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A review of off-target impacts of pesticides used in Australian almond production.

Prepared by Agriculture Victoria Research (Invertebrate & Weed Sciences) for Hort Innovation project AL16009 'An Integrated Pest Management program for the Australian almond industry'.

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1.1 Summary

The natural enemies of crop pests play an important role in the suppression of pests in many agricultural settings, by performing the ‘ecosystem service’ of biological control. Many different natural enemies of key almond pests have been documented globally and a number of those are known to occur in Australia. A threat to the conservation and maintenance of these beneficial species in any agricultural situation, including almond orchards, is the use of pesticides. Because of the nature of many pesticides and their application methods, off-target impacts will be incurred when they are applied, regardless of the care taken in application. Results from the global research effort on this issue have been used to compile a reference table of the expected level of off-target impacts of pesticides that are permitted for use in almonds in Australia. Information in the table has been selected to reflect the pesticide application rates used in Australia, and wherever possible, their impact on beneficial species known to occur in Australia. This information is intended to help identify pesticides that may be less disruptive to Integrated Pest Management programs, for producers who wish to be more strategic in their pesticide choice to minimise negative impacts on beneficial species in their orchards.

1.2 Introduction & scope

The purpose of this review is to document the potential for off-target impacts of pesticides on beneficial invertebrates in Australian almond orchards. For the purpose of this review, ‘beneficial invertebrates’ are defined as predatory and parasitic species that have the potential to provide some level of suppression of invertebrate pests. The review focuses on pesticides that are currently registered or permitted for use on almonds in Australia, and those registered for use on almonds in the USA. USA pesticides have been included as they represent a pool of pesticides that could be logically adopted for use in Australia. The information provided in this review is intended to help identify pesticides that may be less disruptive to Integrated Pest Management (IPM) programs, for producers who wish to be more strategic in their pesticide choice.

Fungicides and herbicides can also have negative impacts on beneficial invertebrates; however, these are not addressed in this current review. Pheromone-based mating disruption and trapping products are also excluded.

This document briefly introduces the beneficial invertebrates that have been identified in almonds to date, the potential off-target impacts of pesticide use and some concepts behind the determination and interpretation of pesticide impact ratings. The majority of information on pesticide impacts compiled from the sources listed in the bibliography is embodied in Table 5.

1.3 Background

1.3.1 Beneficial invertebrates and Australian almonds

Beneficial invertebrates play an important role in the suppression of invertebrate pests in many agricultural settings, by performing the ‘ecosystem service’ of biological control. Beneficial invertebrates can include species that are indigenous, naturalised, or deliberately introduced to perform specific services via biological control programs.

A review of the potential for biological control of the two key pests in Australian almonds, carob moth (Pyralidae: *Apomyelois ceratoniae*) and carpophilus beetle (Nitidulidae: *Carpophilus truncatus*) (Lubanga et al. 2018) found that 59 different natural enemies of carob moth had been documented globally. A number of those are known to occur in Australia, some of which have been observed in almonds during field activities for Project AL16009 ‘An Integrated Pest Management program for the Australian almond industry’ (Table 1). Additional invertebrate predators (Table 2) and potential parasites (Lubanga et al. 2018, Table 6) have also been observed in Australian almond orchards, although they have not yet been directly associated with carob moth. The same authors found only eight records of wasp parasites of Nitidulid beetles (the beetle family containing *Carpophilus* species), one of which is known to occur in Australia. No record was found of parasitic or predatory species directly associated with *C. truncatus*. Several entomopathogenic nematodes were also identified as attacking carob moth or Nitidulid beetles, and entomopathogenic fungi were noted as having some potential for management of almond pests (Lubanga et al. 2018; Tables 2 & 4). In addition to the known and potential natural enemies of carpophilus beetle and carob moth referred to above, there is also most likely a wide range of parasites and predators that are contributing to the suppression of other almond pests such as mites, aphids, Indian meal moth and Oriental fruit moth in Australian orchards.

While it is often difficult to quantify the overall contribution of biological control to pest suppression, there is little doubt that where they are present, parasites and predators are actively attacking other invertebrates, including pest species. The conservation of existing or augmented populations of beneficial invertebrates within almond orchards could therefore be expected to contribute, to some degree, to orchard pest management.

