverfly larvae; parasitoids which include many large to very small wasps and flies; and pathogens that cause invertebrate diseases.

Predators consume vast amounts of prey over the course of their development. They are free-living and are usually as big as, or bigger, than their prey. Predators may be generalists, feeding on a wide variety of prey, or specialists, feeding on a few closely related species.

Parasitoids are similar to parasites, but where true parasites usually weaken but rarely kill their hosts, parasitoids always kill the host insect. In contrast to predators, parasitoids display a high level of host-specificity, and develop on or within a single host.

Pathogens are diseases that attack pest insects. Pathogens of agricultural pests are usually bacterial, fungal or viral.

A key aim of an IPM approach is to reduce the impact of insecticides on all three groups of these beneficial invertebrates. Most importantly, natural enemies provide a cornerstone to IPM and the sustainable pest management of most/many key pest groups. They work to naturally lower pest numbers and thereby reduce the required number of insecticide applications, which in turn extends the time to chemical resistance and reduces costs for growers.

There are many naturally occurring species that keep pest invertebrate populations in check. These natural enemies play a vital biological control role in many cropping systems. Some species are transient – moving in and out of crops, often following the movement patterns of pests, while others are resident – permanently living within the system and usually having limited dispersal capabilities.

The lifecycle and seasonal activity of different natural enemies varies markedly. Some resident species like ground beetles and spiders have an annual lifecycle and so can be quite effective in the early stages of the crop cycle, although their populations can be devastated by early season foliar insecticides. The more transient species like hover flies, parasitoids and lady beetles gradually accumulate in the crop over winter and early spring, when their impact becomes noticeable.

Further resources on natural enemies of grain crop pests can be found in the grains *I SPY* manual and in the GRDC's *Beneficial Insects – The Back Pocket Guide*. The key natural enemies of crop pests in the southern region are listed below.

a. Natural enemies of RLEM

RLEM have a range of natural enemies, including mite predators (the most important predatory group, as detailed below). These predators are most effective in stable, pasture-based systems where their populations can grow enough to regulate pest populations. However, during the cropping phase, particularly during the establishment of winter crops (autumn and early winter), generally predators are not able to reliably suppress damaging mite populations below economic thresholds.

Snout mite

There are several species of snout mite, including the pasture snout mite and the spiny snout mite. Adults have bright orange-red bodies with eight legs. They are 2 to 3 millimetres long and have a very pointed snout (mouthpart). Nymphs are similar, but are smaller and have only six legs. Snout mites are highly mobile and fast moving. They pass through several generations per year. They are most commonly observed in grains crops from autumn until spring.

Snout mites are distributed throughout most of Australia and can be found in a variety of habitats. They are predators of all earth mites, lucerne flea and other springtails (Collembola).

Other mite predators

Like the snout mites, the introduced Anystid mite is also red-bodied, is 3mm in length, and moves in a circular motion earning its common name, the 'whirly gig mite'. There are also a number of native Mesostigmata mites that grow to 4mm in length and are brown in colour. These feed on earth mites but are less effective consumers of mites than are Anystid mites.

b. Natural enemies of GPA

Aphid parasitic wasps

There are many different wasp parasitoid species in the Aphelinidae and Braconidae families that attack pest aphids. Aphid parasitoids are minute wasps (2 to 3mm long), very slender and brown to black in colour. Females lay their eggs into the bodies of live aphids (usually wingless), eventually killing them. The immature parasitoids develop within the aphid body before emerging as adults. In crops, the activity of aphid parasitoids is seen as aphid 'mummies', which look like swollen, bronze-brown coloured, motionless aphids. In winter-grown crops, suppression of aphid populations by parasitoids is most common from late winter through spring, although their effect can be limited if broad-spectrum sprays are applied, or if the aphid populations enter a rapid growth phase.

Parasitism is only visible in the later stages of parasitoid development. If mummified aphids make up 10 per cent of the total aphid population within a paddock, it is likely the majority of the remaining aphids have also been parasitised. This is an indication the population is likely to crash within two weeks.

Aphid parasitoids are specialists, usually attacking just a single pest species. They can only live where and when their host occurs. Adults live several weeks and pass through many generations a year. Aphid parasitoids are found throughout rural and urban Australia. They are commonly observed in southern crops in spring and summer.

Brown and green lacewings

Adult brown lacewings are mottled brown in colour and 6 to 10mm long, while adult green lacewings are 15 to 20mm long and pale to bright green in colour. Both have prominent eyes and long antennae. Their clear membranous wings are typically folded in an upside-down v-shape and are large with numerous veins, giving a lacy appearance.

Lacewing larvae have prominent legs and distinctively protruding sickle-shaped mouthparts. They lack wings and have bodies that are long and tapering but can vary from thin to stout in shape. In addition to GPA, they feed on soft-bodied insects found on vegetation and the soil, including other aphids, caterpillars, thrips, mites and moth eggs. They are commonly observed in southern crops in spring and summer.

Brown lacewing adults are mottled brown in colour and 6 to 10mm long.

PHOTO: ANDREW WEEKS, **cesar**

Lacewing larvae have prominent legs and distinctively protruding sickle-shaped mouthparts. PHOTO: ANDREW WEEKS, **cesar**

Lacewing larvae are commonly observed in spring and summer.

PHOTO: ANDREW WEEKS, **cesar**

Green lacewing adults are 15 to 20mm long and pale to bright green in colour.

PHOTO: ANDREW WEEKS, **cesar**

Hoverflies

Adult hoverflies are 4 to 7mm long. They have very distinct eyes, dark-coloured flattened bodies with black and yellow bands (like bees) and have only one set of wings. As the name suggests they 'hover' over objects, feeding on the pollen and nectar of flowers and scouting for oviposition sites. They look similar to bees or wasps, however they do not have a constriction between the thorax and abdomen and their antennae are much smaller. Hoverfly larvae are blind, legless maggots that are green in colour, with a pale stripe running down the back, and are 8 to 10mm long. They are often mistaken for pest caterpillars such as diamondback moth (further emphasising the importance of correct identification) and have a voracious appetite for aphids.

Hoverflies are found throughout Australia. In addition to GPA they attack a range of soft-bodied insects, although they prefer aphids. They are common in flowering crops such as canola, pasture paddocks and on some roadside flowering weeds, and are often observed in southern crops in spring and summer.

Hoverfly larvae are blind, legless, maggots that are green in colour and 8 to 10mm long. PHOTO: ANDREW WEEKS, **cesar**

Hoverflies attack soft-bodied insects but prefer aphids. PHOTO: **cesar**

Ladybird beetles

There are numerous types of ladybird beetles, but three species commonly found are the white collared ladybird, the common spotted ladybird and the transverse ladybird. Adults are round to oval shaped, with black spots on red, orange or yellow shells. Larvae have grey/black elongated bodies with orange markings and may be covered in spines or white fluffy wax material. The egg to adult stage takes three to four weeks, and adults can live for several months.

Ladybird beetles are found throughout Australia. Both adults and larvae are predatory. In addition to GPA, they feed on other aphids, thrips, mites, moth eggs and small caterpillars. They are found in all crops and commonly observed in southern crops in spring and summer.