Table 1. Natural enemies of carob moth known to be present in Australia (AgVic 2020, Lubanga et al 2018).

Group/Order	Family: Species	Common name	Role	Observed in Australian almond orchards
Wasps (Hymenoptera)	Trichogrammatidae: Trichogramma carverae	Trichogramma	Egg parasitoid	✓ *
	Braconidae: Unknown	Parasitic wasp	Larval-pupal parasitoid	✓ *
	Chalcididae: Brachymeria?	Parasitic wasp	Larval-pupal parasitoid	✓ *
	Chalcididae: Antrocephalus mitys	Parasitic wasp	Larval-pupal parasitoid	
	Venturiaceae: Venturia canescens	Parasitic wasp	Larval parasitoid	
	Bethylidae: Goniozus jacintae	Parasitic wasp	Egg parasitoid	
Lacewings (Neuroptera)	Chrysopidae: Mallada signata	Green lacewing	Generalist predator	✓
Beetles (Coleoptera)	Melyridae: Dicranolaius bellulus	Red and blue beetle	Generalist predator	✓
Bugs (Hemiptera)	Anthocoridae: *Orius* sp.	Minute pirate bug	Generalist predator	✓
Earwigs (Dermaptera)	Forficulidae: Forficula auricularia	European earwig	Generalist predator	✓ *
Mites (Acari)	Pyemotidae: Pyemotes ventricosus	Predatory mite	-	
	Blattisociidae: Blattisocius tarsalis	Predatory mite	-	
Nematodes (Rhabditida)	Heterorhabditidae: Heterorhabditis bacteriophora	Predatory nematode	-	
* directly observed parasitising or predating carob moth eggs, larvae or pupae in almonds in Australia.				

Table 2. Additional generalist predators observed in Australian almond orchards (AgVic 2020).

Group/Order	Family: Species	Common name	Role
Lacewings (Neuroptera)	Hemerobiidae: Micromus tasmaniae	Brown lacewing	Generalist predator
Beetles (Coleoptera)	Coccinellidae: Coccinella transversalis	Transverse ladybird	Generalist predator
	Coccinellidae: *Stethorus sp.*	Stethorus 'Mite destroyer'	Predator of mites
Hoverflies (Diptera)	Syrphidae: Melangyna viridiceps	Hoverfly	Generalist predator

1.3.2 Pesticides and Australian almonds

Almonds have been grown commercially in Australia since the early 1900's (Philip 2017). Historically, Australian almonds have been relatively free from economically significant insect pests, and as a result there has been little need for pesticide use in the industry. However, after the extremely wet harvest season of 2011, the two key insect pests, carob moth and carpophilus beetle emerged as serious economic threats to the industry. In late 2011, following record high crop losses due to carob moth, the Almond Board of Australia (ABA) obtained an emergency use permit from the Australian Pesticides and Veterinary Medicines Authority (APVMA Permit PER13233) to allow the industry to use the insecticide chlorantraniliprole (DuPont Altacor ®) - a product with a history of use against the related navel orangeworm (Pyralidae: *Amyelois transitella*) in Californian almond production. Additional pesticides were subsequently made available to Australian almond producers, including the broad-spectrum pyrethroid bifenthrin, but despite an overall increase in pesticide use, crop damage levels remained unacceptably high. The 2018 crop for example, suffered an average 10% insect damage, costing the Australian industry over $25 million (Almond Board of Australia, personal communication, July 1, 2020). As of May 2021, there are currently 31 pesticide products (insecticides/miticides) based on 16 different active ingredients (Table 5), registered or temporarily permitted for use in Australian almonds (APVMA online product/permit search, accessed May 2021).

1.3.3 Pesticides – costs & benefits

A key threat to the conservation and maintenance of beneficial invertebrate populations in any agricultural situation, including almond orchards, is the use of pesticides. Because of the nature of many pesticides and their application methods, off-target impacts will be incurred when they are applied, regardless of the care taken in application. The level of impact depends on numerous factors including the beneficial species and type of chemical involved, and the efficiency and timing of application. In some cases, the impacts can be long-term. A single hull-split application of bifenthrin for example, left residues on almond twigs that remained toxic for at least six months to the predatory mite, *Galendromus occidentalis* (Hamby et al. 2013). That predator is considered the main bio-control agent for spider mites in Californian almonds and was introduced into Australia in the 1970s for spider mite control (James 2001).