Both adult and larvae ladybird beetles are predatory. PHOTO: GRDC

Larvae have grey/black elongated bodies with orange markings and may be covered in spines or white fluffy wax. PHOTO: ANDREW WEEKS, **cesar**

A parasitoid wasp lays its eggs into the developing larvae of the Diamondback moth. PHOTO: ANDREW WEEKS, **cesar**

c. Natural enemies of DBM and corn earworm caterpillars

Parasitoid wasps and flies of caterpillars

There are many species of ichneumonid and braconid wasps (more than 20) that attack pest caterpillars, although several species of the parasitic tachinid fly are also common. Adult wasps vary greatly in length from 2 to 30mm long; flies vary from 5 to 10mm in length. The wasps are highly variable in colour, have elongated and slender bodies and possess long antennae. The flies resemble houseflies, although they have distinct bristles on their abdomen. Many adult wasps and flies rely on nectar (from neighbouring vegetation) for sustenance.

The wasps lay their eggs inside caterpillars while fly adults lay their eggs in or on caterpillars. The parasitic larvae hatch and feed inside the caterpillar and either pupate inside or outside, killing the caterpillar as they emerge. Some wasp and fly parasitoids specifically parasitise pupae.

Most species of parasitoids attack a range of caterpillar pests, while others are highly host-specific. Adults live several weeks and pass through many generations a year. Caterpillar parasitic wasps and flies are found throughout Australia. They are observed in southern crops throughout the year.

Parasitoid wasps of moth eggs

There are several species of the Trichogramma and Teleonomus wasps that are specific parasitoids of moth eggs. Egg parasitoids are difficult to see because of their small size (0.4 to 0.8mm), smaller than a pinhead and even smaller than the size of a moth egg. These wasps are brown or yellowish with red eyes.

Egg parasitoids kill their hosts before larval hatch, thus preventing crop damage by emerging caterpillars. Hence, their activity is rarely noticed. If parasitised, these eggs will turn black and one to three adult wasps will emerge in about 10 days. Egg parasitoids are found throughout crops and on the edge habitat of crops and remnant vegetation, making them susceptible to broad-spectrum insecticides. Small populations are found in native vegetation which in some areas serve as an overwintering habitat.

Predatory shield bug

There are several species of shield bug (such as spined predatory shield bug and the glossy shield bug) that vary in size and shape. Adults are 10 to 15mm long and have shiny, shield-shaped bodies, often with patterns and spikes, and the wings distinctively cross on their backs. Nymphs are dark red and brown with the early instars being bright red. There are multiple generations per year and adults usually live for several months.

Predatory shield bugs are found throughout Australia, most often in the canopy of crops. Adults and larvae use their piercing/sucking mouthparts to feed on caterpillars and moth eggs. They are seen year-round on weeds and native vegetation, and in crops infested with moth larvae. They are commonly observed in southern crops in spring and summer.

Damsel (or Nabis) bug

Adult damsel bugs are 8 to 12mm long, have a slender light-brown body, with a narrow head, large protruding eyes and long antennae. The snout is fine, curved and carried under the body when not feeding. Damsel bugs move quickly when disturbed. Juveniles (nymphs) are similar but smaller in size and without wings. They are common throughout Australia and generally found in the canopy of crop plants. In addition to DBM and corn earworm, they are predators of other caterpillars, aphids, leafhoppers, mites and mirids.

Damsel bugs are commonly observed in southern crops in spring and summer. Adult damsel bugs may be found on weeds, winter crops and perennial crops such as lucerne.

Damsel bugs are 8 to 12mm long move quickly when disturbed.

PHOTO: J WESSELS, QDAF

Other natural enemies of caterpillar pests and moth eggs

Brown and green lacewings and ladybird beetles attack and destroy moth eggs, and small caterpillars and hoverfly larvae will attack small caterpillars (for more details, see Natural enemies of GPA). Most generalist predators, such as ground beetles, spiders and earwigs, will consume moth eggs and caterpillars, particularly as these fall or crawl to the ground.

d. Generalist predators

Carabid (ground) beetles

Adult carabid beetles are variable in size and shape. They typically range from 5 to 25mm in length, but a few species can be larger. Adults have flattened 'hot water bottle' shaped bodies, large bulging eyes on the sides of the head and prominent mouthparts that protrude forward. They are flightless nocturnal beetles. Larvae can be confused with wireworms as they are similar in shape and are soil dwelling. Both adults and larvae move rapidly. Carabid beetles often only have one generation per year, so populations can take more than a year to re-establish after the use of insecticides. Carabid beetles are found throughout Australia, more so in undisturbed habitats. Larvae and adults are predatory and feed on ground-dwelling soft-bodied prey such as caterpillars, aphids, mites, wireworms, earwigs and slugs. They are observed in southern grains crops year-round.

Spiders

Spiders are highly diverse and abundant predators with at least six groups commonly found in grains crops. These include the wolf, huntsman, trapdoor, jewel, flower and jumping spiders. Some are hunters (ground-dwellers), while others are active in the crop canopy and are generally web-builders. Most species live more than one year, with annual breeding cycles. Spiders have eight legs and vary in size from 1 to 150mm long. Spiders are commonly found throughout Australia in urban and cropping environments. They are effective predators of most invertebrates including aphids and caterpillars. They are observed in southern grains crops year-round.

Native earwigs

Native earwigs are similar to European earwigs but are reddish-brown with darker abdomens and pincers. They are widespread and feed on leaf litter, as well as attacking other insects. There are many species in Australia. The most effective predatory species, the common brown earwig, has an orange triangle behind its head on the wing case. They are nocturnal, probably have one generation a year and adults are approximately 35mm long. Earwigs are commonly observed in southern grains crops from autumn to summer and are common over most of Australia, particularly in sandy habitats, and can be found in colonies under timber, stones or mulch. They are predators of soft-body invertebrates, including caterpillars, mites and aphids. European earwigs, best known for the damage they cause in emerging crops, are omnivorous and capable of feeding on small soft-bodied pests. (It should be noted that earwigs can be omnivorous – and act both as pests and natural enemies. Refer to PestNotes to read more about earwigs).

Native/common brown earwigs can cause damage in emerging crops, but can also act as natural enemies.

PHOTO: GRDC

3.4.2 CONSERVING AND MANAGING BENEFICIALS

Insecticide selection

In part, IPM strategies aim to balance the contribution of beneficials with the need to protect the crop from significant loss. The terms 'soft' or 'selective' are frequently applied to insecticides (active ingredients) that kill target pests but have minimal impact on non-target organisms.

> **Where insecticide use is warranted (based on monitoring and the use of thresholds), it is preferable to choose the most selective or 'soft' insecticides (for example, biopesticides such as Bt sprays and NPV for caterpillars, synthetic insecticides such as pirimicarb for GPA, and chlorantraniliprole for corn earworm) that are less harmful to beneficial invertebrates. Broad-spectrum insecticides invariably kill many non-target organisms like beneficials, which can lead to pest flare-ups later in the season.**

In practice, there are varying degrees of 'softness' and some insecticides are selective or safe for one group of natural enemies but not another. A guide to the relative harshness or softness of major chemical groups is shown in Appendix 2. Unfortunately, soft chemical control options are not available for all pests and selective insecticides are not always expected to provide 100 per cent mortality of the target pest, but aim to suppress population numbers, allowing biological and cultural methods to further contribute to keeping pest numbers at acceptable levels. They are also more expensive than the broad-spectrum alternatives.

Biopesticides are often the softest options. Bt (*Bacillus thuringiensis*) is a naturally occurring bacteria which produces spores that contain an invertebrate toxin. There are a number of different strains of Bt, each usually specific to an invertebrate group. The major advantage of Bt is that it is essentially non-toxic to people and animals. Bt-based insecticides are often applied as liquid sprays on crop plants, where the insecticide must be ingested to be effective. Bt is susceptible to degradation by sunlight. Most formulations persist on foliage less than a week following application. Rain or overhead irrigation can reduce effectiveness by washing Bt from crop foliage. Bt is most suited for small caterpillars, including DBM and corn earworm, less than 5 to 8mm in length, but not large caterpillars (over 5 to 8mm in length).

Nuclear polyhedrosis virus (NPV) is a viral disease of native budworm and corn earworm caterpillars that occurs naturally in the Australian environment. The commercial NPV product can be used in a variety of field crops, including all pulses and cereals. NPV is an excellent product for corn earworm management, not only because it is very effective (frequently giving more than 90 per cent control) but because it preserves the full range of beneficial insects in the crop (such as Microplitis and Trichogramma wasps).

Insecticide seed dressings (such as Gaucho®, Cosmos® and Poncho® Plus) may also be an alternative control option; these are relatively more directed at the pest than foliar sprays and smaller quantities of chemical are applied per hectare. They are also popular because they persist for longer than foliar sprays and can offer a wider spectrum for controlling other pests. Their use may delay the need for applications of foliar sprays, giving beneficial insects time to build up. Nevertheless, seed dressings should only be used if the risk of potential pest pressures is high. They are not benign to beneficial invertebrates and the risk of resistance development to seed dressings is significant.

Native vegetation – promoting and enhancing beneficial numbers

Perennial native vegetation is an important alternate habitat for beneficials. The stability of perennial vegetation provides habitat (shelter, flowers/nectar, alternative hosts) otherwise not found in cropping fields, especially when in fallow. While pest species can be found in native vegetation, most pests do not persist on native hosts, so native vegetation has a low risk of contributing to pest numbers. Areas containing native vegetation (grasses, shrubs and trees) such as fenceline tree plantings, windbreaks, riparian corridors, open grasslands and roadside verges all provide habitat for beneficials.

Landscape ecology can be manipulated in such a way that promotes natural enemies and aids IPM strategies. The use of windbreaks in providing a reservoir for key functional invertebrates and their impact on pest species is a relatively new area being examined. Research has demonstrated that pest numbers, including (but not limited to) RLEM, in adjacent paddocks can be reduced by predators and other beneficials having the option of sheltering in windbreaks.

The plant composition of windbreaks is important, with long grasses, shrubs and flowering plants offering complexity and nutrition sources for adult beneficials, such as the hoverfly. Complexity in turn provides more niches for important beneficial invertebrates such as spiders, predatory mites, parasitoids and pollinators. Thus, relatively simple measures, such as management of windbreak understorey, can be used to maximise the use of naturally occurring biological control.

Monitoring for beneficials

Factoring in the contribution, or potential contribution, of beneficial insects (natural enemies) to a management decision is not easy. Identifying which ones might have an impact on the pests in that crop and estimating how much impact they might have is important when determining whether beneficials are likely to suppress the pest population below threshold, or whether you will need to treat the pest infestation to prevent crop loss. It is possible to monitor the presence and activity of some beneficial species, particularly larger predators and some parasitoids. Monitor for these beneficials at the same time as monitoring for pests. In general, the same sampling techniques will work for both pests and beneficials.

Beneficial species that are very small, that are active at night or that dwell below ground can be difficult to monitor. IPM Guidelines for Grains provides some handy indicators of key beneficial invertebrate activity in crops.

Approaches to better manage beneficials

- Tolerate some pest damage early in the season (beneficials require prey as food).
- Delay spraying if the beneficials are increasing at a comparable or faster rate than pests and if pest damage is below economic threshold levels.
- Leave some areas unsprayed if these areas are harbouring beneficial species.
- Spray late evening to minimise direct exposure to some beneficials.
- Use refuge areas (such as shelterbelts with shrubs/trees) or nursery crops, which help to conserve sources of natural enemies.

3.5 Cultural and physical control

Cultural and physical practices for pest control were utilised long before the advent of chemical control methods. The goal is to make the crop environment less suitable for invertebrate pests, or spatially manipulate pest populations by agronomic practices to prevent them establishing where they may cause crop damage.

These practices can minimise pest attack for many crop pests and achieve partial or complete pest control. Their effectiveness is often underestimated and not fully utilised. Where appropriate, specific examples have been drawn relating to RLEM, GPA, DBM and corn earworm.

Removal of green bridge

'Green bridge' refers to the role that weeds and volunteer crop plants play in helping pests cross from one cropping season into the next. Late summer or early autumn rainfall can trigger the establishment of green bridges in areas where winter cropping dominates. Resulting weeds often provide pests with a food source that allows them to develop and increase. They can also increase the risk of disease (particularly viral if the host supports both the virus and the vector). For example, brassica and other broadleaf weeds (such as wild radish, wild turnip, capeweed, volunteer canola and lupins) are preferred hosts for GPA and can act as a green bridge for both the aphids and turnip mosaic virus (TuMV). To reduce the risk of virus transfer into a new crop of canola, the weeds need to be removed three to four weeks prior to planting. A similar approach is recommended for cereal aphids and associated viruses which can be propagated in green bridges of grasses.

Ideally, eradicating green bridges should be an area-wide effort and should involve good communication between growers and with local governments. If control occurs only on individual farms, insects can move into crops from neighbouring properties.

Crop rotation options

Some crop plants can be resistant or susceptible to invertebrate attack and can be used in rotations when pest numbers threaten to be high. For example, chickpeas deter most invertebrates (including RLEM) except *Helicoverpa* through high levels of malic acid in their leaves. Some varieties of narrow leaf lupins are resistant to GPA and other aphid feeding damage (Tanjil and Wonga) while others are susceptible (Yorrel and Tallerack). Lentils are also more tolerant of (and less preferred by) RLEM than many other crops. Cereals have growing tips that are concealed and hence can tolerate much higher levels of RLEM damage than pulses and canola. For continuing pastures, consider selecting varieties with known mite tolerance. The pasture legume *Trifolium glanduliferum* (cv. Prima gland clover) is less susceptible to RLEM feeding. Subterranean clovers – Narrikup, Bindoon and Rosabrook – may suffer less damage from RLEM than other varieties. In the final instance, the selection of a variety should, of course, be based on the most productive option, but pest susceptibility should be a conscious consideration.

Grazing management

Grazing can be effective in managing populations of some pasture pests such as RLEM. Appropriate grazing of pastures can have flow-on benefits to subsequent crops in the rotation. Intensive grazing of pastures has been shown to reduce the abundance of mites. Shorter pastures can lower the relative humidity at the surface and increase mite mortality and limit food resources. Ideally graze to less than 1.4t/ha food on offer, three to four weeks prior to the Timerite® date. Heavily grazed spring paddocks should not require an insecticide spray.

Stubble management

Stubble retention influences the incidence of many pests. Stubble, particularly standing stubble, reduces the number of GPA alighting on the crop. GPA are more attracted to an open canopy with bare earth visible between crop rows.

In contrast, stubble favours the increase of some resident pests such as bronzed field beetles, weevils, slaters, millipedes, slugs, snails and armyworms. High stubble levels on the soil surface can also promote some soil insects due to a food source, but this can also mean that pests continue feeding on the stubble instead of germinating crops. Stubble provides a shelter from bird predators, increases moisture and cools the soil surface in favour of pests like snails. As is the case with weeds and diseases, when a paddock experiences an increasing burden from these resident pests from year to year, the stubble may need to be strategically managed by burning, windrowing, baling, grazing or incorporation (via cultivation) if its retention leads to high populations of invertebrate pests that impact on following crops.