From a producer's perspective, the main effect of negative impacts on beneficial invertebrates is likely to be secondary pest outbreaks due to 'ecological release'. This occurs when pest species that were previously suppressed by their natural enemies, are freed from the effects of predation and parasitism (Gross & Rosenheim 2011; Hill et al. 2017). Secondary outbreaks of pest mites are seen in almonds (Bentley et al. 1987; personal observation) because of the impact of pesticides on important mite predators, as mentioned above. Such outbreaks may then require or prompt further pesticide treatments with the risk of additional off-target impacts and increased costs (e.g. Gross, & Rosenheim 2011).

Regarding protection of the almond crop from initial infestation, the difficulty in delivering pesticide to the upper portions of trees (where carob moth damage is concentrated), and to the hull split in particular (the site of entry by carpophilus beetle and carob moth), has been well documented (Rosenzweig & Furness 2013; Siegel et al. 2019), with the latter study concluding that "Less than 1% of the insecticide in the tank was deposited on the almond suture". The same difficulties apply to attempts to reduce the field population of these pests already within nuts, where they are protected from contact with pesticides. For example, after a commercial application of chlorantraniliprole at hull split, a survey of carob moth larvae found almost half were unaffected, and in field experiments, kernel assessments at harvest found that carob moth damage was reduced by a hull split application of chlorantraniliprole in only one of three seasons (Madge et al. 2015). For these reasons, the balance between potential benefits of pesticide application (reduced kernel damage) and potential costs (e.g. negative impacts on beneficial species) plus real costs (e.g. chemicals, equipment, labour) needs careful consideration.

Despite their drawbacks, pesticides do have a role to play in IPM programs and can lead to successful pest management outcomes when effectively combined with biological control and other IPM-compatible strategies such as mass trapping and mating disruption (Higbee 2021). For this reason, it is important that pesticides be assessed for impacts on beneficial species in almonds (Zalom & Irigaray 2010), and that orchard managers make informed decisions about the use of pesticides, considering cost, effectiveness, timing and mode of application, environmental contamination, and the potential consequences of off-target effects.

1.4 Pesticide impacts on beneficial invertebrates

1.4.1 Products vs active ingredients

Because of the differences in concentration of active ingredients (a.i.) between commercial pesticide products, the complexities of potential interactions between different a.i., and the infinite combinations of a.i. and their concentrations in spray tank mixes, most research trials on the impact of pesticides on invertebrates consider each a.i. in isolation. When choosing a pesticide for a particular purpose, with off-target impact ratings as a guide, it is up to the user to select an appropriate product based on the relevant a.i.

1.4.2 Modes of impact

Pesticides can have lethal or sublethal effects on beneficial invertebrates via contact (direct spray or fresh or dry residues) and ingestion (consumption of contaminated hosts/prey or other food sources such as pollen and nectar). Sub-lethal effects include changes in oviposition behaviour, fecundity, sex ratios, developmental rate, mobility, orientation, navigation, and feeding behaviour, leading to decreased population size and efficacy as biocontrol agents. For example, adult green lacewings exhibited reduced survival and fecundity and produced offspring with reduced survival rates when fed on nectar produced by sunflowers that were grown from seed treated with chlorantraniliprole (Gontijo 2014). It is clearly important to include the more subtle and longer-term impacts on beneficial invertebrate populations, not simply immediate toxic effects, when generating and using pesticide impact ratings.

1.4.3 Comparing impacts

Comparing the impacts of different pesticides on beneficial invertebrates can be problematic as there is no universally-applied standardised procedure for testing. Experiments have been conducted in a range of settings including laboratory, glass house and in-field, using various application methods and chemical rates. There are also multiple methods used for measuring the impacts, involving observation of various combinations of the effects mentioned above. Fortunately, more research on pesticide impacts now appears to comply with a set of ‘Guidelines to evaluate side-effects of plant protection products to non-target arthropods’, published by the International Organisation for Biological and Integrated Control (IOBC) (Candolfi et al. 2000), making direct comparisons easier.

1.4.4 Sources of information

Three main sources have been used in compiling the table of off-target impacts of pesticides:

IOBC. A database of the effects of pesticide a.i. on a selection of beneficial invertebrates is maintained by the International Organisation for Biological and Integrated Control (IOBC), (IOBC 2021). The database was established by the IOBC-WPRS (West Palaearctic Regional Section) ‘Working Group on Pesticides and Beneficial Organisms’ together with the IOBC ‘Commission on Guidelines for Integrated Production’. It contains ratings of pesticide impacts (Table 3) derived from published, peer-reviewed reports of field and laboratory experiments that comply with the IOBC standards for pesticide studies, including trials that are required for the registration of pesticides within the European Union. An Australian field study (Thomson & Hoffmann 2006) found that IOBC ratings of agricultural chemicals used in vineyards could be linked to the overall composition of beneficial invertebrates within those vineyards. The authors concluded that their results “reinforce the usefulness of IOBC or other rating systems based on laboratory testing for predicting likely effects on commercial vineyards” and that “IOBC toxicity ratings appear useful in making informed choices about toxicity load”.

Table 3. . IOBC rating scale for pesticide impacts on beneficial invertebrates (Sterk et al. 1999).

IOBC Rating	Laboratory studies	Field studies
1 (harmless)	<30% mortality	< 25% mortality
2 (slightly harmful)	30–79% mortality	25–50% mortality
3 (moderately harmful)	80–99% mortality	50–75% mortality
4 (harmful)	>99% mortality	>75% mortality

Koppert. A database of side effects of pesticides on natural enemies is also maintained by Koppert Biological Systems (Koppert Biological Systems 2021). The Koppert database collates data from their own research trials and field observations as well as from published research reports and the IOBC.

Stand-alone reports. Where possible, gaps in the data table were addressed by reviewing individual published, peer-reviewed research reports (see Bibliography).

1.4.5 Interpretation of disparate impact ratings

Apparent discrepancies in pesticide impact ratings can arise from use of the different testing methods mentioned earlier. The most common approaches to determining pesticide impacts on invertebrates are:

- Laboratory bioassays. The test organisms are 100% exposed to direct sprays or spray residue, with no access to untreated refuge areas. These represent ‘worst-case’ scenarios.
- Field trials. Spray coverage will often be less than 100% and the organisms usually have access to refuges within and adjacent to the treated area. These represent ‘real-life’ scenarios.

Because of these differences, in some cases, levels of mortality observed in laboratory bioassays are very high (IOBC rating 4), while those seen in field trials with the same chemical are considerably lower (IOBC rating 1-3). This review has preferentially used the impact ratings from field trials where available, on the assumption that they are likely to more closely reflect the impacts expected in field situations.

Similar discrepancies can arise from the use of different impact assessment criteria, in particular the toxicity to individuals in the short-term vs longer-term population trends. Because both impacts are important to the functioning of biological control systems, the higher of the two ratings have been used in this review.

1.4.6 Relevance to the Australian context

1.4.6.1 Invertebrate species

The effects of pesticides on different species within a broad functional group e.g. predatory bugs or parasitoid wasps varies, meaning broad conclusions on the effect of pesticides across a whole group can be misleading. Additionally, there are limited studies on the specific beneficial invertebrate species found within Australian almond orchards. In this review, impact data relating to species found in Australian almonds was used where possible, but in the absence of directly relevant studies, the effect of pesticides on insects within the same genera or functional groups were used.

Given the many inconsistencies among published studies and the lack of data on species specific to Australian almond orchards, it would be prudent for the Australian almond industry or pesticide companies to conduct pesticide impact assays specific to the suite of beneficial insects found in Australian almond orchards.

1.4.6.2 Pesticide application rates

Different field and laboratory experiments on the impact of pesticides on particular species can involve quite different application rates, resulting in apparent discrepancies in impact ratings for the same chemical. To address this, the impact ratings of each a.i. reported here were selected from studies that used application rates as close as possible to the field application rates (g/ha or g/l) for which that a.i. is registered for use, for dilute spraying on almonds in Australia. For a.i. not registered for Australian use, the relevant USA application rate was used.