Cultivation

While cultivation has no real impact on RLEM, other than through the removal of hosts, it does indirectly encourage GPA in young crops by removing any soil cover (see stubble management). However, cultivation can be used to disrupt other pest invertebrates that dwell in the soil for all or part of their life cycle (for example, weevils, cockchafers). Conversely, minimum or zero till can also result in a changing pest complex with the increase and survival of some predatory insects and earthworms, but also of certain pests including snails, slugs, earwigs and slaters.

3.6 Strategic use of insecticides

Effective pest and plant damage monitoring and use of pest (economic) thresholds will help ensure insecticides are only applied when needed.

Crop monitoring

Timely crop monitoring is essential to detect pest populations before they can cause significant crop loss. For some pests, it is critical to detect them before they are too large to control effectively or become entrenched in feeding sites where they cannot be controlled.

Monitoring numbers of pest and beneficial species over time by sampling crops can provide an estimate of the impact that beneficials may be having. For example, large numbers of ladybirds, lacewings or hoverfly larvae detected in sampling of canola crops indicates these beneficials are feeding on pests within the crop.

Monitoring over a number of weeks allows you to understand the population dynamics of the pests and beneficials. By maintaining records, you can assess whether populations are increasing or declining, and whether the beneficials can maintain pests below threshold levels.

Monitoring pre-season weeds for the presence of insects will provide an indication of potential pest pressure that may affect crop seedlings at germination.

There are numerous monitoring techniques available including visual searching, beat sheet, sweeping, suction sampling, pitfall trapping and shelter (refuge) traps. These are explained in detail on the IPM Guidelines for Grains website. Monitoring for RLEM is most accurately done with suction sampling, but visual searching is mostly used when time is limited. Similarly, sampling for DBM or corn earworm is most accurately achieved with beat sheets, but the much less accurate sweep netting is popular because it allows more rapid assessments.

Keeping records of pest and beneficial density in crops is essential for making decisions about management. This is particularly true for DBM, as beneficials play such an important role in suppressing populations. A pre-formatted sheet makes recording in the field easier and ensures you don't forget to record specific information such as crop growth stage, percentage of flowering and size of larvae. Standardised recording sheets ensures the same data is collected, regardless of who checks the paddock. It also makes it easy to transfer the field data to a spreadsheet to review changes in pest density over time.

Further information on monitoring, and an example of a recording sheet, can be found in the monitoring section of the *I SPY* manual.

Economic thresholds

The presence of a pest in a crop is not an automatic trigger for control. Attempting to prevent all damage rarely makes economic sense. Economic thresholds (ET) help to rationalise the use of insecticides and are one of the keys to profitable pest management and a cornerstone of integrated pest management (IPM). The development of economic thresholds requires knowledge of pests, their damage, crop responses to damage, estimates of likely crop value and costs of control.

An economic threshold can be defined as the critical pest density causing damage equal in value to the cost of control (insecticide and application). The ET is a quantitative measure and usually specified as the number of pests found per unit of crop area using a specified (standard) sampling technique. Yield loss and quality reduction are usually the critical factors (threshold types) governing control decisions.

The majority of economic thresholds available for insects in grains are nominal thresholds, where the relationship between pest density and yield loss has not been determined experimentally, but estimated based on experience of consultants and researchers. Nominal thresholds are not flexible in situations when crop values and spray costs vary widely, for example during seasonal price fluctuations. Yield-based economic thresholds have been developed for DBM, RLEM, corn earworm and various aphids; these use measured losses from invertebrate feeding that has a direct impact on yield, where the value of the damage caused is in direct proportion to the numbers present. In the absence of nominal or yield-based thresholds, risk assessments are sometimes recommended as a more practical approach. More options are provided on the IPM Guidelines for Grains website.

In general, the thresholds help to take out the guesswork of when to intervene. Thresholds are, at best, flexible guidelines that require constant revision and up-to-date knowledge based on system changes. In addition, the economic importance of a particular pest species will vary with crop type and developmental stage.

Insecticide use and beneficials

Conserving strong populations of beneficial insects starts with making well-informed decisions on the use of insecticides that recognise the following:

a) **Broad-spectrum insecticides dramatically reduce the abundance of beneficials**
The routine use of low-cost, non-selective insecticides can be very effective, but can also lead to changes in the populations of beneficials and non-target pests and increase potential chemical resistance.

For beneficials, the time it takes to rebuild populations depends on the species. For resident species like carabid (ground) beetles and some species of hunter spiders, which have only one generation per year, it could take two years for populations to recolonise and re-establish. For more transient species like hoverflies and parasitoids, populations might re-establish after a month or two, depending on the availability and vicinity of unsprayed refuges.

b) **Insecticides can have unexpected consequences for other pests**
Pest populations are often kept in check by both natural enemies and by competition from other pests. For example, applying chemicals with specific activity (such as bifenthrin) against redlegged earth mite will frequently lead to a substantial increase in lucerne flea numbers through the removal of both natural enemies and competition. Finally, through removal of beneficials, secondary pests may flare up, which can be more problematic than the initial pest problem. For example, growers have noted that by increasing their insecticide usage against RLEM they have not solved their plant damage problems, as they have selected for pests that are more difficult to kill, such as Balaustium mites.

c) **Insecticide drift**
Insecticides can drift onto areas of native vegetation thereby depleting beneficial numbers there as well.

Insecticide application

During spraying, insecticides must be applied to achieve maximum efficacy on the pest. This generally entails fine droplet sizes that penetrate and coat canopies with low drift and high coverage. Nozzle selection, water rates and addition of non-ionic surfactants all have a bearing on application effectiveness. Poor application effectiveness can increase selection for resistance (caused by exposure to sub-lethal doses) and may even result in the need for a second application (further increasing selection pressure for resistance). A good example is in spraying for DBM control. To achieve the necessary canopy penetration and coverage for late-season DBM control, water volumes of no less than 100 litres/ha (ground applied) should be used. Hydraulic nozzles spaced at 50cm producing a medium spray quality (e.g. 110-03 flat-fan nozzles) have provided good control of DBM in canola crops and reduce drift when effective products, at label rates, are used. Always refer to label directions for product-specific spraying set-up instructions, in conjunction with relevant RMS guidelines and the GRDC Spray Application Manual.

Regular systematic monitoring of pests and beneficial species is essential before applying insecticides. PHOTO: ALISTAIR LAWSON

3.7 Crop-specific IPM considerations

While IPM strategies may target specific pests, in reality, crops are attacked by complexes of numerous pest species that vary in importance across regions, paddocks and years. Growers are usually faced with management decisions at the crop level, replicated across the farm. Cereal, pulse and canola crops have specific pest risk profiles and IPM considerations. In general, non-chemical IPM options (cultural, physical, rotations) are available during non-cropping periods, while in-crop IPM is based around the strategic use of insecticides (risk assessment, thresholds, selective and/or biological insecticides) which aim to complement rather than disrupt biological control and minimise impacts on non-target species (such as resistance selection). In this section, IPM advice specific to crop type is provided.

Canola

IPM considerations: A large complex of more than 30 pest species attacks canola, and seedlings are particularly susceptible to damage. Leaf rasping-type pests (mites, lucerne flea) damage the germinating seed (including emerging cotyledons) and leaf surfaces, while chewing-type pests (beetles/weevils, earwigs, caterpillars) and molluscs (snails and slugs, also rasping-type pests) readily damage and/or remove cotyledons, leaves, stems and whole seedlings. The transmission of viruses prior to the rosette stage by even small number of infected aphids, particularly GPA, can impact yield. Following establishment, canola has a high capacity to tolerate leaf damage by pests, without yield impact. For example, damage caused by RLEM and lucerne flea beyond the four-leaf growth stage has a rapidly diminishing impact on yield. In spring, a pest complex (aphids, caterpillars, Rutherglen bug) can damage floral parts, leaves and pods, reducing grain weight. A diverse complex of beneficial invertebrate species becomes abundant in spring and can exert strong regulation on pest populations. Selective insecticide products are available for aphids and caterpillars. Broad-spectrum insecticides should generally be avoided in canola during spring to avoid selecting for resistance in non-target species (Table 2) and avoid destruction of natural enemies, which can cause secondary pest flares. Factors increasing pest risk in canola include a previous pasture phase, history of resident pests, summer weeds creating a green bridge, and warm and wet autumns supporting pest population growth.

Monitoring canola during the first three to five weeks after sowing is critical. As canola is typically the first crop sown during busy seeding operations, growers can lack this opportunity. Insecticide decisions made prior to sowing should be guided by assessment of pest risk. Commercial canola seed is usually distributed with a standard neonicotinoid seed dressing (4A). When not assessed against risk, this results in a prophylactic approach that limits some IPM practices and/or rotational strategies of an MoA group, central to resistance management.

Pulses

IPM considerations: Pulse crops are grown in rotations with cereal and canola crops for their valuable grain, which is marketed for consumption by humans (or stock), and as break crops for their benefits as a weed and disease break and replenishment of soil nutrients. Some pulses are unsuitable hosts for pest species and, in weed-free paddocks, reduce pest pressure in subsequent crops. Invertebrate pests can reduce grain yield but also grain quality, which is a key IPM consideration. At establishment, rasping-type pests (lucerne flea, earth mites) damage leaf surfaces while chewing pests (weevils, earwigs, pill bugs, slugs, caterpillars) may remove hypocotyl, cotyledons, leaf parts, whole leaves or seedlings. Pulse crops vary in their susceptibility to pest attack. Chickpeas contain malic acid, which can deter many pests (such as RLEM and certain aphids). Lentils are also very poor hosts for RLEM. At the seedling stage, crops with robust stems (beans, field peas) often outgrow moderate pest attack while crops with delicate stems (lentils, lupins, vetch) are more susceptible to seedling losses. Pulse crops are susceptible to infection by persistent and non-persistent viruses, some of which are seed-borne, which can be spread by aphid vectors primarily during autumn and spring.

In spring, Helicoverpa moths attack floral structures, pods and grain, Etiella attacks lentils, pea weevil attacks peas, and aphids attack all crops. For Etiella and pea weevil, spray timing is critical to control adults invading crops before females lay eggs, after which the juvenile stages enter developing pods and cannot be controlled. Temperature-based models are available to predict the timing of Etiella and pea weevil invasions. In lentil and pea crops, the relative timing of Etiella, pea weevil and Helicoverpa invasions into crops can vary between years, and hence careful monitoring is needed to determine the timing (and number) of any insecticide sprays that may be required. For Helicoverpa, pheromone traps and networks detect moth flights and provide early warning of potential larval activity in crops. Dynamic economic thresholds are available for direct damage caused by Helicoverpa in pulse crops. Depending on cost structures, in smaller-seeded pulses (such as desi chickpea), spray decisions for Helicoverpa can generally be made on calculated yield losses without risking penalties for reduced grain quality, but this may not apply for larger-seed grains (faba beans, field pea), where there is a higher likelihood of unacceptable levels of partially chewed grain.

Seed dressings and selective insecticides for aphids (pirimicarb, sulfoxaflor) are available in some pulse crops. Biological insecticides based on nucleopolyhedrosis virus (NPV) are available for Helicoverpa species.

Cereals

IPM considerations: Cereals are typically a lower-risk crop than canola or pulses, due to generally lower overall crop value and fewer damaging pests. In cereals, rasping-type pests (earth mites, lucerne flea) do cause some leaf surface damage, but less so than in other crop types. Chewing pests (weevils, wireworm) feed on leaves or roots while slugs can damage or remove leaves and seedlings. In higher rainfall regions, certain aphids can transmit viruses early in the season. Seedlings have a protected growing tip and can often recover from light or even moderate damage. In winter and spring, attack by aphids and caterpillars (armyworm) can reduce grain weight, while snails (in affected areas) can climb plants and contaminate harvested grain. Pest risk increases following a grass-dominant pasture phase and where summer rainfall creates a green bridge of weedy grasses.

In areas where Russian wheat aphid occurs, decisions about whether to apply neonicotinoid seed dressings (under permit PER82304) need to be made prior to sowing, guided by perceived pest risk. Prophylactic use should be avoided. Selective insecticides (pirimicarb) are available for aphids.

TABLE 4 A typical rotation with IPM options targeting key pests. The selection of IPM options is guided by paddock risk. Use of IPM practices aids in reducing risk of resistance evolution.

Season	Crop	Crop stage	Key pest complex	IPM option*	Target pests	Details of IPM option
Spring	Pasture	N/A	Many pasture pests (redlegged earth mite, other mites, lucerne flea, caterpillars, beetles/weevils)	Timerite® insecticide	Redlegged earth mite	Prevents the spring generation of mites producing oversummering diapause eggs, thereby minimising the following autumn population
				Heavy grazing	Redlegged earth mite, other mites, lucerne flea	Heavy grazing changes the microhabitat and reduces the survival of summer egg stages
Summer		**GRAZED or FALLOW**				
Autumn	Canola	Pre-seeding		Assess paddock risk	Redlegged earth mite and other key establishment pests	See 'Risk assessment and best bet' (Appendix 1). A previous pasture rotation increases pest risk
		Seeding	Redlegged earth mite, other mites, lucerne flea, earwigs, millipedes, cutworm, slugs, false wireworms, green peach aphid (virus)	Agronomic practices where appropriate for rapid crop establishment: high-vigour varieties (hybrid), sow into standing stubble, seed compaction	Green peach aphid, slugs and other key establishment pests	Standing stubble minimises bare ground and reduces aphid landings Soil compaction around the seed reduces the likelihood of slugs and other soil pests (for example, false wireworms) locating the germinating seedlings
				Pre-emergence: decisions on use of SD or PSPE are based on pest risk, RMS Post-emergence: monitoring, ET-based FI decisions, RMS	Redlegged earth mite and other key establishment pests	Strategic, targeted insecticide use where warranted, guided by pest risk, following RMS guidelines. ET available for redlegged earth mite. Spot or border spraying can be useful tactical responses
				Molluscicide baits coinciding with seeding (slug-affected patches)	Slugs	Protect seedlings from active slugs. Applied in high-risk areas
Winter		Vegetative	Pests are only occasionally problematic	Monitor and assess paddock risk		Low-risk period for virus spread by aphids (little aphid movement less than 17°C) Canola readily compensates for most pest feeding damage (including aphids) that may occur
Spring		Flowering/ ripening	Diamondback moth, aphids, Helicoverpa	Monitoring and ET-based spray decisions Selective/soft insecticides to conserve biological control. Avoid broad-spectrum products	Diamondback moth, aphids, Helicoverpa	Biological insecticides are available for diamondback moth (Bt) and Helicoverpa (NPV) Selective synthetic insecticides available for diamondback moth (emamectin, spinetoram) and aphids (pirimicarb, sulfoxaflor) Refer to beneficial impact table (Appendix 2)
Summer		**GRAZED or FALLOW**				
Winter	Wheat	Pre-seeding		Assess paddock risk	Redlegged earth mite and other key establishment pests (see 'Seeding')	See 'Risk assessment and best bet' (Appendix 1)
				Keep paddock free of medics, broadleaf weeds and grasses	Redlegged earth mite, other mites, lucerne flea, Russian wheat aphid	Weed-free paddock for three to four weeks before sowing reduces pest (and virus) carryover
				Graze stubbles	Snails, slugs, millipedes, earwigs, slaters	Disturbing and flattening stubble removes shelter and dries the soil surface, reducing survival of pests
				Control the 'green bridge' of grasses in/near paddock	Russian wheat aphid and other cereal aphids	Removing non-crop aphid hosts minimises colonisation of newly emerging cereals

TABLE 4 (cont.)