Where pesticide impact experiments used a.i. application rates that were significantly higher or lower than the rates applicable to almonds, the impact ratings were applied as shown in Table 4.

Table 4. Application of IOBC pesticide impact ratings.

	IOBC impact rating	
Experimental a.i. application rate	1 (harmless)	2 (slightly harmful) or 3 (moderately harmful) or 4 (harmful)
< half the field rate	No rating inferred	2+ or 3+ or 4
Between half and double the field rate	1	2 or 3 or 4
> double the field rate	1	No rating inferred

Where volume-based label application rates (g/l) needed to be converted to area-based rates (g/ha), such as for interpreting the IOBC Pesticide Side Effect database (IOBC 2021), the following spray volume application rates were used (almond producers, pers. com.):

- early-season (light foliage), e.g. spring aphicide 1,500 l/ha
- mid-late season (full foliage), e.g. hull-split spray 2,000 l/ha
- dormant drench (no foliage), e.g. winter oil 3,000 l/ha

1.5 Pesticide impacts table

Table 5 lists levels of impact on beneficial invertebrates, of pesticide active ingredients that are registered or available on limited permit for use in almonds in Australia and the USA. Where information for beneficial invertebrate species that are found in Australian almond orchards is missing, species from the same genera or functional group (e.g. predatory mites) have been used. More than one species from each group has been included in the table to demonstrate that the impact of pesticides can vary among species within the same group. The effect of pesticides has been categorised by the four levels designated by the IOBC as described above and in the table legend.

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1.8 Table 5. Off-target impacts of pesticides used in Australian and USA almond production.