Season	Crop	Crop stage	Key pest complex	IPM option*	Target pests	Details of IPM option
Summer		**GRAZED or FALLOW**				
		Seeding	Lucerne flea, earth mites, cutworm, aphids (virus), Russian wheat aphid, wireworms	Use an SD (4A) only in high-risk situations (avoid prophylactic use)	Russian wheat aphid and other cereal aphids	A 'green bridge' of grasses in March and April increases risk Using SD only as needed reduces impacts on non-target pests (resistance) and beneficial invertebrates
				Avoid using PSPE insecticides unless high risk Post-emergence: monitor, ET-based decisions	Mainly lucerne flea, Russian wheat aphid. In some regions, slugs, mites and other sporadic pests	Cereal crops are less susceptible (than canola) to earth mites and other establishment pests ET available for redlegged earth mite (refer to section 1) Insecticide choice: follow RMS
		Vegetative	Armyworm, common cutworm, aphids	Monitoring and ET-based spray decisions Pirimicarb (aphids). Spot treatment when warranted	Armyworm, common cutworm, aphids	ET available for armyworm, Russian wheat aphid, oat aphid Pirimicarb conserves natural enemies Spot treatment conserves natural enemies in untreated areas
		Heading/ ripening	Armyworm, aphids	Monitoring and ET-based spray decisions	Armyworm, aphids	Refer to PestFacts regional updates for optimal time to monitor armyworm
Summer		**GRAZED or FALLOW**				
Winter	Lentils	Pre-seeding		Assess paddock risk	Redlegged earth mite and other key establishment pests (see 'Seeding')	See 'Risk assessment and best bet' (Appendix 1) Reduced risk of redlegged earth mite and other mites following a weed-free cereal rotation Check history of slaters and weevils as lentils are susceptible
		Seeding	Lucerne flea, earth mites, cutworm, weevils, aphids (virus), slaters	Pre-emergence: avoid using PSPE insecticides unless high risk Post-emergence: monitor and ET-based spray decisions	Lucerne flea, earth mites, slaters, weevils	
		Vegetative	Aphids (virus)	Monitor and assess paddock risk	Aphids	Low-risk period for virus spread by aphids (little aphid movement less than 17°C)
		Flowering, podding, pod-fill	Etiella moth, Helicoverpa, aphids	Monitor moth flights (degree–day model). ET-based spray decisions, well-timed sprays	Etiella moth	Insecticide sprays must target adult moths before females lay eggs
				Monitor, ET-based spray decisions, well-timed sprays (10 to 15mm larvae), selective/soft insecticides to conserve biological control. Avoid broad-spectrum products	Helicoverpa, aphids	NPV is available for small Helicoverpa (less than 7mm) to minimise negative impacts to beneficial pollinators and natural enemies

SD = seed dressing, PSPE = post-sowing pre-emergent insecticides, FI = foliar (post-emergence) insecticides, ET = economic thresholds, RMS = resistance management strategy, NPV = Nucleopolyhedrosis virus

Further reading

1. Online documents

***Beneficial Insects – The Back Pocket Guide* (Southern and Western Regions). GRDC (2012)**

IPM Guidelines for Grains https://ipmguidelinesforgrains.com.au
The IPM guidelines provide an extensive collection of tools and strategies to manage pests in grain cropping systems. The IPM guidelines use a problem-solving approach drawing on the available tools that are working within a specific crop. The website contains information about the main pests of grains, the major grain crops and a range of supporting information to guide users in making better decisions about pest management.

***I SPY – Insects of Southern Australian Broadacre Farming Systems Identification Manual and Education Resource* © 2018**
Published in 2012 and updated in 2018, *I SPY* is a comprehensive 212-page resource manual for southern Australian broadacre farmers and advisers covering basic taxonomy, important invertebrate groups and identification keys, and descriptions of common species, as well as information on monitoring, IPM principles and biosecurity. To download a pdf of the manual, order hard copies, or for more information, visit the GRDC website.

***Pests and Beneficials in Australian Cotton Landscapes* CottonInfo (2016). www.cottoninfo.com.au**

PestNotes www.cesaraustralia.com/sustainable-agriculture/pestnotes

Resistance management strategies (RMS) for pests in Australian grains

- RMS for green peach aphid and a report on the science that informed the RMS
https://grdc.com.au/GPAResistance Strategy
- RMS for redlegged earth mite and a report on the science that informed the RMS
https://grdc.com.au/FS-RLEM-Resistance-strategy
- RMS for diamondback moth in Australian canola and a report on the science that informed the RMS
https://grdc.com.au/fs-resistancestrategy/diamondbackmoth
- RMS for *Helicoverpa armigera* in Australian grains and a report on the science that informed the RMS
https://grdc.com.au/GRDC-FS-Helicoverpa-resistance-management

2. Published references

Edwards, O (2015). 'Investigation into the possible recent incursion of an insecticide-resistance biotype of green peach aphid into Australia'. GRDC project CSA00051.

Horne, PA; Page, J; Nicholson, C (2008). 'When will integrated pest management strategies be adopted? Example of the development and implementation of integrated pest management strategies in cropping systems in Victoria'. *Australian Journal of Experimental Agriculture* 48, 1601-1607.

Ridsdill-Smith, TJ; Pavri, C (2015). 'Controlling redlegged earth mite, Halotydeus destructor (Acari: Penthaleidae) with a spring spray in legume pastures'. *Crop and Pasture Science* 66(9), 938-946.

Umina, PA; McDonald, G; Maino, J; Edwards, O; Hoffmann, AA (2019). 'Escalating insecticide resistance in Australian grain pests: contributing factors, industry trends and management opportunities'. *Pest Management Science* 75, 1494-1506, DOI 10.1002/ps.5285.

Appendix 1

Assessing risk and applying ‘best bet’ IPM strategies

TABLE 5 Best bet IPM strategies for redlegged earth mite (RLEM)
Similar principles also apply to other earth mites and lucerne flea

Pre-season (previous spring/summer)	Pre-sowing	Emergence	Crop establishment
Assess risk. High risk when: ■ history of high mite pressure ■ pasture going into crop ■ susceptible crop being planted (canola, pasture, lucerne) ■ seasonal forecast is for dry or cool, wet conditions that slow crop growth If risk is high: ■ ensure accurate identification of species ■ use Timerite® (RLEM only) ■ heavily graze pastures in early-mid spring	In any case: remove green bridges (such as capeweed/medic) three to four weeks prior to and during establishment. If high risk: ■ consider RLEM-tolerant crop, where appropriate (chickpeas, lentils) ■ use higher sowing rate to compensate for seedling loss ■ use an insecticide seed dressing on susceptible crops ■ plan to monitor weekly until crop established ■ consider scheduling a post-emergent insecticide treatment (using a different MoA from previous year’s application) If low risk: ■ avoid insecticide seed dressings (especially cereal and pulse crops) and plan to monitor until crop establishment	Monitor susceptible crops through to establishment using direct visual searches. Be aware of edge effects; mites move in from weeds around paddock edges. If spraying: ■ ensure accurate identification of species before deciding on chemical ■ consider border sprays (RLEM) and ‘spot’ sprays (lucerne flea) ■ apply economic thresholds ■ spray prior to the production of winter eggs (within three weeks of emergence) to suppress populations and reduce risk in the following season	As the crop grows, it becomes less susceptible unless growth is slowed by dry or cool, wet conditions.