	Registered ✓ Permit P						Predatory mites				Predatory beetles		Predatory bugs		Lacewing	Parasitoid wasps		Earwigs	Entomopathogenic fungi	Entomopathogenic nematodes		
Active ingredient	**Aust.**	**USA**	**Target pest**	**MOA**	**Phys+**	**Field rate g a.i./ha**	*Amblyseius swirskii*	*Neoseiulus californicus*@	*Phytoseiulus persimilis*@	*Typhlodromus pyri*@	*Cryptolaemus montrouzieri*@	*Harmonia axyridis*	*Orius insidiosus*	*Orius laevigatus*	*Chrysoperla carnea*	*Trichogramma brassicae*	*Trichogramma cacoeciae*	*Forficula auricularia*@	*Beauvaria bassiana*@	*Heterorhabditis bacteriophora*@	*Steinernema carpocapsae*@	*Steinernema feltiae*@
abamectin	✓	✓	Mites, leafminers	6	N&M	13.5	3	4	4	1	1, 3L		4	4	3*, 4	4	4			1	1L	
acequinocyl		✓	Mites	20B	R	339.3	1	1	1	1	1L		1	1	1							
Bacillus thuringiensis^		✓	Caterpillars	11A	M	1905.4	1	1	1	1	1		1	1	2	1	1	1	1	1	1	
bifenazate	✓	✓	Mites	20D	R	624.0	3*	1	2	4	1L	2	1	1	1							
bifenthrin^	P		Carpophilus beetle	3A	N&M	150.0	4*	4	4	4			4	4	4	4				1	1L	
buprofezin		✓	Sucking insects, beetles	16	G&D	2255.7	1	1	2	2	2		1, 2N	1, 2N	2	1		1		1	1L	
carbaryl		✓	Insects, mites	1A	N&M	5604.2	3*	3	3	4		4	4	4	4	4	4			1		
chlorantraniliprole	✓	✓	Carob moth	28	N&M	126.0	1*	1	1*	1	1L	1	1#	1	1	1#	1#	1		1	1L	
clofentezine	✓	✓	Mites	10A	G&D	300.0	1	2	1	1	1*, 1	1	1	1	1	1	1		1+			
clothianidin^	✓		Carpophilus beetle, carob moth	4A	N&M	400.0	4*	4*	4*	4	4			4	4							
cyfluthrin		✓	Insects, mites	3A	N&M	24.9	4*	3	4	4			4	4	4	4	4	4	2+	2	2L	2+
diazinon		✓	Insects, mites	1B	N&M	1246.9	3*	2*, 2	2	4			3	3	4	4	4			2	2L	
diflubenzuron		✓	Caterpillars	15	G&D	280.2	1*	2	1	1		1, 4L	1, 4N	2	4	1		4		1	2L	
emamectin benzoate		✓	Caterpillars	6	N&M	16.8	4*	4*	4*				4, 4*	4, 4*	4	2						
esfenvalerate		✓	Insects, mites	3A	N&M	118.6	4*	3	4*	4			4	4	4	4				1	1L	
etoxazole	✓	✓	Mites	10B	G&D	77.0	2*	3*	3*, 4E	3			3	1	1							
fenbutatin oxide		✓	Mites	12B	R	1401.1	2*	1	2	2	1		1, 2N	1, 2N	1	1						
fenpropathrin		✓	Insects, mites	3A	N&M	447.6	4*	3	4	4	4		4	4	4	4	4	2		3	3L	2+
fenpyroximate		✓	Mites and some insects	21A	R	224.2	2*	1	4	1	1		1, 2N	1, 2N	2		2					
hexythiazox		✓	Mites	10A	G&D	210.2	1	1	1	1	1	1	1	1	1	1				1	1L	
lambda-cyhalothrin		✓	Bugs, beetles, caterpillars	3A	N&M	44.8	4*	4*	4	4			4	4	4	4	4	4		1	1L	2+
metaflumizone		✓	Ants	22B	N&M		1*	1*	2*				2	1, 2N	1					1	1L	
methoprene		✓	Ants	7A	G&D		1*	1*	1					1	1					1	1L	
methoxyfenozide	✓	✓	Caterpillars	18	G&D	384.0	1	1	1	1	1		1, 2N	1	2	1						
paraffinic oil	✓		Mites and San Jose scale	NA	Unk	50820.0	4*		2	4					4						1L	
petroleum oil	✓	✓	Aphids, mites	NA	Unk	33040.0	4*	2	3		1		1	2	1					1	1	
phosmet		✓	Insects, mites	1B	N&M	3373.8	2*	1*, 1	4	4		4		4	4	4	4	4		1	1L	
pirimicarb	✓		Aphids	1A	N&M	360.0	1	1	2	2	1		1	2, 3N	2	4	4					
propargite		✓	Mites	12C	R	3586.7	3	3*, 1	4	4			3	3	4	1	2			3	3L	
pymetrozine	✓		Aphids	9B	N&M	150.0	1	1	1	1	1L	2	1	1	1		3					
pyriproxyfen		✓	Scale, beetles	7C	G&D	120.5	1	2	2	2	2	4	1	1	2	1						
spinetoram	✓	✓	Caterpillars, aphid, scale	5	N&M	105.0	4*	4*	3*		1		4	4	4		4					
spinosad		✓	Caterpillars, aphid, scale	5	N&M	175.1	4	3*, 1	2	4	4L		1	2, 3N	4		2#					
spirodiclofen		✓	Mites	23	G&D	180.0	2*	2*, 2	4*, 4	2			2, 4N	4	2							
sulfoxaflor	✓		Aphids	4C	N&M	37.5	1*, 3	1*	1*	1	2*	2	3	3*	1*	3#						
sulfur (lime sulfur)	✓	✓	Mites and thrips	Unk	Unk	15000.0	4		4	4				3	4		4	1	2+			
tetraniliprole	✓		Carpophilus beetle	28	N&M	50.0				1					1							

^ ssp. Kurstaki

@ known to occur in Australia

+ Targeted physiology

N&M - Nerve & Muscle

G&D - Growth & Development

R - Respiration

M - Midgut

Unk - Unknown/non-specific

IOBC toxicity rating		Study type: Laboratory	Study type: Field
1	Harmless	<30% mortality	< 25% mortality
2	Slightly harmful	30–79% mortality	25–50% mortality
3	Moderately harmful	80–99% mortality	50–75% mortality
4	Harmful	>99% mortality	>75% mortality
	Blank cells indicate no available data, or that the available test data relates to application rates that are not close enough to the field application rate in almonds to be relevant.		

Cell notations

E = Eggs

L = Larvae

N = Nymph

* = population effect

= Result against other species in the same genus