TABLE 6 Best bet IPM strategies for GPA in canola. Similar principles also apply to other aphids

Summer/autumn	Winter	Spring
Assess virus risk. High risk where: ■ high summer and autumn regional rainfall events that create a widespread brassica green bridge ■ warm conditions post-sowing (May–June) favour early aphid build-up and regular aphid flights If high risk: ■ uUse an insecticide seed treatment to manage virus spread (such as TuMV) by GPA aphid ■ remove *Brassica* weeds and volunteers three to four weeks before sowing. Ideally this is done area-wide via neighbouring growers	Monitor establishing crops for GPA (and other aphid) colonisation going in to winter and in in water-stressed crops, from late winter when daily temperatures start to rise above 17°C. NB: In crops beyond stem elongation, direct feeding by GPA populations rarely impacts on yield. Water-stressed crops can be more exposed to damage. High risk where: ■ warm or mild conditions in early winter, or when there is a forecast for warm and dry conditions that favour aphid development ■ aphids forming dense colonies on growing tips ■ no beneficial activity and/or aphid parasitism (if 10 per cent of aphids are parasitised, the population may be under control) If high risk: ■ consider border sprays with a selective aphicide (pirimicarb or sulfoxaflor) to prevent/delay build-up and retain beneficials	Monitor trends in GPA and other aphid and beneficial populations in crops over time. Use thresholds to guide spray decisions, considering crop stage and moisture stress. High risk where: ■ the crop is water stressed (GPA and other aphids) ■ infestation rapidly increasing during early flowering to bud formation (other aphids) ■ forecast is for warm and dry conditions to continue ■ low/no parasitism and beneficial activity (NB: this can also happen if synthetic pyrethroids/organophosphates are used to control DBM/native budworm) If spraying: ■ use soft products (pirimicarb, petroleum spray oils or sulfoxaflor) to retain beneficials, recognising the need for MoA insecticide rotations

TABLE 7 Best bet IPM strategies for DBM

Summer/autumn	Winter	Spring
Assess risk. High risk where: ■ high summer rainfall creates a green bridge of brassica hosts (e.g. Lincoln weed, wild radish, volunteer canola) ■ warm summer/autumn conditions favour early DBM build-up In any case, remove brassica weeds and volunteers three to four weeks before sowing. Ideally this is done area-wide via neighbouring growers.	Monitor crops for moths and larvae from mid-winter. Assess risk. High risk where: ■ DBM population present in mid to late winter ■ warm temperatures in mid to late winter ■ seasonal forecast is for a warm/dry spring If high risk: ■ consider a Bt spray to control small larvae (smaller than 1mm) and delay population build-up. Best where most larvae are small and beneficial activity and/or DBM parasitism (e.g. *Diadegma* sp.) is detected	Monitor crop with a sweep net for larvae until maturity. Use thresholds to guide spray decisions, considering crop stage and moisture stress. High risk where: ■ warm and dry conditions favour rapid population development ■ low beneficial activity and/or DBM parasitism (such as *Diadegma* sp.) (NB: this can also happen if synthetic pyrethroids /organophosphates are used) ■ moisture-stressed plants If spraying: ■ consider Bt to control small larvae less than 8mm – best where most larvae are small and beneficial activity and/or DBM parasitism (such as *Diadegma* sp.) is detected ■ prefer emamectin or spinetoram to control larger larvae ■ avoid synthetic pyrethroids /organophosphates which destroy beneficial insects (may flare pests) and increase resistance selection in DBM ■ rotate insecticide MOA groups across seasons ■ monitor after spraying to determine need for repeat application ■ ensure good spray penetration into the canopy

TABLE 8 Best bet IPM strategies for corn earworm

Summer/autumn	Winter	Spring
Assess risk. High risk where: ■ pheromone traps reveal enduring presence of corn earworm moths ■ larval populations in prior crops shown to be corn earworm If high risk: Use cultivation to 'pupae bust' paddocks of prior-infested crops	No risk.	Monitor for moths from Oct–Nov with pheromone traps. High risk where: ■ based on expert advice average weekly numbers exceed five to 10 moths (*H. armigera* only) If high risk: ■ timely monitoring of susceptible crops is critical – continue until crop is dry and unattractive, or harvested ■ use thresholds to guide spray decisions ■ use soft options first – consider biological insecticides (Bt or NPV) to control small larvae (less than 5 to 7mm) ■ rotate insecticide MoAs through the crop cycle ■ ensure efficacy of insecticides

Appendix 2

Impact of insecticides used in Australian crops on predators, parasitoids and bees

TABLE 9

Active ingredient (or chemical subgroup)	Persistence[1]	Invertebrate groups									
		Egg parasitoids[2]	Larval and pupal parasitoids[3]	Predatory beetles[4]	Predatory bugs[5]	Beneficial thrips	Predatory mites[6]	Lacewings	Spiders	Ants	Toxocity to bees
Bacillus thuringiensis (Bt)	short	VL	VL	VL	VL	VL	VL[7]	VL	VL	VL	VL
Nuclear polyhedrosis virus (NPV)	short	VL	VL	VL	VL	VL	VL[7]	VL	VL	VL	VL
Paraffinic oil	short	VL	L[7]	VL	VL	VL	L-H[7,8]	VL	L	H	VL
Chlorantraniliprole[9]	long	L	-	L	VL	VL	L[7]	VH	VL	L	VL
Primicarb	short	M	M	VL	L	L	L-H[7,10]	VL	VL	VL	VL
Indoxacarb	medium	VL	-	L	VL	VL	L[7]	M	VL	VH	H
Diafenthiuron	medium	M[7]	-	M	L	L	VH[7]	VL	L	H	M[7]
Abamectin	medium	M[11]	H[7]	L	M	M	-	VL	M	H	H
Emamectin	medium	M	VH[11]	L	H	M	-	L	M	VL	H
Sulfoxaflor[12]	medium	M	L-H[11,13]	L	L	H	L[11]	H	VL	H	VH
Spinetoram	medium	-	-	-	-	-	-	-	-	-	H[7]
Clothianidin	long	M	H	M	L	VL	-	H	M	VH	VH[7]
Imidacloprid	long	M	VH	H	H	H	H[7]	L	L	H	M
Thiodicarb	long	M	-	VH	M	H	-	VL	M	M	M
Methomyl	short	H	VH	H	M	H	VH[7]	M	M	H	H
Dimethoate	short	H-VH[7]	H	M	M	M	L-VH[7,14]	VH	M	VH	H
Fipronil	long	M	L-VH[7,15]	L	L	VH	VH[7]	L	M	VH	VH
Organophosphates[16]	short-medium	H-VH[7]	VH	H	H	H	VH[11]	L-M[7,17]	M	VH	H
Carbaryl	short	VH[7]	VH[7]	H	H	H	H-VH[7]	VH[7]	VH[11]	-	H
Thiamethoxam	unknown	-	VH[7]	VH[7]	VH[11]	-	M-VH[18]	H-VH[11]	L[11]	-	VH[7]
Methiocarb	long	VH[7]	VH[7]	VH[7]	VH[7]	-	VH[7]	VH[7]	L[11]	-	VH[7]
Synthetic pyrethroids[19]	long	VH	VH	VH	VH	VH	VH[7]	VH	VH	VH	H

The absence of a letter associated with a toxicity rating indicates the data was sourced from the *Cotton Pest Management Guide 2018-2019* (www.cottoninfo.com.au/publications/cotton-pest-management-guide; accessed 3 July 2019).

These toxicity ratings are derived from field assays. Overall impact rating (% reduction in natural enemies following application): VL (Very Low) <10%; L (Low) 10-20%; M (Moderate) 20-40%; H (High) 40-60%; VH (Very High) >60%. A dash (-) indicates no data available.

IMPORTANT NOTICE: Although the authors have taken reasonable care in the advice, neither the agencies involved nor their officers accept any liability resulting from the interpretation or use of the information set in this document. Information provided is based on the current best information available from research data. Users of insecticides should check the label for registration in their particular crop and state, and for rates, pest spectrum, safe handling and application details.
Further information on products can be obtained from the manufacturer.

PLEASE SEE FOOTNOTES PAGE 33 ▶

TABLE 9 (cont.)

FOOTNOTES:

1 Persistence of pest control: short = < 3 days; medium = 3-7 days; long = > 10 days. Source: *Cotton Pest Management Guide 2018-2019* and National Pesticide Information Center (http://npic.orst.edu/ingred/products.html; accessed 9 March 2019).

2 Egg parasitoids include multiple species of the genus *Trichogramma* (for example, *T. pretiosum*, *T. dendrolimi* and *T. cacoeciae*). Toxicity ratings based on adults.

3 Larval and pupal parasitoids include *Eretmocerus* spp., *Aphidius* ssp., *Dacnusa sibirica* and *Encarsia formosa*. Toxicity ratings based on adults.

4 Predatory beetles include ladybird beetles, red and blue beetles, and other predatory beetles. Toxicity ratings based on adults.

5 Predatory bugs include big-eyed bugs, minute pirate bugs, brown smudge bugs, glossy shield bug, predatory shield bugs, damsel bugs, assassin bugs and apple dimpling bugs. Toxicity ratings based on unknown life-stages.

6 Predatory mites include *Amblyseius* ssp., *Euseius gallicus*, *Feltiella acarisuga*, *Hypoapsis* ssp., and *Typhlodromus pyri*. Toxicity ratings based on adults.

7 Data sourced from the Biobest Side Effect Manual (www.biobestgroup.com; accessed 15 June 2019). Unknown toxicity assay methods (for example, field versus laboratory bioassays). Biobest toxicity classes were equated to the following toxicity ratings in this table: Class 1, <25% mortality = L; Class 2, 25-50% mortality = M; Class 3, 50-75% mortality = H; Class 4, >75% mortality = VH.

8 Toxicity rating of L for *Hypoapsis* ssp., M for *Amblyseius swirskii* and *Amblyseius californicus*, H for *Amblyseius cucumeris* and *Amblyseius degenerans*.

9 Chlorantraniliprole toxicity ratings based on *Cotton Pest Management Guide 2018-2019*; note the field rate of chlorantraniliprole in cotton is 52.5 g a.i/ha while field rate in grain crops is 24.5 g a.i/ha (based on Altacor® label).

10 Toxicity rating of L for *A. californicus*, *A. swirskii* and *Hypoapsis* ssp., H for *A. cucumeris*, *A. degenerans*, *Eseius gallicus* and *Feltiella acarisuga*. Corroborated from IOBC Pesticide Side-effect Database, which indicates a toxicity rating of L-H toxicity when applying 250 g a.i./ha.

11 Data sourced from International Organization for Biological Control (IOBC) Pesticide Side-effect Database (www.iobc-wprs.org). Toxicity ratings based on field, extended laboratory and/or laboratory bioassays. IOBC toxicity class were equated to the following toxicity ratings in this table: Class 1, <25% mortality = L; Class 2, 25-50% mortality = M; Class 3, 50-75% mortality = H; Class 4, >75% mortality =VH.

12 Sulfoxaflor toxicity ratings based on Cotton Pest Management Guide; note the field rate of sulfoxaflor in cotton is 48-96 g a.i./ha while field rate in grain crops is 12-96 g a.i./ha (based on Transform® label)

13 Different toxicity ratings based on days after treatment (DAT) effect on *Aphidius rhopalosiphi* in field trials using 7-48 g a.i./ha, L toxicity at 21 DAT, H at 0 DAT.

14 Toxicity rating of L for species *Hypoapsis* ssp., H for *Amblyseius californicus* and *Feltiella acarisuga*, VH for *A. cucumeris* and *A. degenerans*.

15 Toxicity rating of L for *Encarsia formosa*, H for *Eretmocerus* ssp., VH for *Aphidius* ssp. and *Dacnusa sibirica*.

16 Organophosphates includes omethoate and chlorpyrifos. Data for dimethoate is presented separately.

17 Toxicity rating of M for omethoate, H for chlorpyrifos.

18 Toxicity rating of M for *Amblyseius californicus* and *Hypoapsis* ssp, H for *A. swirskii*, VH for *A. cucumeris* and *A. degenerans*.

19 Synthetic Pyrethroids may include alpha-cypermethrin, cyfluthrin, bifenthrin, esfenvalerate, deltamethrin, lambda-cyhalothrin and gamma-cyhalothrin. Synthetic pyrethroid toxicity ratings based on Cotton Pest Management Guide; note the field rates vary between cotton and grain crops, for example, the field rate of alpha-cypermethrin in cotton is 30-50 g a.i./ha, while the field rate of alpha-cypermethrin in grain crops is 5-40 g a.i./ha (based on Alpha C 100 EC® label).

Appendix 3

IRAC Mode of Action (MoA) classification of insecticides registered in Australian grain crops*

TABLE 10

IRAC chemical Modes of Action classification (sub) group		Example active ingredients	Example registered products
Group 1A	Carbamates	Methomyl, pirimicarb, thiodicarb	Pirimor®, Aphidex
Group 1B	Organophosphates	Omethoate, dimethoate, chlorpyrifos	Le-mat®, Lorsban®
Group 2B	Phenylpyrazoles	Fipronil	Cosmos®
Group 3A	Synthetic pyrethroids	Alpha-cypermethrin, bifenthrin, gamma-cyhalothrin	Astound®, Dominex®, Fastac®, Trojan®
Group 4A	Neonicotinoids	Imidacloprid, thiamethoxam	Gaucho®, Cruiser Opti®, Poncho Plus®
Group 4C	Sulfoximines	Sulfoxaflor	Transform®
Group 5	Spinosyns	Spinetoram, spinosad	Success Neo®
Group 6	Avermectins	Emamectin benzoate	Affirm®, Wizard® 18
Group 11A	Microbial disruptors of insect midgut membranes – *Bacillus thuringiensis*	*Bacillus thuringiensis* (Bt)	Dipel®
Group 12A	Inhibitors of mitochondrial ATP synthase – Diafenthiuron	Diafenthiuron	Pegasus®
Group 22A	Voltage-dependent sodium channel blockers – Oxadiazines	Indoxacarb	Steward®
Group 28	Ryanodine receptor modulators – Diamides	Chlorantraniliprole	Altacor®
UN	Compounds of unknown or uncertain mode of action	Nuclear Polyhedrosis Virus (NPV) Parraffinic oils	Vivus Max Canopy®

SOURCE: WWW.IRAC-ONLINE.ORG/DOCUMENTS/MOA-CLASSIFICATION

*Current as of 2 July 2019.

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